

LAND & WATER AUSTRALIA

Environmental water allocation: principles, policies and practices

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Contents

Preface	5
Acknowledgments	5
The debate on environmental water allocation	6
Water reform	6
Constraints	7
Unresolved and emerging issues	8
Socio-economic challenges	8
Improving water allocation and water-trading arrangements	8
Assessment of the costs and benefits of increasing allocations to the environment	8
Understanding and managing the impacts of reductions in allocations for consumptive water use	9
Development of cost-effective ways to enhance environmental flows	9
Improving administrative arrangements for the management of water allocations	9
How should we decide?	10
'Environmental water' — different things to different people	12
Rivers and wetlands	12
Groundwater	13
Terrestrial vegetation	13
River base-flow systems	13
Aquifer and cave ecosystems	13
Wetlands	13
Terrestrial fauna	14
Estuarine and near-shore marine systems	14
Common assumptions reconsidered	15
Spare water	15
Incremental decline in flows	16
Rivers will recover from many perturbations	16
The natural disturbance regime of rivers is important for the maintenance of their biodiversity	16
Maintenance of habitat will ensure the persistence of species	16
Riverine communities (and particularly those of semi-arid regions) are driven by abiotic rather than biotic processes	16
Approaches to implementation	18
Water quality	18
Methods used to estimate environmental water requirements	18
Advantages and disadvantages of the different methods for rivers	19
Recent developments	19
Gaps	20
General principles	21
Deficiencies	21

Current policy in Australia	22
Policy needs	22
Influences	23
Case studies	24
Barmah–Millewa Forest, Victoria and New South Wales	24
Burnett Basin, Queensland	25
Campaspe River, Victoria	25
Lachlan River, New South Wales	25
Macquarie Marshes, New South Wales	26
Murrumbidgee River, New South Wales	27
Snowy River, New South Wales and Victoria	27
Lessons learnt	29
Implementation	29
Development and delivery of optimal environmental-flow regimes	30
Using adaptive management to achieve ‘value for volume’	30
Research	30
Knowledge gaps	31
Future directions	34
Existing legislation relevant to environmental water	34
Principles for environmental water legislation and policy	35
New science and methods	35
Concluding remarks	37
A future vision	37
References	38

Preface

In recent decades it has been widely recognised that the impact of human society on the environment is beginning to threaten the basic foundation upon which we depend for food, shelter and a sense of wellbeing. Of all the resources that are important to people, perhaps the one most under pressure is water. Traditionally, the focus has been on water quantity, getting enough to do what we want. Now the concern is about the health of our aquatic ecosystems, as well as human needs, both being dependent on the availability and quality of water.

Water is basic to a large number of values that are important to people. In addition to its direct and immediate life-supporting attributes, it is also essential for the continued functioning of most other ecosystems in the natural environment. The level of human impact on the natural world is now so great, however, that in many situations it has become necessary to deliberately set aside a proportion of the available water so that the environment and its ecosystems can continue to function. Water used for this purpose is described by the all-embracing term 'environmental water'. However, as this discussion paper shows, that umbrella description includes a great variety of different strategies, aims and situations.

As a result of the changes induced by development over the past century or more, many hydrological systems (rivers, lakes, wetlands, groundwater systems etc.) have been substantially altered from their pre-development state and are undergoing further rapid transformation. There is increasing pressure to take a holistic or integrated approach to the management of these systems. In many cases, it is clear that a return to pre-development environmental conditions, 'the river's natural state', is not a management option although there is a widespread assumption that it should be.

For society and the managers responsible for any particular hydrological system, the central questions are:

- what values should shape water management?
and, more specifically,
- once the aims are defined for a particular hydrological system, how can they be achieved?

This document seeks to contribute to the national debate on those issues.

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The debate on environmental water allocation

Disquiet about the impacts of large dams and the degradation of rivers became a major public issue involving many scientists, activist groups and concerned individuals in the early 1970s when remote Lake Pedder was flooded and the wild rivers of Tasmania were threatened by hydro-power developments.

One year after the adoption of Agenda 21 at the Rio Summit for Sustainability in 1992, the Commonwealth Government and all State governments and Territories committed Australia to the principles of ecologically sustainable development. These principles have many implications for the management of waterbodies both marine and freshwater. This commitment to ESD led to a wide-ranging program of water reforms, requiring restructuring of the water industry and formal allocations of water to the environment. Since then, rivers and wetlands have been recognised as legitimate ‘users’ of water, and jurisdictions have been defining and implementing water allocations to sustain and restore ecological processes and the biodiversity of water-dependent ecosystems.

Rainfall is unevenly distributed across Australia and its frequency and intensity are extremely variable. These have been a major influence shaping settlement since 1788. To secure reliable water supplies, the early colonists started manipulating water flows soon after they arrived. Since then, a multitude of water control devices, locks, floodplain levee banks, and nearly 450 dams with walls higher than 10 metres have been built. In the Murray–Darling Basin, there are now more than 3600 weirs and other structures. Over 50 schemes to transfer water either within or between catchments have also been completed.

Australia now has the highest per capita water storage capacity in the world, with 79% of this water used for irrigation. Most of this water is held in a few very large storages, the 10 largest holding about 50% of the capacity. As a result, many Australian waterbodies and streams are very highly modified. The total volume of river flows has been substantially reduced, and flow patterns over time fundamentally have been altered in many of the continent’s great rivers. This is true of the River Murray, the major headwater tributaries of the Darling in New South Wales, the Burdekin, Fitzroy,

Proserpine, Pioneer, Burnett and Brisbane rivers of Queensland, some coastal rivers in New South Wales, the Snowy River in Victoria, the Ord River in Western Australia, and the Gordon and other Tasmanian rivers. Many small stream systems throughout the continent have also been affected.

For most rivers, there have been significant changes to the frequency and duration of the times when the rivers and their wetlands are dry or wet, the geographical distribution of floods and the links with other environmental cycles and events. In some cases there is less water, in others too much. Some wetlands and temporary streams that used to be dry periodically are now permanently wet, or have lost their natural seasonal pattern of wet and drier months. As a result, the environment within which Australia’s riverine flora and fauna evolved has undergone rapid change, making a reduction in biodiversity unavoidable.

Water reform

Fear of irreversible environmental degradation is a key concern for governments. Australia is the only megadiverse country in the Organization for Economic Cooperation and Development, but its plants and animals are increasingly under threat from habitat disruption including declining river flows. Permanent degradation of water resources is seen to reduce opportunities for future generations. Governments also have to respond to the international status given to ecosystems placed on the Ramsar list of major wetlands.

In 1994, in response to growing environmental concerns and the need for economic restructuring of the water industry, all three tiers of government in Australia — Commonwealth, State/Territory and local — committed themselves to national water reform. The Council of Australian Governments (COAG), representing the Commonwealth Government and all States and Territories, drove the process. The reform package required governments to “implement comprehensive systems of water allocations and entitlements backed by separation of water property rights from land title and clear specification of entitlements in terms of ownership, volume, reliability, transferability and, if appropriate, quality”.

To give policy guidance to jurisdictions and water managers responsible for implementing the reforms, the Commonwealth and State governments approved 12 national principles for the provision of water for ecosystems. These principles are designed “to sustain and where necessary restore ecological processes and biodiversity of water dependent ecosystems” by means of environmental water allocations that are legally recognised and founded on the best scientific information available.

Under the Australian Constitution, State and Territory governments have responsibility for the management of the surface and groundwater resources of the continent (except for those on Commonwealth land). Thus, to implement the COAG water reforms, all jurisdictions have had to introduce new water legislation and make adjustments to their policies and institutional structures. This has led to diverse legislative and institutional arrangements, and a wide variety of water allocations for the environment. These reflect different geographic, climatic and ecological conditions, past policies, water management practices and commitments to water users, and scientific and methodological developments.

The COAG program was introduced in response to increasing scientific evidence and community concern about environmental decline. Data published since implementation started have given further support to the reform effort. Reports have continued to focus on the declining health of Australia’s rivers, with the lack of flowing water seen as a critical cause. Recent high profile reports include “Australian Water Resources Assessment 2000” (NLWRA 2001) and the Australia State of the Environment report (Australian State of the Environment Committee 2001). The former identifies 26% of Australia’s river basins as approaching or beyond sustainable extraction limits and 34% of Australia’s groundwater management units as approaching or beyond sustainable extraction limits.

These reports have been backed up by widespread media coverage of rivers running dry. The campaign run by *The Australian* newspaper about the state of the River Murray is a prime example of the level of media involvement in these issues. Community opinion is mixed, however, as members of many communities are directly reliant on water use for their economic survival.

Constraints

There are some very significant forces constraining efforts to introduce effective environmental water allocation programs. One factor has been the lack of resolution of several key questions, making it very difficult to debate the issues constructively.

What, for example, is an appropriate balance between environmental and human water consumption? This is clearly an issue that should involve the resolution of conflicting values by society as a whole. It can be only partially informed by science, which is still struggling to describe and understand the environment and the impact of water diversions upon it.

There is also a need to decide who should make major decisions and how different interests should be represented. To what degree should matters be left to regional communities? How should national and international concerns be dealt with?

Who should pay is another unresolved issue. This question particularly arises in river systems in which the water resource has been over-allocated to consumptive uses. Reducing allocations will incur costs on water users and, in some cases, make enterprises economically unviable.

For many consumers, the need to clearly describe the benefits of allocating water for the environment is a significant issue. While every kilolitre of water used for production can be readily translated into economic benefits, no such direct calculation can be done for the environment.

A constraint of a different sort is the continued use of ageing irrigation infrastructure that leaks, is poorly designed to minimise evaporation losses and is unsympathetic to fish passage. Its poor condition makes it more difficult to improve flow regimes and gain extra water for the environment by reducing water losses.

There is also a demand from industry for more certainty and predictability about access to water. This conflicts with the need to develop a more flexible approach able to take advantage of opportunities created by environmental events such as floods or to implement policies such as ‘translucent’ dams that automatically allow a given proportion of any rainfall to flow through the storage to the river downstream. Even greater flexibility (and uncertainty for diverters) will be required to deal with the impacts of climate change.

It will be some time before the public is in a position to take a comprehensive approach to the discussion of environmental flows. In many areas, the research needed is only just beginning. In addition, most public discussion to date has concentrated on the water needs of surface systems. There is now growing recognition of the importance of the environmental water needs of ecological systems dependent on groundwater. That is just one of the issues that is likely to become more prominent in the future.

Unresolved and emerging issues

There is at present no accepted method for assessing the value of the benefits that environmental allocations provide. Rudimentary attempts have been made to compare the direct short-term benefits of water use for the environment with the potential economic gains from using the same volume for industry or agriculture.

However, this view of the environment as a user, in competition with other water users, is deeply flawed, as are most attempts to compare values over the short term. The human economy is a component of the natural economy, and cannot function without the goods and services that natural systems supply, usually for free. Unless the natural resources that provide beneficial uses are protected, we will not be able to make use of them in the long term.

Most concern and activity in Australia has focused to date on environmental flows for riverine systems. The debate over environmental flows can be partitioned into three different arenas. The first is river systems that are thought to still have potential for increased exploitation of their water. These systems are regarded as neither overused or over-allocated. The second includes those river systems that are not yet fully used but would be if all allocations were taken up to the full. These systems could be defined as over-allocated but not yet overused. The third, is those systems that are clearly over-allocated and overused. Most of the discussion to date relates to the last group, but management of the other two categories will be increasingly important in the future.

Socio-economic challenges

The socio-economic challenges associated with environmental-flow enhancement in over-allocated and overused river systems can be divided into broad categories:

- improving water allocation and water-trading arrangements
- assessing the costs and benefits of increasing allocations to the environment
- understanding and managing the impacts of reductions in allocations for consumptive water use
- developing cost-effective ways to enhance environmental flows

- improving administrative arrangements for the management of water allocations.

Improving water allocation and water-trading arrangements

Typically, environmental-flow enhancement is most challenging in overused and over-allocated systems. The most common cause of this over-allocation is administrative failure to set a 'cap' on total allocations and then keep the sum of all allocations within that 'cap'. In the case of rivers subject to highly variable annual flow, there can also be a misjudgment as to the environmental needs of the system and the amount of water available for use.

As part of the pursuit of opportunities to secure water for the environment, further research is needed on the most appropriate way to define water rights, allocate them and facilitate trading. In particular, we need to:

- improve the definition of rights to use water so that so-called improvements do not result in the erosion of environmental values
- improve trading arrangements so that trade results in environmental improvement rather than harm.

Assessment of the costs and benefits of increasing allocations to the environment

A related issue is the question of how much water should be allocated to the environment and to environmental flows. While there is a multitude of scientific methods for assessing environmental water needs, techniques for assessing costs and benefits are still in their infancy.

In particular, consideration needs to be given to environmental allocations in groundwater systems. In the last few years, scientists have begun to understand the biodiversity significance of subterranean groundwater ecosystems and groundwater-dependent vegetation complexes. As well as being important in their own right, groundwater systems interact with surface-water systems.

Many environmentally important wetlands, for example, are best described as the intersection of a groundwater system with the land surface. Moreover, in some systems a significant proportion of the water in a river — particularly its baseflow — comes from groundwater.

Understanding and managing the impacts of reductions in allocations for consumptive water use

Announcements that a government is thinking about increasing allocations to the environment often produce strong reactions from local communities. Two types of concerns are apparent. The first focuses on changes in expected future income as a result of loss of production opportunities or increased cost. The second set of concerns focuses on perceived rights to compensation, and arguments that any costs should be shared widely.

One of the main research challenges is to understand and predict the consequences of strategies proposed to enhance environmental flows. This includes cost-effective ways to manage the impacts of structural adjustment.

On the other hand, it also needs to be kept in mind that programs to improve the condition of the environment will often lead to significant economic benefits. Initial research into opportunities to enhance environmental water allocations has indicated that they can induce significant changes in investment in irrigation, recreation and tourism at the regional level. For example, a decision to enhance environmental flows can be a spur to hasten investment in new technology. In places where this occurs, the result could be an rise rather than a fall in regional economic activity. In other areas, however, there could be significant reduction in investment. To help people better understand the pros and cons of enhancing water allocations there is a need to develop appropriate modelling systems.

Development of cost-effective ways to enhance environmental flows

In parallel with work on the impacts of environmental water allocations, there is an urgent need for research into the best ways to get more water for the environment. The simplest option is to reduce *pro rata* all volumetric allocations. This simple mechanism, however, has higher transaction costs than many other options: it will often take water away from the most efficient water users, and fail to target areas where environmental externalities are highest. Research into clever ways to secure water allocations, including obtaining water from overland flows and farm dams, could produce significant benefits.

In addition to research on options to secure water rights for the environment, it may be possible to develop sophisticated allocation arrangements so that less water needs to be secured. Similarly, it may be possible to design allocation and inter-temporal trading arrangements so that the quantity of water available to water consumers is highest in times of greatest need. Possibilities include the creation of carry-forward arrangements and the exploration of opportunities to store surface water in groundwater systems.

One issue that is very poorly understood is the relationship between the distribution of water allocations and water use. Typically, as much as 20% of the water that has been allocated in the River Murray system is neither traded nor used. Reliable information on the distribution of water licence type by economic activity is scarce, and there is little capacity to model the effects of changes in the definition of an allocation already in use. This needs to be remedied, as it is virtually impossible to predict the effectiveness of different ways of changing water allocations without knowledge about how licences are currently managed.

In parallel with research on ways to secure water allocations for the environment, there is also room for research on other options to improve the environment, such as upgrading water supply infrastructure and changing the strategies used to manage environmental allocations. A related opportunity is research into the benefits of involving philanthropic organisations that could, for example, purchase water for the environment. This is just one example of incentive arrangements that could stimulate philanthropic activity and reduce the need for government intervention in the market.

Improving administrative arrangements for the management of water allocations

A fundamental socio-economic issue to consider is how environmental water should be managed. The challenge is to work out the most effective way to deliver the full suite of social, economic and environmental outcomes sought by society. Should the task be left to existing authorities and existing administrative arrangements, or should new administrative arrangements be established? In particular, if water allocations are secured for the environment, should they be held and managed by a separate entity so that existing caps stay in place, or should they be retired and the cap reduced? Which group or groups of people are best placed to manage Australia's water resources and what powers should they have?

These are just some of the questions that must be answered soon.

How should we decide?

Discussion of the concept of environmental water usually occurs where there is competition between the needs of the environment and society. There are many levels of interest involved. Local communities that are dependent on these natural resources to make a living clearly have a major interest. But other parts of society, further removed, similarly have legitimate interests. These include the obvious one of concern about biodiversity, but also there are issues of taxes being used to subsidise prices for water or fund engineering works such as major storages. In addition, there are international treaty interests involving matters such as Ramsar wetlands to be considered. Further, there is the need to take account of impacts on communities downstream of major diversions or management activities. Finding an appropriate institutional framework to process the concerns of all these interests is one of the great challenges for the development of good public policy for ‘environmental water allocation’.

When the allocation of environmental water is being discussed, the need to clearly define the environmental objectives is often neglected. By default, it is sometimes assumed that the objective should be to maintain, as near as possible, natural conditions. However, many communities depend on substantial diversions from rivers and other waterbodies. If those dependencies are to continue, then the management goal must be something other than the restoration of natural values. To be implemented effectively, water management objectives have to be realistic, achievable and acceptable to the community. It should be noted that the definition of who is seen as having the right to influence these decisions and the nature of what is defined as acceptable and desirable can evolve rapidly. This has been demonstrated by the major changes in community attitudes and processes that have occurred in recent years.

At present in Australia, it seems that stakeholder inclusion in most processes is *ad hoc*. In some cases this can cause an inadequate understanding of the purpose of environmental water allocation programs. As a result, they are perceived by some stakeholders (and many managers) to constitute “water for fish and bugs”, or “duck water”, implying that they should be given a low

priority. Often it is not realised that a reasonable allocation of environmental water is a vital aspect of resource protection for long-term sustainable use. There is a great need for stakeholder education that will firmly link environmental water to human benefit.

In a dramatic change from quite recent public and political opinion, the proposition that rivers and other waterbodies should have an adequate environmental allocation protected from diversion is now widely accepted. In the Murray–Darling Basin, for example, when stakeholders throughout the Namoi Valley were asked in 1998 if they supported environmental flows, over 90% said yes (Nancarrow *et al.* 1998). When a similar sample, further south in the Basin, was asked the same question about allocation for environmental flows in the Murray River in 2001, nearly all respondents (95%) indicated support (Nancarrow and Syme 2001). That does not mean, however, that programs to allocate substantial environmental flows will not face serious political opposition. In practice, even small-scale proposals often receive a powerful, hostile reception.

Why the apparent contradiction?

In part this is because proposals for change tend to attract strong opposition from those who will lose as a result of implementation (even if they are small in number) and only tepid support from the larger group (the community as a whole) that will benefit in the future. The discrepancy is often the product of the way in which the consultation and decision-making process is conducted.

To deal with this problem, governments now usually undertake social research and community consultation before embarking on major environmental water allocation programs. Nevertheless, most consultations to date have concentrated on those groups that will be affected economically by any change. This is despite a strong body of research that has concluded that consultation conducted in that way does not properly take account of way the community as a whole makes decisions about such issues.

An extensive review of the literature examining the way people make decisions about resource allocation and

related environmental issues, concludes that there are three basic motives that determine people's choices (Wilke 1991). These are:

- greed (self-interest in gaining access to resources)
- efficiency (that limited resources are being used without waste)
- fairness (everyone should get a fair go).

More detailed analysis has shown that fairness has distributive and procedural components. Not only should the process produce a fair result, but also the way it is conducted must be fair, giving all parties a chance to have their say and making sure their submissions are considered in an impartial way. Research also shows that this is linked to a strong and widespread sense that decision-making about these issues should involve all people who will be affected.

Interestingly, recent research in the Murray–Darling Basin found that, although most consultations currently concentrate on people's reactions to the economic (greed) and efficiency dimensions of environmental water allocation proposals, it is community perception of the fairness of the result and the process that is the strongest factor determining whether they will be accepted (Nancarrow and Syme 2001).

The clear conclusion from this research is that justice issues should be given a higher priority in programs

involving environmental water allocations. Currently, there is a tendency for consultants primarily concerned with economic costs and benefits and efficiency to work separately from those with a social justice perspective. These approaches need to be brought together to provide a more comprehensive understanding of community thinking about sustainability issues.

Another important issue is the need to integrate with concurrent community consultation processes the scientific investigations undertaken as part of the preparation of environmental water proposals. While it is understandable that researchers prefer to wait until they can present their findings with confidence this means that their results 'come out of the blue' as far as the community is concerned. While the process would be more complicated, it is likely that a better final result will be achieved if the community can be included in the investigation process as it unfolds.

The way in which many social researchers work can also be a problem. Almost paradoxically, given their task, their methods can, on occasion, undermine the usefulness of their findings. The use of elaborate statistical forms of analysis is commonly used to enhance the scientific authority of their work, but to the communities that have been the subject of the research the results often appear alien, rigid, dogmatic, crude and impervious to social nuance.

‘Environmental water’ — different things to different people

Managing environmental water is a complex task. In part this is because the impact can change as the flow moves downstream. For instance, between a major storage and the places downstream where water is diverted, the quantity of water in a river may not be greatly changed from the natural condition but the seasonal pattern of flow may be drastically altered. Further downstream, however, where a large proportion of the river’s water has been removed for human use, any change in seasonal pattern is likely to be dwarfed by the overall reduction in flow levels (the amount of water in the river).

Even ignoring complications such as channel capacity and a host of regulatory structures, water-efficient means of reinstating those aspects of flow desired in different parts of the river will require considerable finesse. It will not be possible to reproduce the full range of flow events that occurred before diversions and regulation began. Another challenge is to reverse the tendency to create uniform flow conditions, which comes in part from efforts to increase the security of supply. As far as possible, we need to reinstate the patterns of variability and unpredictability that were normal in the past.

Today, early in the twenty-first century, Australians have a much keener appreciation of the remarkable features of the continent, including the scarcity, fragility and value of its freshwater ecosystems and the importance of maintaining and restoring river and wetland water regimes. They also have a much better understanding of its extreme climatic variability. These new conditions were challenging for European colonists accustomed to seasonal variability in rainfall but not annual variations that could swing between drought in one year and floods the next.

Rivers and wetlands

To increase water reliability for navigation and irrigation, many weirs, dams and levee banks were constructed on streams and used to regulate and divert flows. Wetlands were altered by draining, infilling or conversion to other uses. These interventions have substantially modified the environment of many of Australia’s waterbodies. Ecological changes in regulated river systems have caused:

- massive loss of wetlands — 90% of floodplain wetlands in the Murray–Darling Basin, 50% of coastal wetlands in New South Wales, 75% of wetlands on the Swan Coastal Plain in the south-west of Western Australia
- decline of riparian forests
- invasion of dry river channels and former wetlands by vegetation
- changes in aquatic plant community structure in regulated river reaches and weirs
- decline in population and species diversity declines of invertebrates, fish and waterbirds
- extinctions of several invertebrate species.

For example, seven invertebrate species disappeared when Lake Pedder in Tasmania was flooded as part of a hydro-power scheme, and leeches previously collected from River Murray wetlands by Victorian hospitals at rates of 25–30,000 per annum have seldom been seen since the 1970s. More conspicuous impacts of flow regulation have been massive blooms of toxic cyanobacteria (blue–green algae) in storages and rivers, most notably the 1000-km long bloom in the Barwon–Darling River in 1991–92. The latter was so severe that a state of emergency was declared and water had to be trucked to rural homesteads and livestock.

Australia’s regulated rivers have also been prone to invasions of exotic species of plants such as water hyacinth, *Hymenachne* and willows, and of fish, especially the European carp. Rivers and wetlands have been degraded in ways that prevent them from sustaining natural aquatic ecosystems and their high levels of biodiversity. They have been replaced with simplified systems of lower diversity dominated by exotic species that will be much less useful to humans in the future.

Water that is deliberately set aside to deal with these problems is often described as an ‘environmental flow’. A disadvantage of that term is that it might be seen to focus only on the physical volume of water involved and fail to highlight the crucial role that management must play if environmental flows are to be effective.

Groundwater

Most public discussion of environmental water has focused on rivers and surface water. However, in a dry continent such as Australia, groundwater also plays a major role in maintaining diversity of plants and animals. In addition, there are estuarine and close offshore marine environments where freshwater is an important environmental influence.

When we discuss the dependency of ecosystems on groundwater we need to take account of one or more of four basic groundwater attributes:

- flow or flux — the rate and volume of supply of groundwater
- level — for unconfined aquifers, the depth of the watertable below the ground surface
- pressure — for confined aquifers, the potentiometric head of the aquifer and its expression in groundwater discharge areas
- quality — the chemical quality of groundwater expressed in terms of pH, salinity and/or other potential constituents, including nutrients and contaminants.

There is now a growing body of literature on the ecology of groundwater-dependent ecosystems in Australia. Hatton and Evans (1998) reviewed much of this literature and concluded that most was based on investigations undertaken from a purely ecological perspective. Few studies considered groundwater processes and specific details of ecosystem or community dependency on groundwater. Hatton and Evans identified four types of groundwater-dependent ecosystems:

- terrestrial vegetation
- river base-flow systems
- aquifer and cave ecosystems
- wetlands.

It has since become apparent that there are at least two more distinct types of groundwater-dependent ecosystems:

- terrestrial fauna
- estuarine and near-shore marine ecosystems.

Terrestrial vegetation

This class of groundwater-dependent ecosystem includes vegetation communities that do not rely on expressions of surface water for survival, but which have seasonal or episodic dependence on groundwater. Terrestrial vegetation communities are among those most threatened by changes in groundwater level associated with irrigated and dryland agriculture. This is particularly true for small patches of remnant vegetation and those in areas where regional groundwater levels have risen substantially since European settlement. Increased recharge under

agricultural land use has caused groundwaters to rise closer to the surface. In many cases, they are now permanently within the root zone of the vegetation and sufficiently shallow for direct evaporative discharge to salinise the soil.

River base-flow systems

Base flow is that part of stream flow derived from groundwater discharge and bank storage. Dry season flows in permanent and semi-permanent streams in northern Australia may be almost entirely provided by base flow. Base flow contributes to wet-season flows in such streams, but not to the same extent. Base flow contributes year round to flows in many coastal and inland streams in south-eastern Australia, and may contribute to flow in inland streams, although the extent of the contribution may be difficult to determine in some cases due to river regulation.

Riparian and aquatic ecosystems in base-flow-dependent streams would be, to a greater or lesser extent, groundwater dependent. Demarcation between groundwater-dependent terrestrial vegetation and wetlands and base-flow-dependent systems may be difficult, with the three types of community representing a spectrum of habitat, groundwater and surface-water dependency. Contamination of the riverine aquifers by nutrients, pesticides and other toxicants can adversely affect dependent ecosystems in base-flow streams. Aquatic communities are likely to be the worst affected.

Aquifer and cave ecosystems

This category comprises the aquatic ecosystems that may be found in free water within cave systems and within aquifers themselves. It has been argued that aquifer ecosystems represented the most extended array of freshwater ecosystems across the entire planet. Australian studies of these ‘stygean’ ecosystems have traditionally related to cave, rather than aquifer systems, but there is a growing body of information on the latter.

Many aquifer ecosystems have developed in very stable environments. Subtle changes in groundwater quality due to contamination by, for example, agricultural chemicals or septic tank effluent, can result in significant changes in ecosystem function. The potential sensitivity of aquifer ecosystems to changes in groundwater quality raises the prospect of their use as bio-indicators.

Wetlands

Groundwater-dependent wetland ecosystems are those that are at least seasonally waterlogged or flooded. Examples include mesophyll palm vine forests, paperbark swamp forests and woodlands, swamp sclerophyll forests and woodlands, swamp scrubs and heaths, swamp shrublands,

sedgelands, swamp grasslands, swamp herblands and mound springs ecosystems.

Changes in watertable level may have important implications for these communities. Prolonged lowering or raising of the watertable is likely to change the composition of species, favouring species adapted to drier or wetter conditions, respectively. As with terrestrial vegetation, the development of more shallow saline groundwaters may result in the salinisation of the plant root zone and the subsequent collapse of ecosystems.

Terrestrial fauna

There is an additional group of groundwater-dependent fauna whose reliance on groundwater is not based on the provision of habitat, but on groundwater as a source of drinking water. Groundwater, as river base-flow or discharge into a spring or pool, is an important source of water across much of the country, particularly in northern and inland Australia and other areas with arid or semi-arid climates. Its significance is greater for larger mammals and birds, as many smaller animals can obtain most of their water requirements from the food they consume.

Groundwater-dependent terrestrial and riparian vegetation and wetlands may be used by terrestrial fauna as drought refuges. Access to groundwater allows vegetation to maintain its condition and normal phenology (eg. nectar production, new foliage initiation, seeding). Populations of some birds and mammals retreat to these areas during drought and then recolonise

formerly drier parts of the landscape following recovery. To ensure the long-term survival of such animal populations, it is crucial to maintain vegetation communities by providing for their water requirements.

Estuarine and near-shore marine systems

These groundwater-dependent coastal ecosystems include mangroves and salt marshes, lakes, seagrass beds and marine animals. Many of them face increasing threat from groundwater contamination and water quality decline. Urban, commercial and tourism developments, and intensive agriculture, are important risk factors in many coastal areas. Groundwater can also be contaminated by nutrients from fertilisers and septic tank effluent, agricultural pesticides, and metals and hydrocarbons from commercial and urban land uses. Exposure to contaminants poses direct short and long-term threats to ecological processes. Elevated nutrient levels can cause algal blooms that may render (at least temporarily) marine and estuarine habitats unsuitable for key species.

Groundwater level in some coastal aquifers will strongly influence ecosystem health. Acid sulfate soils are activated when iron sulfides in the soil are exposed to oxygen if groundwater levels are lowered by drainage, groundwater pumping or drought. The very acid drainage waters from these soils may result in sensitive species being killed or displaced. Flocculation of iron in the water may result in aquatic or marine communities being smothered.

Common assumptions reconsidered

Over the last decade research on environmental flows has expanded rapidly. This section discusses some of the underlying assumptions. Science has a leading role in setting environmental-flow requirements but it is only one part of a process that also requires ‘best experienced judgement’, value choices, and social and educational skills for its success. While scientists can define the habitat preferences of aquatic biota, and model flows and hydraulic conditions with some accuracy, these are just the starting point for a complex public-policy-development process that must take place to sustain water resources. The process requires careful use of good science and complex judgments about social priorities.

Six **major assumptions** can be identified in the debate about environmental water allocations:

- there is spare water in rivers
- the effects of reducing flows in rivers are initially slight, but increase as more of the flow is abstracted
- rivers will usually recover from small and transient perturbations
- the natural disturbance regime of a river is important for the maintenance of its biodiversity
- the maintenance of habitat will ensure the persistence of species
- riverine communities (particularly those of semi-arid regions) are driven by abiotic rather than biotic processes.

In considering these points, two important principles of conservation ecology should be considered:

- the maintenance of natural biodiversity is the key to the health of ecosystems and to their sustainable utilisation
- modifying the flow regime in a river will inevitably have effects on the biota and the functioning of ecological processes in the river.

Spare water

The assumption that rivers contain ‘spare water’ underlies all methods for the assessment of environmental water requirements for rivers. It is reflected in the common wish to abstract water from a river while retaining the original environmental values

particular to that river system. However, if the water resources of a river are to be exploited, then there will be less water left in the river, and it is unavoidable that this will, to a greater or lesser extent, affect the character of the river ecosystem.

Although it is not possible to reduce a resource with no effect on its environment, there are three main justifications commonly put forward for assuming that a river has spare water that can be diverted with no serious environmental impacts. These are discussed below.

The naturally highly variable flow regimes of most rivers mean that biota can survive long periods of low flow

In rivers in the more arid parts of the world such as Australia and South Africa, annual discharge may vary dramatically from year to year. However, it seems a reasonable contention that a lower-than-normal flow regime that still incorporates all the major features of the previous natural regime, will not permanently change the biota of a river.

Other things such as catchment condition being equal, it therefore seems likely that a carefully designed modified flow regime that maintains the ecologically important components of the natural flow regime should be adequate to maintain a river’s natural biota. The method used to harvest the water would nevertheless be a major factor in determining success.

It is not essential to maintain all rivers in a near-pristine condition

Given the demands being made on our major rivers, it is not realistic to attempt to return them to the environmental state they were in at the start of European settlement. As part of the social process of defining goals for river management, it is important to work out the aims that should apply to each river and possibly to each section of each river. Is the primary purpose to support irrigation, provide fish or bird breeding habitat, to be an aesthetically pleasing recreation area or something else? Once that political decision is made, then science can help decision-makers decide how to achieve the goal that has been set.

Major floods cause structural damage to rivers, and it would be better if the flood water were trapped in storages and used later to increase low flows

Although very large floods do fill the storages, thus providing water that can be used to supplement low flows, the impact of those large floods on the river is not significantly modified by the relatively small volume that is retained in the storages. This is in contrast to the situation with small to medium floods which may be largely intercepted, with serious implications for wetlands further down the system.

Incremental decline in flows

It is widely assumed that the effects of reducing flows in rivers are initially slight, but increase as more of the flow is abstracted. There are several guidelines that provide rule-of-thumb suggestions as to how much water can be extracted. One such system (dating from the 1970s) that is used widely, states that rivers can be maintained in an “excellent to outstanding” condition if more than 60% of the flow is kept in the channel, that 30% will maintain “satisfactory” conditions, and that if only 10% of flows is retained, this will result in “survival” conditions. However, recent benchmarking studies in eastern Australia (Brizga *et al.*, 2002) show that significant ecological impacts can occur even at low levels of water extraction and will vary significantly from river to river. It is therefore unwise to prescribe universal percentages. In addition, an important task for science now is to come to a consensus on, and adopt, the best available methods for assessing environmental water needs, so that results from different studies will be comparable.

Rivers will recover from many perturbations

The assumption that rivers usually recover from minor, transient disturbances appears to be justified. However, recovery may not occur when there is permanent and severe flow modification, physical damage to the river channel, riparian zone or floodplain, or no, or degraded, refuges left for recolonisation. In addition, it is important to note that rivers that have recovered from severe disturbance in the past, may not be able to do so again. Their capacity to revive will depend on whether tributaries that formerly provided refuge are in good condition and on the state of the catchment, which may have become degraded by inappropriate land uses. As human-induced disturbance of catchments increases, the ability of the rivers to recover from impacts declines inexorably.

The natural disturbance regime of rivers is important for the maintenance of their biodiversity

Disturbance caused by flood or other major events is an important theme in stream ecology. The frequency and/or intensity of disturbance will determine when, if ever, a community will reach equilibrium. Disturbance has a major impact on productivity, nutrient cycling and spiralling, and decomposition. Many river ecologists regard disturbance as the most important feature of streams for study. They see it as the dominant organising factor in stream ecology. The problem is to evaluate how much of the natural disturbance regime can be sacrificed without significantly affecting the future state of a river, and, similarly, how much human-induced disturbance the riverine biota can tolerate or recover from.

Maintenance of habitat will ensure the persistence of species

It is often assumed that the best way to sustain the life in a river is to maintain the physical, hydraulic habitat. However, a sound knowledge of the use of different habitats by the full range of plants and animals is a prerequisite for judging the effects of flow-related habitat reduction. It should be noted that the successful completion of life cycles of riverine species is dependent on more than the availability of hydraulic habitat. Moreover, the description of habitat needs to take into account the different requirements of each species, the impact of invasions by alien species, their sequential life history stages, and the need to maintain the habitats of their food species.

Many methodologies used to assess flow acknowledge the importance of other physical and chemical controls such as temperature and water chemistry. Those factors are often perceived to be partially linked to their position in the catchment and the way it is managed, and thus outside the province of flow manipulation alone. A comprehensive effort to maintain the ecological health of a river will obviously require a catchment-management plan as well as a flow-management plan.

Riverine communities (and particularly those of semi-arid regions) are driven by abiotic rather than biotic processes

Most flow-assessment methodologies are concerned mainly with one component of the river ecosystem — its flow regime, reflecting its overwhelming importance in sculpturing the ecosystem. But the question remains: how significant are the roles of other abiotic (non-living) forces and of biotic interactions in determining the nature

of the ecosystem? Abiotic factors other than flow that can, when changed, become the dominant influence on riverine biota include water chemistry, temperature, and sediment load. This, however, does not invalidate the hypothesis that a carefully designed modified flow regime should be able to maintain the biota at some preconceived condition, provided other influences are also controlled. Nevertheless, while it seems largely true that abiotic processes are the main determinants of river communities, the danger with this perspective is that influential biotic processes may be ignored.

In semi-arid environments such as Australia and South Africa it seems that river organisms live in highly variable and unpredictable flow regimes. Such organisms are more likely to spend their lives surviving floods and droughts than creating complex interacting communities that are mediated by competition. "Hardy opportunists" is a

description often applied to species that survive the rigours of South African rivers. It seems applicable also to semi-arid river systems in Australia. Many stream communities are in a state of perpetual recovery from frequent disturbances. From this perspective, species are either entirely non-interactive or the interval between disturbances is too short to allow interactions to eliminate species. This assumption is not yet confirmed and it may be that in some instances disturbance leaves particular river communities vulnerable to predation from sources that are not significant under other conditions. In addition, although these semi-arid systems appear robust in response to many forms of disturbance, that does not mean they are simple or will be resilient in the face of future, cumulative disturbances. Effective management will require a highly developed scientific understanding of their fragility and capacity for adaptation, the product of millions of years of evolution.

Approaches to implementation

Once there is agreement in principle to improve the environmental condition of a given aquatic ecosystem the question is: how should that be done?

The process of deciding what sort of environmental-flow regime should be planned for is only partly scientific, and requires value judgments of researchers, managers or stakeholders. In themselves, these judgments are not 'scientific'. For example, the consequences of flow reduction for a fish community can be assessed by scientific investigation but the decision as to whether those impacts are acceptable is one for society. A process for environmental-flow assessment that stops at predicting the effects of alternative flow regimes is incomplete. At some stage, someone or some group has to decide which option will be implemented.

As the options for environmental-flow response management have become better understood there is an increasing trend to adopt a suite of methods at different levels of detail, rather than apply a single method to all situations. The use of multiple levels of assessment has been considerably developed under the South African National Water Act (Republic of South Africa 1998) and the results of assessments of a wide variety of rivers in that country are now available.

As environmental-flow methodologies have evolved, there has been a move away from a 'minimum flow' concept to recognising the importance of flow variability, along with magnitude, frequency, duration, timing and rate of change. Australia, with South Africa, has led the way in the development of holistic environmental-flow response methodologies (Arthington *et al.* 1992) designed to protect riverine ecosystems (rather than individual target species). Although the greatest activity in environmental-flow work has been in the United States of America, most of that work has been designed to improve or maintain conditions for economically important angling species such as salmon and trout, rather than the health of the total stream system.

Water quality

Water quality is a very elusive concept that varies according to the objectives adopted for management of

the waterbody in question. The development of methods to link environmental-flow and water-quality requirements is at an early stage, and there are critical problems still to be solved. No single method has been universally accepted as the best, and choice will vary according to management objectives and the resources available. Methods for linking environmental flows to water quality are being pioneered in South Africa.

Methods used to estimate environmental water requirements

Hydrology-based approaches usually rely on the use of historical hydrological data, and are often referred to as fixed percentage or standard-setting methodologies. They assume that the provision of some proportion of the natural flow regime will maintain sufficient of the required hydraulic habitats, and therefore the fishery or other desired ecological feature. They frequently attempt to define a 'minimum flow'. Expert judgment is often incorporated to increase the quality of the assessment.

Hydraulic rating methodologies use rated river cross-sections to measure changes in hydraulic parameters such as depth or wetted perimeter with changing flow, and relate these changes to increased or decreased habitat availability.

Habitat simulation methodologies use multiple cross-sections to model habitat changes, usually in terms of depth, velocity and substratum types, and may be linked to habitat preference measures for selected biota.

Holistic methodologies are designed to evaluate ecosystem requirements, in contrast to most of the environmental-flow-assessment methodologies described above which aim to assess the flow requirements of individual species or ecological components. Holistic methodologies employ groups of specialists from different disciplines (eg. fish, invertebrate and riparian vegetation biologists, social scientists, geomorphologists and hydrologists) and the final assessment is a consensus view of the flows that are needed to meet the requirements of a variety of critical species and components.

Advantages and disadvantages of the different methods for rivers

Hydrology-based approaches are inexpensive and rapid, with simple data requirements. They have potential for regionalisation, are suitable for reconnaissance-level assessments, and can be upgraded by added professional judgment or local input. They have no ecological information to support them, however, and there is therefore low confidence in the answers they provide, which are consequently difficult to 'defend in court'. There is also a danger they will be extrapolated to other regions where they are invalid.

Hydraulic rating methodologies incorporate ecological habitat information and are relatively inexpensive and simple to apply. They are flexible in the way they can use available data and suitable for catchment assessments at the reconnaissance level. However, they involve simplistic assumptions based on the extrapolation of single cross-sections and are usually confined to in-channel biota. They produce results that have only low to medium levels of confidence and are difficult to defend.

Habitat simulation methodologies involve high resolution characterisation of habitat availability for target organisms and are flexible for the assessment of different flow scenarios. They are in frequent use, with a high degree of scientific acceptability and are legally defensible in the USA. However, they are resource and time intensive and largely confined to target species.

Holistic methodologies involve the assessment of ecosystems (and are not limited to the needs of just a few species). This requires a multi-disciplinary consideration of riverine processes. They are flexible in their capacity to use available data and there is high confidence in the answers obtained because they use a process that encourages the range of scientists involved to come to a consensus. This makes them very defensible and there is also a potential for regionalisation. However, this approach is resource intensive and there is a risk of conflicting results from different specialists, given the degree of subjectivity or judgment required.

Recent developments

Methodologies for managing environmental allocations are evolving rapidly. In part the differences are the product of the varying availability of resources and different policy needs.

Downstream response to imposed flow transformations (DRIFT)

DRIFT is a South African example of the holistic approach to environmental-flow analysis. It aims to predict the consequences of successive levels of flow

reduction, and therefore approaches the problem from the top-down, as opposed to other holistic methods which proceed by identifying specific flows needed at different times. With DRIFT, researchers identify the ecological consequences of a series of progressively reducing (or increasing) discharges. The consequences for each component (fish, invertebrates, riparian vegetation, geomorphology etc.) are entered into a database that allows the information to be processed to show the levels of degradation or improvement of each component under a wide range of flow scenarios. Social and economic costs and benefits are included in the final analysis. The method has been tested on several rivers in South Africa.

Flow stress/response (FSR)

Another South African methodology, the flow stress/response method (FSR) assesses the ecological consequences of reductions in low flow. As part of the process, specialists apply a standardised index of stress to low flows at a given river site. For example, the responses of in-channel organisms are characterised at three levels: first, the level below which there is a significant reduction in abundance; second, the level where there is an increasing risk to critical life stages (such as breeding); and finally the level that causes local extinction.

Once there is a correlation between stress levels and flow, the hydrologist can provide time series, duration curves and spell analyses of stress levels for any low-flow scenario. The FSR is not an alternative to the other holistic methodologies, but can be incorporated into most methodologies to provide a risk-based assessment of the critical points where increasing stress on the ecosystem causes significant change as low-flow regimes are manipulated. It has been used for a number of South African rivers.

Benchmarking

Benchmarking is an approach that is receiving considerable attention in Australia. Like DRIFT it is also 'top down'. It identifies key flow characteristics that are considered to be ecologically or geomorphologically significant. The effects of changes in these characteristics are benchmarked by comparison with similar river reaches that have already been modified. As developed during the Fitzroy Water Allocation and Management Planning project, this method has the capacity and flexibility to evaluate the consequences of many different scenarios of flow regulation and appears to be particularly suitable for poorly studied areas.

A similar, although less detailed, process known as FLOWS, has been developed by the Victoria Department of Natural Resources and Environment. The specifications for development of the process required that it should be applicable to regulated and unregulated

river systems, be repeatable and scientifically defensible, be capable of completion within 12 months and cost within the range \$30,000–\$40,000. It is not suitable for use in estuaries or large wetlands. During its development a number of weaknesses were identified, primarily involving the integration of different issues and disciplines in a restricted time frame, and the lack of adequate understanding of the flow-based relationships of the biota. Such shortcomings are associated with most holistic methods.

Gaps

Work on river systems has developed unevenly and there are significant gaps in knowledge.

Estuaries

Most of the work to develop environmental-flow assessment methods has focused on riverine systems. The study of methods for use in estuaries is still in its infancy. However, significant progress has been made by a team at Port Elizabeth University in South Africa. Their approach documents the geographical boundaries of an estuary, comparing its present environmental state to a predicted reference condition, and calculates an 'estuarine health index'. The ecological importance of the estuary is then rated according to a national system.

The importance rating is combined with the health index to set the ecological reserve category for the estuary. After discussion about the values that are significant for that particular estuary, ecological objectives are set, either to maintain the estuary within its current class or to promote it to a higher class. River flows are then 'reserved' to meet those objectives. Finally, monitoring protocols are also recommended to improve public confidence in the original judgment regarding its ecological reserve category.

Based on monitoring of a range of South African estuaries, which has provided up to 10 years of data in some cases, it has been found that assessments of the freshwater requirements of estuaries are particularly dependent on basic data sets. These include the relationship between flow and salinity in permanently open estuaries and the relationship between flow and mouth condition in temporarily open estuaries.

It should be noted in addition that the environmental-flow requirements set for the river upstream of an estuary may not be adequate to cater for the estuary's water requirements. Of importance too for other aquatic ecosystems, it was found that it is not possible to extrapolate results from one estuary to another. Two estuaries occurring next to each other may have different freshwater requirements. In one case, a stream might carry a light sediment load and enter the sea with the protection of a rocky headland that reduces wave action,

requiring only a fairly low flow to keep the mouth open. In a second case, the sediment load might be large and the mouth might have no protection from wave action. The latter situation could require higher levels of flow to keep the mouth open.

Wetlands

Although wetlands are important, their water needs have received little study. In part this is a product of recent thinking shifting from conserving or managing individual wetlands to planning for whole rivers, based on the recognition that wetlands cannot be managed effectively in isolation from their parent river. While that is valid as a general principle, there are important attributes that are neglected by that broad-brush approach. Recognition of the needs of wetlands is hindered in part by the general lack of case histories that are written up and accessible. However, a first attempt at distilling this sort of information into a guide for wetlands water requirements for extensive floodplain complexes including end-of-system wetlands has been published by Roberts *et al.* (2000).

The water requirements of wetlands can be estimated in two ways: top-down or bottom-up, corresponding to hydrology–hydraulics or ecology-driven.

Hydrological–physical. In its simplest form, the volume of water required to meet a specified target (eg. wetland filling) can be measured or estimated from wetland dimensions and expressed in terms of required inflow at a relevant upstream gauging station. Time series of river flows (simulated natural or historic as appropriate) can then be used to establish frequency, timing etc. of the flow conditions. In its more complex forms, estimates of volume and in-flows can be refined to include a water budget approach incorporating gains and losses as it flows across the wetland or floodplain.

Ecology. Ecological approaches use specific knowledge of water-regime requirements for a particular species, community or processes, to estimate the storage volume of the whole wetland. This specific knowledge can be derived from informed observation, experiments or accumulated information, and the requirements may be expressed as depth × duration × season. Estimates of the river-inflows that are needed are then derived from the estimated storage volume, and can be refined to allow for wetland losses and inputs, transmission losses and the environmental conditions.

Groundwater

Many groundwater-dependent ecosystems exist in environments that have been modified by human activity. While the environmental importance of groundwater is increasingly being recognised, it has to be assessed

against the social and economic benefits of non-environmental uses for agriculture, human consumption or industry.

There are very few case studies in Australia where the environmental water requirements of groundwater-dependent ecosystems have been determined through direct field research. At this stage, very little is known about how groundwater-dependent ecosystems respond to changes in groundwater regimes.

General principles

The concept of environmental water allocation only has meaning when there are human objectives for the waterbody that involve change from the previous hydrological pattern. As a starting point, it must be acknowledged that, if water is to be used, the waterbody will no longer be in its natural state.

It is usually assumed that there are no absolute thresholds at which riverine ecosystems will ‘crash’, within a ‘reasonable’ level of water abstraction. The definition of environmental-flow requirements is therefore set somewhere along a continuum of increasing flow reduction, leading to increasingly severe environmental consequences. The implicit assumption of all environmental-flow-assessment methods is that these consequences will be slight for initial reductions in flow, but will become exponentially more severe as reductions tend towards zero flow.

State and Territory governments have made varying degrees of progress in addressing groundwater environmental allocations. Of particular note is the New South Wales State Groundwater Dependent Ecosystems Policy (2002). The Commonwealth, in consultation with the National Groundwater Committee, is currently considering the development of national principles for water allocation to groundwater-dependent ecosystems. This Commonwealth interest has been, in part, prompted by the listing of “the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin” in the *Environmental Protection and Biodiversity Conservation Act 1999*. Delivery of this

charge implicitly requires recovery plans to encompass and implement protection and management of associated groundwater environmental flows.

Deficiencies

- There have been few attempts to verify the effects of implementing environmental water regimes in any country.
- There is fairly high confidence in predicting the short-term biological effects of flow manipulation. However, the longer term effects on sediment input/output, and therefore on changing channel structures and habitat types, are still very uncertain.
- Supplying adequate flows will not achieve environmental objectives unless water quality, catchment land use, riparian over-grazing and other problems are addressed at the same time.
- There is a mistaken tendency to respond to catchment and water quality problems by allocating additional flows (eg. for dilution of effluent). Water quality, and many other problems should ideally be dealt with at source, so that the recommended flow regime can be designed to deal only with flow-related problems.
- In many cases, the physical capacity of a flow-regulating structure may limit possible flow manipulations. There may be no capacity to release warmer water from the upper levels of storage or it may not be possible to release large flushing flows because of the small size of the release systems.
- In many cases current policy is to make releases to ‘top up’ natural floods. However, trigger mechanisms to ensure that high flow releases are synchronised with natural events are problematic: until an event has peaked, it is difficult to predict how big it will be.
- Decisions to release water may also be contentious, especially in the case of the first flood of a wet season, when priorities for storage are highest, and there is no way of knowing how wet the season will be. Delivery of high flows to specified reaches that may be long distances downstream, are also difficult, because flood peaks may attenuate, and river losses be significant, requiring a very high release to achieve a moderate flood peak downstream.

Current policy in Australia

In 2001, the National Competition Council undertook, for the first time, a detailed audit of reform in the rural water sector examining pricing, property rights, water trading and environmental issues. Assessing achievements so far, the audit found that the States had made sufficient progress to receive their 2001–02 National Competition Policy (NCP) payments. Several submissions about environmental flows were received from irrigator and environmental groups, but none questioned the importance or need for environmental reform.

Commenting before the National Competition Policy audit was released, Tim Fisher from the Australian Conservation Foundation conceded that progress in water reforms relevant to environmental flows would have been less without the NCP pressure (Fisher 2000). However, he found that, even with the leverage of cash payments, the States have put more emphasis on progress in microeconomic reforms than on environmental reforms. In his judgment, New South Wales was the only State where environmental-flow programs were being widely and consistently applied. He concluded that other States have been very slow to act, or have performed poorly or failed to complete implementation of measures addressing the most critical environmental aspects.

This assessment is backed up by a recent study of legislation in South Australia, Tasmania, Victoria and Western Australia, which found that none of the four primary Acts embodied a specific commitment to achieving measurable river management or river protection standards (Maher *et al.* 2002, Appendix 2). The authors found that, except for in South Australia, the primary Acts in those States do not require formal integration of catchment plans with water-allocation plans. They do not explicitly acknowledge the need to manage cumulative effects of water infrastructure and water-use decisions. Neither do they require limits to be set on water developments before catchments come under stress. Half of the States have not explicitly matched their environmental-flow provisions to the undertakings agreed to in 1996 by their ministers at meetings of Australian and New Zealand Environment and Conservation

Council (ANZECC)/Agricultural Resource Management Council of Australia and New Zealand (ARMCANZ).

The four States included the provision of environmental flows as one of the criteria that should be explicit in management plans and have varying degrees of primacy over other demands. While the focus is still essentially on resource use and access, legislation rarely stipulated a commitment to identifiable outcomes or minimum measurable standards for ecological protection and river health. Some legislation specifies key principles for water management; these incorporate ecosystem needs, but do not necessarily give them primacy.

Legislation in the four States does not as yet push for environmental flows which restore riverine ecosystems to some desired and defined future state, as opposed to just maintaining or slightly improving existing conditions in highly modified or degraded river systems. There are few requirements to set limits and administer caps within planning and impact-assessment processes and there are limited powers of veto over development projects by statutory catchment bodies where they exist.

At present, all four States have environmental protection legislation supported by environment-protection policies. At best, the ‘environment’ still has to compete for its water needs with other users. It is important to note that current Western Australian catchment planning processes have the weaker ‘advisory only’ status as is also the case with catchment plans in Tasmania. Victoria, New South Wales and South Australia, on the other hand, have developed frameworks that provide statutory legitimacy for integrated catchment management processes.

Policy needs

Some idea of what this means is provided by two other surveys conducted a little earlier (Maher *et al.* 1999). They suggest that environmental-flow policies should:

- have volumetric, seasonality and other water-quality components
- include the capacity for introducing some annual variability
- have clearly stated objectives to meet environmental flows before other uses are allocated

- be based upon ecosystem values, not requirements of other uses (eg. short flushes to wash out blue–green algal blooms)
- be calculated on a rigorous, transparent and scientifically based methodology
- be based upon ecosystem values that establish acceptable ecological benchmarks
- be flexible, to cater for refinement through increased information and understanding.

On reviewing the range of legislation Maher *et al.* (1999) concluded that:

- the seasonality component of environmental flows was not robust, particularly for heavily or over-committed rivers, as seasonality requirements may conflict with extractive demands
- temperature and other quality components of environmental flows were poorly defined
- the potential for addressing environmental flows in fully or over-allocated rivers appeared very constrained
- achieving environmental-flow objectives should be explicitly stated as the priority in legislation and policy
- setting the balance between security for users (certainty) and adaptive management (flexibility) requires care, and that in such calculations, ecologically sustainable development needs, including environmental flows, should be given dominance.

Influences

Some indication of the mixed motives and other hurdles that have shaped a lot of environmental-flow policy is provided by a 1997 study by Allan and Lovett, which concluded that:

- most flows were what was feasible given existing allocations and infrastructure, and are a compromise between optimal and socially acceptable
- the scientific basis for decisions was often uncertain, given lack of data and little monitoring to build upon the poor information base
- the approach was often species-specific, with full integration of ecosystems difficult to achieve
- species with economic/recreational use received disproportionate attention when flow requirements were assessed
- some environmental allocations were undertaken in part to achieve economic and other benefits
- the process is complex, requiring detailed scientific information and cooperation between a number of agencies and community and environmental interests that have often had a long history of competitive relationships.

Although that description is a few years old it is probable that it is still fairly accurate.

Case studies

There are major unanswered questions about the allocation of environmental water, and the legislative and policy framework is still rudimentary, inconsistent and generally inadequate. On the other hand, there are also many examples of river management organisations pushing ahead and experimenting with different types of environmental-flow projects.

There follow here details of examples of progress achieved in a number of basins drawn from a survey of different types of projects. The chapter that follows provides further comment about the same projects.

Barmah–Millewa Forest, Victoria and New South Wales

The Barmah–Millewa Forest extends on both sides of the Murray just upstream of Echuca. It covers approximately 60,000 hectares, and its marshes, lakes, streams, grassland and woodland support a diverse spectrum of indigenous flora and fauna. The sustainability of these ecosystems relies on the dynamics of natural water flows through the forest.

The major river of the Barmah–Millewa Forest is the Murray, and flow patterns are dominated by management of the Hume Dam (operational since 1936). The first priority of river management has been to provide the irrigation industry with security of water. From an environmental perspective, this has generally caused flooding to be less effective. Extensive flooding tends to result from short periods of high releases (from the Hume Reservoir) which are not long enough for environmental benefit, while unnaturally high flows in summer, to deliver supplies to irrigation, prevent low-lying areas of the forest from drying out.

In response to growing public concern about these problems, in 1993 the Murray–Darling Basin Ministerial Council allocated 100 gegalitres (GL) per year for the environmental requirements of the Barmah–Millewa Forest.

The Barmah–Millewa Forest Water Management Strategy was subsequently developed to provide the

objectives and policy framework for management of the environmental-flow allocation.

Interim operating rules for the storage and release of the environmental-flow allocation were not agreed until March 2001. However, accounting for the allocation began in the 1997–98 water year. This allowed the first use of the allocation in 1998, when 100 GL was released to extend the effect of floodwaters originating from the Ovens River catchment. This flood was not considered a significant event.

In the Spring–Summer of 2000–01, there were two releases, in September and November, of environmental-flow allocations totalling 341 GL that bridged a series of natural flooding events to provide a single sustained flood. The scale of this flooding was considered to be a one-in-five-year event. The environmental releases that made it possible to create this continuous flood constituted about 8% of the total volume of water that entered the forest.

A comprehensive monitoring program that took account of river hydrology, flooded area, frogs, birds, tree and understorey health, water quality, water levels and water temperatures accompanied the releases. Favourable ecological response was readily apparent. The slow recession of floodwaters allowed completion of important bird-breeding events, producing one of the most successful breeding seasons since the mid-1970s. Nine frog species were also recorded in the Barmah Forest (including two not previously recorded there), and many invertebrate and small fish species were observed.

Issues and challenges

There is little question of the success of the 2000–01 environmental water allocation, but it is also clear that:

- the environmental-flow allocation is not sufficient in size to be useful by itself if released in the absence of a natural flood
- there need to be specific programs to control the increase in exotics and pest species (eg. common carp and mosquito fish) which also benefit from flooding

- there is a need to anticipate and budget for costs associated with ex-gratia payments to landholders affected by over-bank flows.

Burnett Basin, Queensland

In the Burnett Basin, the environmental-flow allocation has been integrated into the overall river-management plan. The prior environmental needs of the river are taken into account in developing the plan's thresholds of low, medium and high flows that determine when other demands can be met. The plan for the Burnett basin has been developed with community consultation, backed by a technical advisory panel. It has not involved clawback of allocated water but rather the setting of a water-sharing index based on river performance over an extended period.

Campaspe River, Victoria

In 1996, the Campaspe was chosen as a focal river for extended in-stream ecological research aimed at establishing the impact of environmental flows. This is a well-funded program intended to extend over several years. Findings of the Campaspe environmental-flow study will directly inform Victorian legislation on water allocation entitlements. It is anticipated that many of the findings will be transferable to other situations and systems.

A reservoir (Lake Eppalock) and two weirs (Campaspe Weir and Campaspe Siphon) regulate the Campaspe River. Regulation and management has had the effect of tripling natural summer flow and halving natural winter flows. This has contributed to environmental impacts, such as declines in water quality and native fish populations, and increases in salinity and numbers of exotic fish species.

The Campaspe Project is investigating ways to deliver effective environmental flows and help native species compete against exotics in a small, over-committed system where the environment carries the full weight of variable rainfall (the supply to irrigation remaining a fairly constant volume in most years whether dry or wet).

From the beginning, however, it was agreed that the project would operate only during winter–spring, allowing the existing pattern of high flows during the summer–autumn to continue, to avoid disrupting established irrigation activities.

As part of the project, the Broken River was chosen as a reference stream to assess changes in four focal indicators:

- fish populations — introduced and native populations, recruitment of young fish and population/community structure

- fish larvae — breeding patterns and success of different species
- macro-invertebrate communities — used as an indicator of the effects of altered flow regime
- the condition of populations of three shrimp species known to have a large in-stream biomass and to be an important component of the diet of fish.

Two phases of the project were planned. The intention was that the first three years would be used to undertake benchmarking research documenting conditions before the introduction of the new regime. The second two-year phase would monitor the impacts of releasing 25% of inflow (to Lake Eppalock) from May to October (inclusive). Dry conditions in the catchment have delayed implementation of the second phase.

Lachlan River, New South Wales

Successful implementation of environmental flow policies depends on the capacity of managers to make good use of the best scientific information and explain the results effectively to the wider community. The information required for decision-making about environmental flows can be categorised into four broad types:

- baseline data on the state of the river and changes to the natural flow regime
- links between flows and ecosystem processes and functions
- information about operational factors and constraints
- an understanding of the socio-economic implications of any proposed course of action.

In the Lachlan, information for the first and third of these categories is broadly available. However, there is widespread perception that there are serious gaps in relation to flow-ecosystem links and the socio-economic impacts of particular options.

Management coherence is also an issue. The extent of differences between stakeholders is shown by the wide range of attributes nominated as indicators of a healthy river. Poor integration of these different perspectives makes it hard to present to the broader community a clear vision of the purposes of the environmental-flow program.

The institutional arrangements of the Lachlan River Management Committee (LRMC) are characterised by:

- consensus decision-making (as distinct from decision via majority vote)
- adaptive management based on a general acceptance of the need for 'learning by doing' in light of the uncertainty of information on a very variable river system

- social capital, a term used to describe the increased trust, inclusiveness, and mutual respect between LRMC members that had developed since the more antagonistic relations of the first few months. This has allowed more open, 'non-defensive' use of information.

There are unresolved issues associated with the 'science–management' relationship in the Lachlan River project:

- there were substantial differences between stakeholders as to the relative importance of scientific rigour, the concept of 'ownership', and of outcome-oriented information
- means of communication — while there was general support for the current mix of communication (written material, oral presentations, discussion and field visits), individuals differed in their preferences
- level of detail — it was felt that the LRMC needed to deliver information in a manner that better catered for the wide variation of detail desired by individual participants, and the need to balance time with over-simplification.
- sources of information — consensus was limited on whether the LRMC made optimal use of all available information, particularly local community knowledge/information.
- uncertainty — planning within an uncertain framework and limited capacity to provide scientific certainty did not sit easily with the need to deliver specific environmental outcomes. There was concern that, despite optimal use of existing knowledge and best-management practices, the LRMC may still be unable to demonstrate sound environmental gains.

In general, major gains have occurred in the LRMC's control and active seeking of information, with increased integration occurring as a result of the introduction of working groups and scoping papers, and the development of a more open environment in which information is used. Barriers to information use included the lack of an ecosystem-wide approach, gaps in identifying the effects of flows, the limited availability of sound socio-economic information, and the lack of effective criteria for assessing how much weight should be given to different types of information.

Macquarie Marshes, New South Wales

The Macquarie Marshes (supplied by the Macquarie River) is a terminal wetland except during high flows and large floods when flows feed into the Barwon River. Following major floods, more than 150,000 ha may be inundated. About 10% of the total Marsh area is a National Parks and Wildlife Nature Reserve, with the remaining area being freehold/leasehold. The Marshes Nature Reserve was listed under Ramsar in 1986.

Under the natural conditions that existed before the impact of recent development, the marshes had dry periods punctuated by large floods in winter–spring — reproducing this natural variability of flow pattern is critical to maintaining the wetland functions. However, river regulation has reduced the streamflow variability and the volume of water reaching the Marshes. It is estimated that extraction of water from the Macquarie River and tributaries has reduced the size of the wetland by 40–50% during the 50-year period 1944–1993.

Following World War II, an allocation of approximately 50,000 ML to achieve flooding was made. However, by the early 1980s, irrigation in the Macquarie Valley was increasing at a rapid rate and, in 1986, a water-management plan was prepared. This made the Macquarie Valley the first river in the Murray–Darling Basin to have an environmental allocation.

Subsequently, increasing concern about environmental decline led to the implementation in 1996 of the Macquarie Marshes Water Management Plan, prepared by a committee made up of government agency staff and involving a community consultation process. The Plan provided for an environmental allocation with a high security component of 50 GL per year, which is available when river flows allow annual water allocations to exceed a defined level. The high security component may be carried over to a maximum of 100 GL (or for 2 years). The general security component of 75 GL is available subject to announced annual allocation, and any unused general security water may be carried over from year to year.

The revised provisions allow a 50 GL per annum increase in the average annual flow to the Marshes, and a similar reduction in average irrigation extractions. This equates to total flow to the Marshes being restored to 80% of the natural average — about 12% below what would be required to meet the Murray–Darling Basin Cap for irrigation diversions from the river.

Use of environmental allocations is typically made in response to inflow cues within the Macquarie Catchment. The cues are set annually and reviewed during the water year. They are based on desired ecological outcomes for the Marshes. The intention is to use environmental allocations to enhance natural flooding events —by influencing either the extent or duration of flooding. The environmental allocation can be called upon to extend the period of flooding to allow the successful breeding of waterbirds.

While sustainable management of the Marshes had widespread in-principle acceptance from the community, there were significant concerns regarding water lost to the irrigation industry and potential flow-on social and economic effects. Such concerns were compounded by

the apparent lack of scientific benchmarks to support the adjustment of the allocation, and the absence of reliable reporting mechanisms to gauge the effects of the allocation adjustment. The restricted opportunity for community involvement in the decision-making process was also a major topic of debate.

Management of the Macquarie Marshes has caused some disagreement between the irrigation and grazier communities — inundation of the Macquarie Marshes has economic benefit for graziers, but reduces the volume of water available to irrigators. Most of this discomfort dissipated with implementation of the 1996 water management plan.

Murrumbidgee River, New South Wales

In 1997, the NSW Government established river management committees to develop river management plans that took account of the need for environmental flows. This was done as part of the implementation of COAG water reforms. To facilitate planning, the NSW Department of Land and Water Conservation provided draft environmental-flow rules that acknowledge the likely detrimental economic impact associated with limiting water use. These set the maximum net farm-gate impact at 10% (ie. 10% loss of irrigation water allocation).

Following intensive regional and community reviews, the Murrumbidgee River Management Committee concluded that the maximum socially and economically acceptable reduction of allocation in regulated channels would be 4–6% (noting seasonal variation of this quantity could make the reduction as high as 17% in dry years). In identifying these values, it was stressed that emphasis must be placed on maximising ‘value for volume’ of environmental allocations. Potential also exists to increase environmental allocations through improved water efficiencies.

Murrumbidgee environmental-flow guidelines have been in operation since 1998. These rules were used to manage an environmental contingency allowance of 25 GL per year — this volume can be and has been supplemented by additional volumes. It is to be increased to 50 GL per year on approval of the (draft) Murrumbidgee Water Sharing Plan.

In addition to maintenance of minimum flows, two types of environmental flows have been implemented. The first is comprised of periodic small flushes of high velocity to scour sediment build-up below the dam and prevent algal blooms stimulated by low flows and poor water quality. These flows also aim to maintain some small-scale variability in the reach below Burrinjuck Dam.

The second type of environmental-flow release involves the discharge of large volumes to mimic natural flooding. Such releases are typically made to piggy-back high flows from Tarcutta Creek (necessary to circumnavigate the Gundagai choke), and facilitate flooding of the middle and lower Murrumbidgee wetlands (typified by floodplain billabongs). Successful wetland flooding of this type was orchestrated in September 1998 and August 2000.

The Integrated Monitoring of Environmental Flows (IMEF) program used for the Murrumbidgee monitors up to 15 selected wetlands one month after inundation, and every two months thereafter (until inundation recedes). Typically, wetland response to inundation is immediate, with clear increases in populations of wetland flora and fauna.

Snowy River, New South Wales and Victoria

The Snowy Mountains Hydro-Electric Scheme is a cooperative scheme shared by the Victorian, NSW and Commonwealth governments that produces electricity and increases the security of water supply along the Murray and Murrumbidgee rivers. Jindabyne Dam was completed in 1967, since which time flows immediately below the dam wall have been 1% of annual natural flow.

The environmental impacts of damming the Snowy River included:

- significant reduction in the size of the river channel and changes in the channel geomorphology from a continually flowing river to a chain of pools
- channel infestation with weeds, particularly willows and blackberries
- invasion of salt wedge at the river mouth
- reduction in breeding waterholes, and subsequently declining fish populations
- declining fish populations due to altered fish barriers created by changed flows
- loss of species habitat (eg. platypus populations have severely declined along the flood plain)
- a significant increase in water temperature harming in-stream biota and water quality
- prolific sedimentation and macro-algae matting
- lost recharge capacity to shallow aquifers around Dalgety, and subsequently negative impacts on agriculture).

In 2000, Victoria, NSW and the Commonwealth agreed to 21% of annual natural flow being financially facilitated and secured for return within 10 years of corporatisation, with an additional 7% of returned annual flow to be made available later, subject to private investment. For the 10-year period during which 21% of annual natural flow will be reinstated, both NSW and

Victoria have committed \$150 million to source the required 214 GL, predominantly through water efficiencies. It is anticipated that a joint government enterprise will be established to oversee expenditure of these funds and the reclamation of water for the Snowy River.

Looking to the future, the availability of three years of extensive, pre-environmental flow, riverine health data provides an excellent foundation for broad research assessing the effects of environmental flows on channel, fish, water-quality and weed management.

Lessons learnt

Collectively, the case studies demonstrate that implementation of environmental allocation necessarily assumes the availability of accurate hydrological data and effective water-accounting practices. Such data and practices underpin recognition and management of all property rights and allocations, ability to secure and manage inter-jurisdictional environmental allocations, cooperation/coordination between successive infrastructures, and the capacity to credit and debit allocations between years.

Implementation

Specific implementation events of environmental allocations were considered in four of the case studies: Barmah–Millewa, Campaspe, Macquarie Marshes and the Murrumbidgee. These events are discussed below from the perspective of ‘non-flooding’ and ‘flooding’ releases. Considering the other case studies:

- environmental allocations have yet to be made available in the Snowy River
- coordinated catchment management of environmental flows has yet to be implemented in the Burnett Basin (although dam-specific releases within the Basin have occurred)
- environmental-flow implementation was not examined in the Lachlan case study.

Non-flooding releases

Efforts were made in the Campaspe River to deregulate 25% of natural winter–spring flows, in order to return some of the natural winter–spring flow variability to the river. The intention was to monitor the effects of this returned variability on in-stream biota. Unfortunately, the effectiveness of the release was compromised by the need to make a significant ‘out-of-season’ irrigation release, resulting in far higher flows than would have been the case under natural conditions or was desirable for monitoring.

This compromised attempt to deliver environmental flows demonstrates the low priority given to allocations for environmental purposes as compared with irrigation use. It is likely that the tension between these priorities is greatest in smaller rivers where there is generally less

flexibility to secure environmental-flow volumes through water efficiencies and/or water trade.

Monitoring of the small flushes of high velocity water released from Burrinjuck Dam demonstrates that they are an effective means of managing sediment build-up and algal blooms. The potential benefits to the riverine environment of the small-scale flow variability are unknown.

Flooding releases

Environmental allocations have been used in the Macquarie Marshes and Murrumbidgee to flood wetlands on several occasions. While environmental allocations in both areas are too small to mimic a full natural flood, the allocations have been successfully used to complement natural floods by increasing the area inundated and extending the duration of the inundation. The long-term impact of this approach has been a general reduction in the size of floods, but an increase in their frequency.

The Barmah–Millewa Forest flood in the spring–summer of 2000–01 was a similarly managed event in terms of environmental flows, but was particularly spectacular as maximum natural inundation conditions were achieved and did not fully subside for five months.

In all case studies of flood events, flooding initiated a boom in wetland biodiversity, populations and productivity. On the downside, however, monitoring in both the Murrumbidgee and Barmah–Millewa indicates that flooding favours introduced pest species such as carp and redfin just as much as it does indigenous species.

The obvious conclusion from monitoring of periodic flooding is that wetlands respond very favourably to wetting and drying cycles, whether natural or managed. Available evidence suggests that (within the contemporary context of heavily committed water resources) the bigger and longer a flood that can be orchestrated, the better will wetlands respond. It is also clear that environmental allocations will never be sufficient to provide a full flood, and that strategic use of these allocations is paramount.

While maintenance of wetlands is unquestionably a priority for environmental allocations management, it is important that the immediate response to flooding events does not negate other purposes of environmental-flow management. Other environmental issues requiring consideration include optimal maintenance of channel environments and effective functioning of ephemeral channels, including those which drain wetlands at the end of flooding events.

Development and delivery of optimal environmental-flow regimes

A number of circumstances can impede the development of ‘ideal’ environmental-flow regimes. These are broadly as follows.

- **Infrastructure constraints** — infrastructure typically causes restrictions to flow in regulated channels. Such restrictions include dam storage capacity, limit of rate of flow release from dams (feasible volume: time ratio of releases), and channel capacity to cope with high flows.
- **Hydrological constraints** — temperature of releases; implications of long-term climate change (occurrence of natural flooding events on which to ‘piggy-back’ environmental allocations); knowledge and effective management of groundwater/surface water interactions.
- **Ecological constraints** — knowledge gaps; competing environmental concerns (eg. flow requirements for wetland flooding may cause undesirable up-stream channel scouring).
- **Industrial competition** — environmental requirements frequently compete against industrial needs, particularly in summer. This is a pertinent issue for security of environmental water in unregulated channels. It can also limit the capacity to replicate natural, dry-season low flows in regulated channels.
- **Social capacity** — implementation of environmental allocation programs can create stress in rural towns, particularly when there is not a clear understanding of the reasons for them or where there is opposition from existing diverters.
- **Political commitment** — allocation of water for environmental purposes is a highly political issue, and this has delayed provision of basic volumes in some cases (eg. the Snowy River).
- **Institutional** — in regions where infrastructure is managed by different institutions, coordination of their objectives and management can be an issue. Poor communications between different bodies involved in environmental-flow management can delay achieving consensus about what should be done.

Using adaptive management to achieve ‘value for volume’

The adoption of adaptive management techniques would facilitate ‘value for volume’ outcomes through strategic use of environmental allocations, particularly where environmental-flow objectives are best achieved by complementing natural flooding and drying events. There is general consensus that current management regimes are based largely on ‘common sense’ rather than established scientific knowledge.

An adaptive approach at all scales of environmental-flow management provides for integration of general and specific science as knowledge progresses, and facilitates optimal management.

Research

The time frames required by legislative commitments for the delivery of environmental allocations limited the capacity to undertake and use locality-specific research for the immediate management of environmental flows. In this context, knowledge across the case studies (with the debatable exception of the Campaspe project) has largely been developed on a ‘need to know’ basis, with decisions relying heavily on expert advice and opinion. This placed considerable professional pressure on scientists to identify the most effective means to achieve environmental outcomes with available environmental allocations. In the Lachlan, it has been suggested that requiring that an estimate of certainty accompanies scientific advice may alleviate this pressure.

Environmental-flow regimes currently in place usually try to better mimic local natural flow variations, and their scientific basis is typically generic findings (eg. healthy wetlands are indicative of healthy rivers) and databases of historic rainfall patterns.

There are several models that can be used to examine particular flow scenarios as a means to aid decision-making. The most widely used of these is the Integrated Quantity and Quality Model (IQQM), developed by NSW and adapted and used by other States. While the IQQM has been progressively developed and modified for a variety of purposes, it is essentially a hydrological model. There is still a lack of similarly effective decision-making models for socio-economic and other such purposes, and so caution must be exercised when using any model for purposes beyond its original intention.

The research focus to date has tended to be on ecological requirements and responses. Such work typically occurs at specific sites and it is therefore uncertain how far its findings can be extended. Methodologies, on the other hand, are frequently readily transferable. Several States have coordinated State-wide programs that make it easier

to compare circumstances and management activities across the jurisdiction.

The most conclusive information to date suggests that mimicking natural inundation and drying cycles promotes the optimal functioning of wetlands. This finding is consistent for all case studies. It is supported by monitoring, which demonstrates that species diversity peaks after inundation, and that the structural diversity of wetlands is significantly reduced by both lack of floods and permanent inundation.

Vegetation, fish, birds and macroinvertebrates are becoming increasingly accepted as good indicators of riverine health. Macroinvertebrates are proving particularly useful, as in-stream species can be chosen and monitored for specific river-management responses (as is being done in the Campaspe project). Limitations of such work include the low capacity to extrapolate findings beyond the specific study areas. Waterbirds and fish are also being widely used as indicators, particularly in the Macquarie Marshes, although the natural migrations of some species can complicate factors. Two examples: the Japanese snipe, a waterbird that breeds in the Macquarie Marshes, lives outside Australia for much of the year; and the Australian Bass, a native fish known to breed in the Snowy River, can migrate along the Australian east coast as far north as Queensland.

While short-term, strategic studies are currently in vogue, longer-term studies are proving very effective in their capacity to support long-term adaptive management frameworks. This kind of science–management relationship is emerging in the work on the Macquarie Marshes.

There are significant existing and on-going gaps in the knowledge bases for both local and generic issues; it must be noted too that there is a significant amount of research under way across the waterways of Australia. This will continue to develop to support adaptive management processes that are now being widely adopted for environmental water management. This research is largely coordinated through State agencies, CSIRO, universities, and key research inter-institutional bodies such as the Cooperative Research Centre for Freshwater Ecology.

Knowledge gaps

Extensive knowledge gaps exist in both the generic and specific understanding of environmental water management and impact. Monitoring in the Snowy River demonstrates that rivers can continue to decline in health over many years — 45 years in the case of the Snowy — without reaching a new stable state after the implementation of an altered flow pattern. This example shows how difficult it is to accurately predict the long-

term effects of environmental-flow management, and shows the importance of maintaining basic long-term monitoring programs.

Adequate resourcing is a predictable research issue. In the context of environmental flows, however, the effectiveness of adaptive management techniques will depend on the provision of an adequate commitment for monitoring and core research. The \$300m commitment that has been made to secure environmental flows for the Snowy River is supported by a budget of only \$800,000 (\$400,000 of which is in-kind support) for developing and managing those flows. Such discrepancies in funding will make it difficult to get the best possible results from available environmental-flow allocations.

Varying approaches to the development of environmental flows have highlighted different general knowledge requirements. The case studies indicate that the areas most consistently short of information are:

- understanding of how altered regimes affect riverine health and how to achieve optimal riverine health in significantly altered flow regimes
- understanding of the socio-economic impacts of different environmental flow regimes
- the specific socio-economic issue of property rights.

These points are considered in further detail below.

Understanding full impacts of flow diversions

It must be recognised that knowledge requirements vary considerably depending on the scale of management, waterway attributes (eg. is flow perennial or ephemeral), and what environmental outcomes are desired.

In essence, we know enough about how flow regimes have been altered (by development and/or diversion), and, at a very general level, consensus has been reached on the aims of environmental water allocations programs.

The sort of information that is required (and is in short supply) is that which establishes the links between changes to existing flow regimes and the potential effects on key environmental attributes. This statement is a precis of the many specific knowledge gaps identified in the case-study summaries. By prioritising environmental attributes for management, an implicit assumption is made that there is a ‘cause and effect’ connection between altered flow regimes and desirable environmental attributes.

Unfortunately, ecological relationships are rarely simple enough to permit ready identification of ‘cause and effect’. Although the creation of wetting and drying cycles in wetlands is a very satisfactory example to the contrary, identifying such relationships in permanently wet environments (eg. perennial channels) is difficult.

Such environments rely on a complex recipe of attributes, any of which may be complicated by factors such as seasonal variation. Preliminary findings of the Campaspe project support this assessment. For example, while it was hypothesised that altered flow regimes in the Campaspe had affected fish breeding, evidence now suggests that satisfactory breeding does occur, but that survival rates and recruitment of juveniles are then reduced by some unknown factor.

Clearly, the complexities and scales of such knowledge gaps will make it harder to identify critical flow characteristics and will retard progress in achieving optimal environmental-flow regimes.

Social and economic issues

Social and economic issues can be broadly defined as being either conceptual or to do with implementation. Conceptual issues are essentially those concerned with community support for and adherence to the management programs required for the delivery of environmental flows. It might be expected that rural communities (those directly affected by changes in flow regimes) and environmental-conservation organisations would be the two groups having the greatest concern about development of environmental water allocations programs, albeit not necessarily from the same perspective. Different approaches were taken in the Burnett Basin and the Murrumbidgee region in the development of their respective environmental-flow regimes.

In the Burnett Basin, a streamlined process was made easier by recognising all existing property rights — this approach assured rural communities of their water securities, and made it easier to focus the debate on how to get the best ‘value for volume’ from the remaining flows available. While there are benefits to this approach, it is clearly not suitable for over-committed streams. It remains to be seen if further degradation in such streams will cause unanticipated community pressure from either rural people or environmental/conservation organisations.

In the Murrumbidgee catchment, extensive efforts were made to facilitate community involvement in the development of regional, environmental water management frameworks. Such efforts were necessitated by the need to reduce irrigation diversions in order to provide minimal allocations to the environment. As part of the ensuing communication process, considerable effort was made to explain how environmental allocations would be used, identify the predicted benefits, and to minimise and explain the need to reduce irrigation allocations. Benefits are that the community has had the opportunity to develop a good understanding of issues surrounding environmental flows, and to contribute to

decision-making, particularly with respect to how much reduction in irrigation allocations local communities can withstand. This input required considerable time and money resources. In the short term, the slower progress resulting from a more informed/involved community versus the benefits of community input/understanding could be debated. In the longer term, it is anticipated that implementation of environmental water allocations programs and reduction of allocations to agriculture will be made easier by better community understanding and ownership of the environmental and sustainability objectives.

Significant issues are raised by the implementation of environmental water allocation programs. Flooding events have particular consequences. Disruption to farm business resulting from over-bank flows must be considered. Assistance was offered to landholders affected by the 2000–01 Barmah–Millewa flood to compensate them for losses caused by over-bank flows. These flows were maintained for the extended period needed to have a significant beneficial effect on the forest. In other areas, rural towns (eg. Gundagai) have encroached on the natural floodplain and have little capacity to adjust to floods. In such circumstances, the water management authorities would, under current arrangements, be held legally accountable for any flooding of the town resulting from releases of environmental water.

Use of environmental flows may also create friction within rural communities. For example, Macquarie Marshes flooding has, in the past, been perceived to benefit graziers at the expense of irrigators. Such disharmony in small rural communities has the potential to cause significant social disruption, and dealing with them must therefore be considered an important part of environmental-flow management.

The Lachlan case study suggests there is a need to better integrate local community knowledge into environmental-flow management, and to establish tighter links between social and biophysical knowledge. Likely loss in the near future of the longitudinal local knowledge held by the senior rural generation is a well-recognised concern. Unfortunately (like so many other issues), it is extremely difficult to develop cost-effective means of documenting this knowledge, and its preservation therefore relies on maintenance of intergenerational corporate knowledge. Local community involvement with adaptive management of environmental flows is one means by which local knowledge can be used in conjunction with developing biophysical knowledge.

Property rights

The issue of property rights associated with environmental flows was not raised through the case

studies. Nevertheless, in the context of increasing demand for water, and a dynamic water trade, it must be acknowledged as a central issue affecting any program introducing a comprehensive approach to environmental allocations in any river system.

Generally, there is no certainty that environmental flows released through one region will retain the status of an environmental allocation downstream of the region it was designated for. This means considerable potential exists for downstream irrigators to make private profit from a ‘public good’ release in upstream regions. This uncertain security of environmental water allocations has the clear potential to reduce long-term community support for environmental allocations.

The Murray–Darling Basin Commission (MDBC) is currently working with the States in the Basin, to develop property-right status for environmental flows. This would enable effective implementation of broad-scale management of environmental flows. It is anticipated that property-right frameworks adopted by the MDBC will have potential for national implementation.

Associated issues include the need to determine how much water is absorbed by the environment, as distinct from how much water is required to facilitate environmental access to that water. Some 4426 GL passed downstream of Yarrawonga from the start of September 2000 to the end of January 2001 in order to fully flood the Barmah–Millewa Forest, but only 1000 GL was absorbed by the forest. There was an environmental allocation of 341 GL within the total flow.

Groundwater environmental allocations

A critical component of implementing environmental water provision that has escaped the ‘case-study’ net is that of allocations of groundwater to the environment. Work funded by Land & Water Australia clearly identified a broad range of groundwater-dependent ecosystems — including rivers themselves (Hatton and Evans 1998).

The market for professional skills in the management of groundwater-dependent ecosystems is expanding. Heavy pressure on existing expertise resulting from implementation of the COAG water reforms (COAG

1994) has prompted the development of a postgraduate course in groundwater-dependent ecosystems at the University of Technology, Sydney. The course was introduced in July 2001.

There is no comprehensive data analysis available that can be used to make sure that contemporary surface-water management initiatives such as the MDBC cap, claw-back of allocations to enable environmental flows etc. have not simply displaced resource accession points from in-stream to adjoining shallow aquifers. As such extractions would normally either induce channel leakage or intercept future in-stream flows, temporal displacement of in-stream water depletion is a valid concern.

Since the completion of the Land & Water Australia National Groundwater Program, there is no nationally recognised funding program for groundwater issues. It is clearly difficult for groundwater priorities to compete with surface water priorities in ‘total water management programs’ when differences in resource response time are great. However, in the long term, the cost of ignoring the linkages could be high. Groundwater research can be expensive. Lack of a coordinated approach to the allocation of groundwater to the environment will severely reduce the use made of available methodologies, with the result that national costs to address associated issues are many times greater than necessary.

Future directions

Decline in Australia's natural resources and environmental assets is a growing political issue, with a wide range of interests now demanding influence over the decisions that will determine what happens in the future. The parliaments of the States and Commonwealth are where most of the resulting tensions are played out. These bodies are responsible for the legislative framework that defines what can be done and how it should be done. They also provide the funds needed for implementation.

However, while parliaments have these ultimate responsibilities, there is a variety of opinion about how they should exercise them. One group of commentators (Maher *et al.* 2002, p. 126) summarised the differences in approach as follows:

The nature of the legislative framework appears to be at a crossroads. The regulatory model is to move forward with structures, statutory plans, administrative processes, etc; and seems to be favoured by stakeholders generally outside decision-making circles and who are disaffected with river managers' performance and accountability to date. The other model is to move forward with inclusive, co-management, multiple mechanisms approaches, with a lower but critical profile for legislation.

On the one hand, it is considered desirable that people working in catchment organisations should know the formal powers and responsibilities of their organisation. On the other, it is obvious that many desired outcomes are better achieved by goodwill, shared investment and partnership, rather than by statute, regulation, charges and compensation.

Many commentators call for a stronger role for the Commonwealth. Given the existence of major conflicts between different interests, they think good and consistent policies based on a well-informed knowledge base needs more than just negotiation aiming at win-win solutions for all parties. To deal with this reality, they call for an independent body to provide objective advice to governments about water allocation and policy. This, in turn, so the argument goes, should be backed by a combination of incentives and sanctions provided by a strong, authoritative Commonwealth Government. Within this framework the States should then be encouraged to embrace 'cooperative federalism'.

Existing legislation relevant to environmental water

Legislation relevant to environmental water falls into two broad areas: statutes affecting land and water users who impact on rivers; and statutes affecting governmental structures, intergovernmental and interagency relations and operations. More specifically, environmental water legislation deals with the following matters:

- **Institutional structures** — laws establishing institutional structures through which river management is actioned, including policy, operation and service delivery aspects. This includes components such as the River Custodian concept, any regional structure for the lead or other agency, and frameworks and processes for stakeholder and community involvement. The latter may be inter- and intragovernmental; or on an interstate, State, regional and/or local basis. Structures addressing the interrelationships between related functional areas and programs such as integrated catchment management and Landcare are also included.
- **Responsibilities and resourcing** — laws addressing river-management roles and responsibilities. This includes inter- and intragovernmental matters, including the relative responsibilities and roles of the Commonwealth and States under the Constitution, and the Administrative Arrangements Acts and related subordinate legislation of each jurisdiction, which establish government agencies, designate lead agencies, clarify spatial, functional and statutory responsibilities and spell out the relationships between lead and related agencies in river restoration. They also define interagency jurisdictional boundaries and at the same time establish coordination and resourcing mechanisms. Co-operative cross-jurisdictional arrangements such as the Murray–Darling legislation are in this group.
- **Outcomes, approaches and plans** — these set out approaches for determining and planning for desired ecological and resource-use outcomes such as water entitlements, environmental values and water quality objectives and catchment-specific management outcomes. The results may be legislated in the form of

topic or area-specific plans, schedules or other subsidiary legislation.

- **Permitting and policing** — legislation addressing the scope and outcomes intended. This includes setting standards such as quantity and quality specifications, processes and/or timetables, as well as legislation which codifies the standing and entitlements of water ‘beneficiaries’ (including State and local governments, the environment, the community and classes in the community). This category covers regulatory enforcement, for example, as well as anti-pollution and pollution licensing statutes, and inspection.
- **Checks and balances** — there are two main components. The first is monitoring and reporting laws, including agency periodic reporting, external/independent performance auditing, River Ombudsman, State of River reporting including in State of Environment reports, and the like. The second relates to community empowerment, including generic and specific statutory review, funding and reimbursements, public standing and appeal provisions, and inexpensive access to information.

Principles for environmental water legislation and policy

Whether the product of the Commonwealth or a State parliament, the legislative framework can range from a statement of principles that is then made operational by the development of appropriate policy and management guidelines, to detailed instructions defining how things should be done. The former gives more flexibility to the organisations responsible for implementation, while the latter confers more authority. The circumstances within which a program is being implemented will determine which quality is more needed.

A recent statement by Maher *et al.* (2002) based on the principles of ecological systems thinking for economic success, good governance, and management systems thinking, highlighted the following principles as relevant to river management. They also provide a useful template for environmental flows.

- The definition of a river should include catchment and impact management, including both above and below ground level, and not be confined to the waterbody, ‘bed and banks’, or floodplain.
- Environmentally sustainable management must be the primary object (not one of several) of catchment management, with measurable and binding standards.

Catchment legislation should be the primary context for other related legislation or policy.

- There should be an integrated hierarchy of planning and management frameworks.

- There should be a single catchment-based custodial agency in each river basin, outcome-focused, equipped with strategic powers, funded in line with its responsibilities, and reporting publicly at legislated intervals against its strategic outcome objectives.
- The catchment agency should include and engage representatives from all stakeholder groups in an open, equitable and adequately resourced manner, incorporate best-practice public consultation and provide structured on-going education.
- There should be coordinated and integrated strategic planning and implementation, with the key vehicle being the catchment strategic plan. Its components should include comprehensive natural-resource inventories, strategies to address cumulative effects and primacy in development assessment. It should be able to bind local government budgets and activities; provide comprehensive natural resource management (NRM) coverage; a mandated review frequency; call-in powers; coverage of both surface and groundwaters; and be able to assess proposed activities and additional impacts of associated land uses.
- The custodial agency should have the capacity to self-fund.
- There should be constructive processes to integrate local government in the implementation process (if different).
- There should be a requirement for continuous improvement and adaptive management.
- The custodial agency should coordinate catchment investment.
- Where appropriate, activities should be licensed with compliance enforced.
- The custodial agency should be subject to independent audit and reporting processes.

New science and methods

To be effective, environmental water allocations need to be part of an integrated approach to environmental management. Failure to manage water sustainably has primarily been the result of insufficient knowledge. There are several critical science and methodological gaps.

Needs include:

- an improved scientific basis for holistic water-resource-allocation policy in urban and rural environments, including linkages between rivers, floodplains, wetlands, estuaries and near ocean environments
- methods to assess the environmental, social and economic effects (including benefits, disadvantages and ecological trade-offs) of environmental water allocation
- good quality science, relating environmental water allocation to water quality, and catchment processes more generally — this is largely absent in Australia and only marginally addressed overseas

- improved understanding of groundwater–surface water interactions, groundwater-dependent ecosystems and the role of groundwater more generally in environmental water allocation programs
- more knowledge of the effects of environmental-flow regimes on estuarine habitat and ecosystems
- improved understanding of the cumulative effects of better flow management at reservoirs, dams and other structures, particularly for algal management, fish passage and control of thermal pollution
- greater understanding of what is involved in extrapolating results from one system to another, which is more often than not a dubious proposition — deciding what is transferable and what needs to be known locally is critical
- more research into the impacts of systemic trends such as climate change and changing land uses
- more attention given to the identification of high-value environmental assets and means for their protection
- detailed assessments of the environmental water needs for specific ecosystems or species
- improved processes for internal ecological trade-offs of different water regimes between species and ecosystems, and between different river reaches
- attention to the freshwater flow needs for estuaries and near ocean environments — so far missing in Australia, although good progress has been made in South Africa
- more research into the long-term effects of water abstraction and/or environmental water allocation
- systematic high-quality scientific testing and verification of the wide-ranging environmental methods in use (none are thoroughly tested).

Socio-economics

In the pursuit of opportunities to secure water for the environment, there is a need for more research into the most appropriate way to define water rights, allocate them and facilitate trading. In particular, research is required on ways to clarify the definition of rights to use water, so that so-called improvements do not result in the erosion of environmental values. It is also important to improve trading arrangements, so that water trading results in environmental improvement and not environmental harm.

With regard to the assessment of costs and benefits of improving environmental flows, smarter models are

needed that can describe the consequences of changes as they occur through time and provide better estimates of marginal costs and benefits.

To improve the understanding of impacts caused by reductions in water allocation to the full range of consumptive uses, requires improved scenario models at the local level. There is also a need for research on economic options for securing water for the environment. While a *pro-rata* volumetric reduction is simplest, this will often take water away from the most-efficient water users and not target areas where negative environmental externalities are highest. It may be possible to develop clever ways to secure water that make better use of farm dams, overland flows, infrastructure upgrading, and are able to supply water at times of highest need.

The adoption of social-science methods for dealing with the social impacts of proposed programs is essential. The understanding of cultural aspects of water management, including Indigenous rights to water, is still in its infancy.

While some important planning, development and actual implementation of environmental flows has occurred in Australia there are still significant issues that need to be addressed in order to achieve successful adoption of flow releases.

Significant research investment is needed to address ecological unknowns, and improve socio-economic modelling. In addition:

- optimal environmental-flow regimes are a long-term ambition requiring highly strategic use of environmental allocations and cooperation between jurisdictions and the private and public sectors
- adaptive management that utilises research findings is critical to progressing towards this goal.

The implementation of environmental flows assumes availability of accurate hydrological data and effective water-accounting practices. Such data and practices underpin the recognition and management of all property rights and allocations, the ability to secure and manage interjurisdictional environmental allocations, essential cooperation/coordination between successive infrastructures, and capacity to credit and debit allocations between years.

Concluding remarks

The choices that society makes about its future management of natural resources are, in effect, choices about what sort of society it wants to be in the future. If it decides to introduce environmental water allocations, that is **not** a vote against economic development. In the long

term, economic prosperity depends on the continued existence of healthy aquatic ecosystems. It is important to remember that rivers that are managed sustainably can satisfy a wide number of important needs, environmental and aesthetic as well as economic.

A vision of the future

Australians value environmental water, the community has confidence in environmental water allocation mechanisms, and the environmental management of water is a major industry in its own right.

References

- Allan, J. and Lovett, S. (1997). *Impediments to managing environmental water provisions*. Bureau of Resource Sciences, Canberra.
- Arthington, A.H., Bunn, S.E., Pusey, B.J., Bluhdorn, D.R., King, J.M., Day, J.A., Tharme, R.E. and O’Keeffe, J.H. (1992). Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems. In: Pigram, J.J. and Hooper, B.P. (eds). *Proceedings of an international seminar and workshop on water allocation for the environment, November 1991*. The Centre for Water Policy Research, University of New England. Armidale, Australia. 282 pp.
- Australian State of the Environment Committee (2001). *Australia state of the environment 2001*. Independent report to the Commonwealth Minister for Environment and Heritage, CSIRO Publishing on behalf of the Department of Environment and Heritage, Canberra.
- Brizga, S.A., Arthington, A.H., Choy, S.J., Kennard, M.J., Mackay, S.J., Pusey, B.J. and Werren, G.L. (2002). Benchmarking, a “top-down” methodology for assessing environmental flows in Australian rivers. *Proceedings of the International Conference on Environmental Flows for River Systems*. 3–8 March 2002, Cape Town, South Africa.
- COAG (Council of Australian Governments) (1994). *Council of Australian Governments Water Reform Agreement*. Australian Government Publishing Service, Canberra.
- Fisher, T. (2000). Water: lessons from Australia's first practical experiment in integrated microeconomic and environmental reform. In: *Workshop proceedings: microeconomic reform and the environment, 8 September 2000*. Productivity Commission; Melbourne.
- Hatton, T. and Evans, R. (1998). Dependence of ecosystems on groundwater and its significance to Australia. *LWRRDC Occasional Paper No.12/98*, 77 pp.
- Maher, M., Cooper, S. and Nichols, P. (1999). Australian river restoration and management criteria for the legislative framework for the twenty-first century, based on an analysis of Australia and international experience. Report to LWRRDC: Brisbane. *LWRRDC Occasional Paper No. 02/00* <www.lwrrdc.gov.au/html/publications/catalogue/rivers_and_riparian_lands/op0200/op0200>
- Maher, M., Nichols, P. and Nevill, J. (2002). *Improving the legislative basis for river restoration and management in Australia — Stage 2 Report*. Report to the National Rivers Consortium: Brisbane.
- Nancarrow, B.E. and Syme, G.J. (2001). *Environmental flow and water quality objectives for the River Murray project: stakeholder profiling study*. Canberra, Murray–Darling Basin Commission.
- Nancarrow, B.E., Syme, G.J. and McCreddin, J.A. (1998). *The development of stakeholder-based principles for defining environmental flows in modified rivers*. A report to the Land and Water Resources R&D Corporation. CSIRO Land and Water Consultancy Report No. 98–25.
- NLWRA (National Land & Water Resources Audit) (2001). *Australian water resources assessment 2000. Surface water and groundwater — availability and quality*. National Land & Water Resources Audit, Canberra.
- Republic of South Africa (1998). South African National Water Act No. 36 of 1998. *Government Gazette* Volume 398, No.19182, 26 August 1998. Cape Town.
- Roberts, J., Young, B. and Marston, F. (2000). Estimating the water requirements for plants of floodplain wetlands: a guide. *Occasional Paper No. 04/00* Land and Water Resources Research & Development Corporation, Canberra.
- Wilke, H.A.M. (1991). Greed, efficiency and fairness in resource management situations. *European Review of Social Psychology* 2, 165–187.