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Opinion

Marine and Freshwater Research, 2009, **60**, 271–279

Ecosystem science: toward a new paradigm for managing Australia's inland aquatic ecosystems

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Abstract. Freshwater ecosystems are a foundation of our social, cultural, spiritual and economic well being. The degraded condition of many of Australia's river ecosystems is testament to our failure to manage these resources wisely. Ecosystem science involves the holistic study of complex biophysical systems to understand the drivers that influence ecological pattern and process. Ecosystem science should underpin both water management and policy. Our understanding of aquatic ecosystems lags behind the increasing problems caused by past land and water management. Current post-graduate training programmes will not provide the aquatic ecosystem scientists needed by government and management agencies to prevent further degradation. We advocate new initiatives to capture the skills, knowledge and innovation of our research community by engaging scientists and managers in large-scale, long-term ecosystem science programmes across Australia and to integrate these programmes with community aspirations, policy, planning and management. We call on management agencies to increase their support for and uptake and use of ecosystem science. We also advocate establishment of national archives for long-term ecologically-relevant data and samples, and clear custodial arrangements to protect, update and facilitate knowledge-transfer. These initiatives need to be supported by more extensive, better-funded post-graduate and post-doctoral programmes in ecosystem science and management.

Additional keywords: degraded ecosystems, educational needs, river ecosystems, water-resource management.

Introduction

In most of Australia, many rivers, lakes, wetlands and other aquatic ecosystems are severely degraded as a result of escalating human demands on the environment. Large regions also have been experiencing a major, prolonged drought that, exacerbated by anthropogenic water extraction, has produced the driest conditions on record (e.g. Bond *et al*. 2008). River degradation and water-resource management are now national priorities (COAG 2004; NWC 2007).

In spite of decades of scientific research in Australia, we contend that the knowledge about aquatic ecosystems required to support water-resource management lags behind the increasing problems caused by past, often piecemeal, management approaches. Indeed, the current scale of research compares poorly with the stated desire of state and federal governments to adopt an ecosystem approach (Connell 2007; Harris 2007). Here, we (*i*) advocate the urgent need for large-scale, long-term, integrated, comprehensive ecosystem science to guide

10.1071/MF08188 1323-1650/08/030271

Table 1. The Bungendore Group's Statement of Values

- Freshwater ecosystems are a foundation for our social, cultural, spiritual and economic well being
- Aquatic ecosystems have intrinsic values which go beyond economic value
- The economy is part of the ecosystem and the health of the two are co-dependent
- Climate change, population shifts and associated resource use have increased the need for urgent action
- Globally, aquatic ecosystems are under serious threat and urgent action is needed to protect them
- Many of Australia's aquatic ecosystems are badly degraded; however, they are worth restoring
- Pathways for change occur through scientific engagement with communities and governments
- The loss of species can reduce critical ecological functions. This is highly undesirable
- There is a major need to ensure intergenerational equity
- There is an urgent need to ensure that advice based on good aquatic-ecosystem science is available to inform land and water management in Australia

water-resource management in Australia, (*ii*) highlight the limitations of current research funding policies and (*iii*) review goals, challenges, and educational needs and opportunities. The views expressed here were developed by scientists focussed on biophysical aspects of aquatic ecosystems; however, we acknowledge the need to include economic and social aspects in holistic management of these complex problems. These needs are not detailed here, although an itemised statement of the group's values is given in Table 1.

Ecosystem science

An ecosystem is 'a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment within its boundaries' (Likens 1992, p. 9). Ecosystems may be large or small and, with appropriate boundaries such as catchment boundaries, provide powerful conceptual models for science and management. Components of ecosystem science include *Ecosystem Thinking*, which is thinking holistically, integratively and long term about complicated problems, and the *Ecosystem Approach*, which applies ecosystem thinking and the ecosystem concept to complicated problems. Different foci can be used, such as natural history, mass balance or material budgets, simulation modelling, comparative studies or experimental manipulation (Likens 1992). The ecosystem approach can be an important quantitative 'tool' for evaluating mass balances for large, complicated ecosystems. *Ecosystem science* then uses ecosystem thinking, the ecosystem concept and the ecosystem approach in addressing scientific questions at a system's level.

Ecosystem science can be used to study complex biophysical systems to understand the drivers – human and non-human – that influence ecological patterns and processes. Biophysical interactions are a focal part of contemporary ecosystem science (e.g. Likens 1992; Harris 2007), although views of ecosystems include concepts of stability and equilibrium (Odum 1971), panarchy (Holling 2001), hierarchical organisation (O'Neill *et al.* 1986) and scale (Levin 1992). Ecosystem science maintains a hierarchical perspective, drawing on research at all scales and levels of biological organisation, including genotypes, organisms, populations, communities, ecosystems, landscapes and bioclimatic regions (Arthington *et al.* 2006; Lake 2007; Parsons and Thoms 2007). The context for all such investigations, nevertheless, is the ecosystem.

Attempts to manage catchments, rivers, lakes and wetlands as integrated ecosystems require integrated holistic, long-term, multidisciplinary approaches, which simultaneously consider the physical, chemical, and biological components of rivers and landscapes. Integration is required across the disciplines of ecology, hydrology, geomorphology, chemistry, genetics, engineering, social science, economics, management, law and policy. Such integrated approaches have been successfully employed in North America and Europe to address acid rain (Likens *et al.* 1972, 1979; Schindler *et al.* 1985), eutrophication (Vollenweider 1968; Schindler 1977; Smith 1998) and environmental problems in forestry (Likens *et al.* 1978). Successful management of these widespread, complex anthropogenic environmental problems was based on knowledge gained from ecosystem science. In the case of acid rain, it was necessary to integrate long-term results on the origin and impacts of atmospheric deposition on aquatic and terrestrial ecosystems and on human infrastructures and health to convince the public and decision makers to take regulatory action that would reduce the sources and thereby reduce the impacts of the anthropogenic acidification (Likens 1992).

Ecosystem science applied to rivers

The current state of Australian river ecosystems, including their catchments and estuaries, and the developmental and climatic threats that they face, present major challenges for intelligent management of land and water ecosystems. Management of these systems is made more challenging by the fact that aquatic ecosystems are inter-connected from their headwaters to the sea, even though they are often managed as separate units. An ecosystem-science approach is needed urgently to underpin natural-resource management, yet such an approach has rarely been applied to environmental problems in Australia (Thoms *et al.* 2006; Harris 2007).

Australia's aquatic ecosystems, including their flora and fauna, are diverse and unique, and adapted to a highly variable climate (Lake and Bond 2007). However, the natural resistance and resilience of these ecosystems have diminished in many areas, particularly those affected by intensive land-use change, loss of riparian vegetation and altered river-flow regimes (Arthington and Pusey 2003; Bond *et al.* 2008). The current severe drought (Murphy and Timbal 2007) has highlighted the difficulties in devising strategies for adaptive management of riverine ecosystems. For example, a decade of research and policy development to implement the cap on water extraction from the Murray-Darling system has proven to be an inadequate management step because the current flows do not even reach the level set for minimum extraction (Connell 2007).

Australia is the driest inhabited continent, and climate change modelling (CSIRO and BoM 2007) indicates that water availability in the southern part of the continent will decrease (e.g. CSIRO 2008) while, at the same time, human demands for water continue to grow. Many already stressed or degraded aquatic ecosystems are likely to undergo irreversible changes, markedly compromising their capacity to maintain the provision of ecosystem goods and services.

Four issues underscore the need for knowledge gained from ecosystem science to be used in management of aquatic systems: (*i*) the limited natural capacity of aquatic ecosystems to withstand the imminent changes in climate and increased demand for water by humans; (*ii*) the impact of land- and water-use and climate change manifested over long periods, with slow recovery (Lake 2005; Lake *et al*. 2007; Bond *et al*. 2008); (*iii*) difficulty in identifying the most effective restoration measures in response to multiple, interacting pressures (Bunn and Arthington 2002); and (*iv*) the complex nature of ecosystem response to change, which is often non-linear, has thresholds, and is expressed at a range of spatial and temporal scales.

Some recent Australian examples of aquatic ecosystem science guiding management

In the mid-1990s, widespread community concerns about occurrences of phytoplankton blooms, particularly toxic species of Cyanobacteria, stimulated extensive research into understanding the eutrophication of Australian freshwater and estuarine systems. This research was underpinned by the following two major research programmes: the CSIRO Blue-green Algal Program (Davis 1997) and the National Eutrophication Management Program (NEMP) (Davis and Koop 2006). The NEMP was a joint initiative of Land and Water Australia and the Murray-Darling Basin Commission from 1995 to 2000 and funded some 24 research projects. Davis and Koop (2006) comprehensively reviewed this research and concluded that the established model for the northern hemisphere of increased nutrient loading, leading to heightened phytoplankton production, was not always the trigger for phytoplankton blooms in the regulated rivers of south-eastern Australia. In these systems, light penetration and thermal stratification are more important, as recently confirmed for the regulated River Murray (Oliver and Merrick 2006). This and other key findings led to a broader, system's view of the processes regulating nutrient delivery, thermal stratification, phytoplankton blooms and eutrophication in Australian aquatic ecosystems.

The rivers of Australia's central arid zone are unique for their extreme flow variability, complex geomorphology, intrinsic ecological character and their largely pristine state (Thoms *et al*. 2006; LEBSAP 2008). A proposal for irrigated cotton crops along Cooper Creek in the Lake Eyre Basin was challenged by scientists because it required a reliable water supply from a highly variable hydrological system characterised by a 'boom-and-bust' ecology (e.g. Walker *et al*. 1997). Although the proposal required a diversion of only 2.5% of the mean annual discharge, the long dry or low-flow periods that are the norm in this region meant that in many years this development would have required all of the flow in the river, leading to major ecological impacts. This proposal was rejected by the government; however, it may be revisited in future reviews of the current Water Resource Plan for Cooper Creek. The prevailing scientific view is that the highly variable flow of rivers in the arid centre of the country would not support any regular water diversions without major ecological consequences. A decade of ecosystem research provides unequivocal scientific support for maintaining the natural flow variability of this arid-zone floodplain river (Arthington *et al*. 2005; Bunn *et al*. 2006*a*, 2006*b*; Balcombe *et al*. 2007).

The environmental problems of the River Murray – and the associated 'lower lakes' (Albert and Alexandrina) and the Coorong (estuary) – are well documented (Mackay and Eastburn 1990; Thoms *et al*. 2006; Davies *et al*. 2008). Significant effort has gone into creating policy and management strategies to improve the condition of this system, including *The Living Murray* initiative of the Murray-Darling Basin Commission (MDBC), which is recovering water for environmental use and building infrastructure to maximise the environmental benefits of this water (MDBC 2008). Knowledge about the River Murray as an ecosystem was critical to the decision to recover water for environmental purposes. This decision coupled outputs from hydrologic models with models of habitat availability for key riverine and floodplain biota on the basis of published studies and expert opinion (SRP 2003; Young *et al*. 2003). This information guided the government's decision to recover an initial 500 GL $year^{-1}$ of water for the environment and to invest AUD $150 million in infrastructure to optimise floodplain wetland watering. Climate change is expected to reduce water availability significantly in the Murray-Darling Basin (e.g. CSIRO 2008), compounding and increasing the difficulty of ecosystem restoration without strategic, large-scale water recovery. Knowledge from ecosystem science, especially ecosystem response to managed river flows ('environmental flows'), is essential to guide future water-recovery decisions, which will be critical to achieve any discernible ecosystem recovery.

Large areas of the Australian continent are currently affected by anthropogenic salinisation, a process, which in some localities has been operating for over a century (Hatton *et al*. 2003). In the Western Australian wheatbelt, more than 1 million hectares are affected by salinisation. The replacement of deep-rooted perennial plants with shallow-rooted annual species has caused saline watertables to rise, leading to salinisation of the land surface and degradation of terrestrial and aquatic ecosystems (Schofield *et al*. 1988). Anthropogenic salinisation is now so widespread in this region that it has become a major ecological, economic and social disaster (Beresford *et al*. 2001). Salinisation of catchments, wetlands and rivers more generally, particularly in southern regions of Australia, has been identified as one of Australia's most serious environmental problems (Lovett *et al*. 2007). Diverse biological and engineering solutions are being applied to this complex problem, including planting trees in groundwater recharge zones, planting salt-tolerant species, constructing shallow drains to prevent waterlogging and using deep drains and groundwater pumps to intercept and transport saline ground water downstream via surface networks. The need for

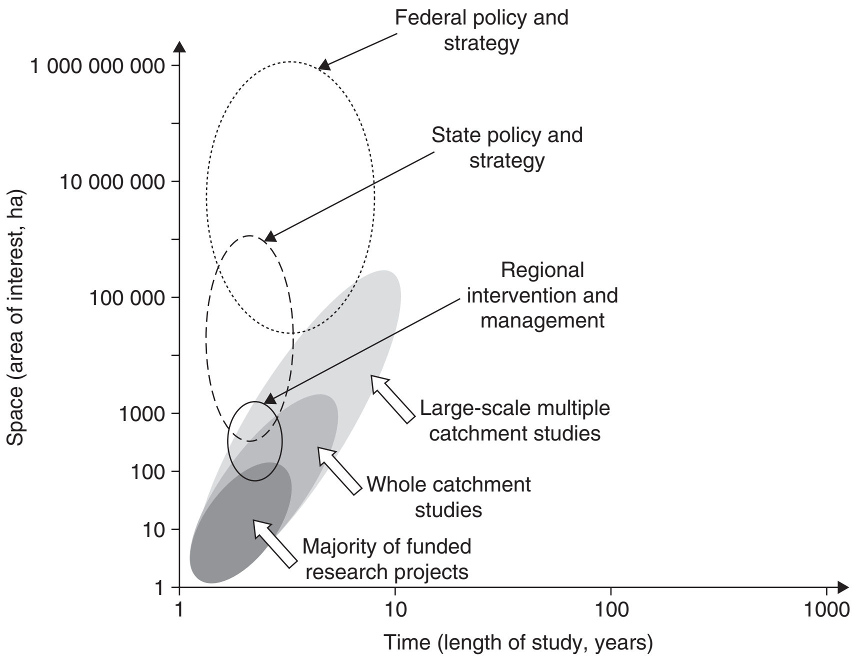

Fig. 1. Diagrammatic representation of the current temporal and spatial scales of research (shaded ellipses), showing the disconnection in the scales at which federal, state and regional policy and management (open ellipses) operate.

management at the ecosystem scale, based on the integration of changes in ground water, surface runoff and catchment dynamics is clear. Although much is known about the causes of salinisation and effective strategies to reduce the impacts (Lovett *et al*. 2007), the role and extent of recovery has been very slow. The causes for this failure are complicated; however, they are strongly related to social and economic pressures.

The recurring theme in these studies is that adopting an ecosystem approach has allowed (*i*) clear identification of drivers or potential drivers of ecosystem processes and ecosystem degradation, (*ii*) sufficient information for realistic cost–benefit analyses and (*iii*) identification of holistic, integrated solutions, which consider major drivers and all ecosystem components. An ecosystem approach often is forced by the nature of the problem, particularly in the case of diffuse or non-linear pressures on a large-scale system. We argue, however, that for all ecological research, the consideration of large-scale ecosystem processes (ecosystem thinking) avoids the inevitable fragmentation, which can preclude the integration of diverse knowledge necessary to guide management solutions. State-of-the-art and long-term monitoring of ecosystem parameters, such as metabolism and species richness, integrated at appropriate spatial scales, can provide critical information to guide long-term ecosystem studies and adaptive management; however, this is in its infancy in Australia.

Challenges

River ecosystems can be viewed as interacting systems of biological, physical and chemical components, operating at multiple scales in time and space and with self-organising properties (e.g. Allan and Castillo 2007; Cullen 2007; Harris 2007). A pattern or response at one scale may be generated or influenced by processes operating at different hierarchical levels (Harris 2007; Parsons and Thoms 2007). Similarly, an ecosystem process may be influenced by patterns occurring at multiple scales. The interplay of pattern and process, or between biotic and abiotic components, generates a complex matrix of interactions. A key challenge for river-ecosystem science is to dissect the patterns and processes in hierarchical, multicausal ecosystems into spatial and temporal domains of influence. This dissection can be achieved most effectively by employing integrated, multiscale research approaches (Dollar *et al*. 2007). Working at smaller spatial scales is logistically simpler, ensures sharply focussed questions and is consistent with the short-term funding models applied by governments and granting agencies. However, working at smaller scales promotes fragmentation, with researchers often working in isolation and producing data that are disconnected in time and space. Working at larger spatial and temporal scales is logistically more difficult, requires addressing of multiple questions and is relatively new to current applied science and management cultures in Australia. Thus, there has been a major mismatch between the large-scale environmental problems faced in Australia and the small-scale, fragmented scientific knowledge and management strategies available to address them (Fig. 1; Cullen 1990).

Scale of investments

It is now obvious that the major threats to Australian river ecosystems (climate change, land-use change, decline in water quality and water withdrawal) all occur at large scales, although with many small-scale impacts. Multi-million dollar investments are being made across all levels of government to 'improve' the integrity of aquatic ecosystems and to ensure their sustainable use. However, few large-scale, long-term, multidisciplinary, integrated research and management programmes have been established, particularly at the ecosystem level, and widespread landscape and river degradation persists (Connell 2007; Cullen 2007). In 2004, the Council of Australian Governments responded with a National Water Initiative (COAG 2004) to address these issues in a coordinated way by the generation and application of ecosystem science. Recently, the Commonwealth Environment Research Facilities (CERF) and the Marine and Tropical Sciences Research Facility (MTSRF) have sought out and funded top-quality science programmes that have attracted additional funding from other sources, including Land and Water Australia and the National Water Commission. Large-scale projects funded under the *Tropical Research and Coastal Knowledge* (TRaCK) and *Landscape Logic* programmes exemplify the scale and scope required to address landscape-level, ecosystem-science and management issues; however, these programmes are just beginning and have limited coverage in Australia. Thus, most Australian river ecosystems probably will not be researched and managed as large-scale systems under existing government initiatives, and the duration of even the CERF studies is not guaranteed.

Research capacity and educational opportunities

It is of major concern that currently Australia lacks the scientific capacity to guide natural-resource management through ecosystem science. A web audit of Australian universities revealed that few truly integrated, aquatic-ecosystem science programmes exist. In many instances, traditional divisions ('silos') between university departments and faculties perpetuate barriers to genuine interdisciplinary education and training. However, the importance of ecosystem science is recognised in specific units. All but two of Australia's 39 tertiary institutions offer units spanning a wide range of components including aquatic ecology, water quality, hydrology, geomorphology, water-resource management and water policy. These units are mostly offered within environmental science, natural-resource management and environmental engineering degrees. These isolated offerings must be enhanced and expanded to provide integrated ecosystem-science programmes.

Integrated graduate and masters programmes, in particular, are essential to train aquatic-ecosystem scientists needed by government agencies (Federal, state and local), industry and community groups concerned with delivering sustainable environmental outcomes. It is well recognised that Ph.D. projects provide a substantial portion of Australia's research effort; however, the relatively short duration (3.5 years or less) restrict the ability of more Ph.D. students to study ecosystem-scale problems. This constraint could be overcome by embedding Ph.D. research projects within a larger ecosystem-science framework designed to address major environmental concerns at regional scales, as has been initiated by CERF and TRaCK, and done overseas in the Hubbard Brook Ecosystem Study (USA), and the Experimental Lakes Area (Canada). Historically, Ph.D. projects have contributed fundamentally to a better understanding of the River Murray ecosystem. Now, given the severity of environmental problems affecting Australian inland waters, a more coordinated approach to Ph.D. training may be needed.

Both intra- and extra-institutional barriers must be addressed before universities can adopt a whole-of-ecosystem approach to their teaching and research. The structure of teaching and research in universities may hamper an ecosystem-science approach because funding to staff and research are vertically organised within disciplines and schools, whereas ecosystem science demands a structure that integrates horizontally across traditional disciplines, faculties and institutions. Just as ecosystem science requires integrated, multidisciplinary research programmes, education programmes likewise need to attract, educate, foster and retain future researchers and managers instilled with the value of ecosystem science. Scholars of ecosystem science should be encouraged to explore cross-disciplinary courses in law, policy, hydrology, the natural sciences and so forth, while still maintaining a strong depth of expertise. Students also need training in how to work in multidisciplinary teams (Likens 2001).

Few Australian organisations are resourced to undertake ecosystem-scale research programmes, leading to the need for cooperation and partnerships. However, collaborative research programmes also need to overcome the inherent intra- and extra-institutional barriers to collaboration. Competition for limited funding is a strong motivator for working in isolation and large, well-funded multidisciplinary research programmes are relatively few in Australia. At the same time, an appropriate funding balance must be maintained between investigator-initiated research and large, cooperative research projects. The CERF programme is trying to tackle this dichotomy with its mix of research Hubs, specific projects and fellowships; however, the pendulum can swing quickly and unexpectedly.

Goals and capacity

With increasing environmental pressures, there is an urgent need to manage catchments, rivers and estuaries as integrated ecosystems. Ecological knowledge is increasing rapidly; however, development and ecosystem fragmentation are still proceeding apace. There is significant failure to protect the condition of the environment because of the inability of managers to integrate complex ecosystem science within the current policy and management framework. This deficiency is often due to resource and time constraints on management, and it is also a capacity issue. A more energetic and focussed pathway is needed for ecosystem science to inform management at national and state levels.

Managers and scientists must develop much better dialogue where 'both parties listen and learn' (Cullen 1990; Cullen *et al.* 1999; Sykes 2007). Clearly, management solutions are much more difficult to attain than just providing the ecological details (e.g. Lawton 2007). Ecosystem scientists are only beginning to feel empowered to respond within a management context. The temporal scale of ecosystem responses to intervention is usually much longer than the duration of policy and management initiatives, and the resourcing and scale of management intervention are often local and focussed on single drivers. In addition, there is uncertainty about the potential for success of management interventions because of spatial-scale mismatches, time lags and thresholds in the dynamics of the systems in question.

There is a need for a significant cultural change to make progress – both within management agencies and within research organisations. First, managers must become more aware of the value of ecosystem science and the knowledge it generates. Managers need to design policy and management tools from an ecosystem perspective by using conceptual models of function and of response to drivers. Ecosystem scientists need to have a greater sensitivity to and engagement in management issues and need training in science communication and in environmental policy. To assist with this problem, managers should be teamed with ecosystem scientists within agencies and policy-development units. Above all, managers and scientists need to define realistic, quantifiable goals for ecosystem management, and develop a fuller integration of ecosystem-based knowledge into policy and management action. These needs are more pressing than ever. Close engagement between managers and ecosystem scientists must become standard practice.

Ecosystem-management goals should be developed with community, government and science input and formulated at realistic scales and for multiple components. Slocombe (1998, p. 483) noted that 'most planners and managers of both ecosystems and economies continue to pursue traditional goals and targets that miss many desirable characteristics of ecosystem-based management goals'. In addition, many environmental management programmes are based around goals that are not specific and realistic, but tend to be aspirational. Although broad goals such as having 'an environment that is healthy, better-protected, well-managed, resilient and provides essential ecosystem services in a changing climate' (*Caring for our Country* programme, Australian Government 2008, p. 3) are laudable, they eventually must be underpinned by specific goals with measurable outcomes. For example, with the flooding of floodplains, we now have specific outcomes such as primary and secondary production, invertebrate and fish recruitment, and waterbird breeding success.

Once specific and realistic goals are defined, ecosystem scientists need to help articulate and design appropriate management interventions and monitoring programmes, and develop research activities that address key knowledge gaps (Poff *et al.* 2003). Without specific and realistic goals, which reflect how ecosystems function and respond to management intervention, even large investments in ecosystem management and restoration (such the National Water Initiative or the Forward Work Program on Water (COAG 2008)) are likely to fail or at best be inefficient in delivering outcomes.

It is time for a cultural shift toward a business model in which government creates a need for knowledge from ecosystem science within which operational goals have relevance to ecosystem outcomes, rather than just servicing policy and management process. Formulation of quantified, realistic, outcome-focussed and achievable goals will drive the ecosystem science 'market' toward greater relevance and utility. There has been a limited demand for ecosystem science in the water-management arena in Australia – historically much of aquatic science has focussed around the implications of changes in water quality or hydrology because of infrastructure development and water management. Much of water-quality research has focussed on toxicology, which has had limited input from ecosystem thinking. Research on water-resource management for environmental outcomes has focussed on environmental water requirements, for which even the conceptual scientific basis has been largely aspirational and with limited evidence (Arthington *et al.* 2006; Harris 2007). More recently, funding programmes have focussed around aspirations for ecosystem restoration (Lake *et al.* 2007).

These areas have had a substantial community profile during the past decade, although accompanied by fragmented and weak policy developments. The focus has often been on developing 'guidelines' (e.g. ANZECC 2000), and protocols for assessment and reporting. The articulation of quantifiable goals, focussed on specific, measurable ecosystem responses and outcomes, has been poor. This situation is improving slowly, especially in the area of environmental water allocation (Arthington and Pusey 2003; Poff *et al.* 2003); however, the investment in ecosystem science to underpin management has been very small relative to the value of the water resource and the size of its markets, and to the intrinsic and extrinsic value of the ecosystems affected and the services provided.

A key example is the National Water Initiative (COAG 2004), a major investor in and catalyst for water management reform and related science in Australia. The Initiative's aspirations include achieving (*i*) transparent, statutory-based water planning, (*ii*) statutory provision for environmental and other public benefit outcomes and (*iii*) improved environmental management practices. However, nowhere in the Initiative's framework is there a clear articulation of ecosystem goals or mention of their importance.

Remedies for the lack of effective ecosystem research and science-based management include a significant, urgent revision of government policy. We also advocate that researchers seek opportunities to integrate and synthesise significant bodies of multidisciplinary, long-term research at multiple spatial and temporal scales. The facility to move freely across scales and disciplines, and to 'see the big picture' is fundamentally important to ecosystem science.

Conclusions and recommendations

The condition of Australian aquatic ecosystems, the magnitude of the threats they face and the power of ecosystem science to present holistic understanding and management solutions, provide an ineluctable case for greater focus on ecosystem science in Australia. However, with a few exceptions, we lack both the capacity and infrastructure to achieve this objective for most of the country. Our concern is that a failure to increase the geographic extent and coordination of collaborative, multidisciplinary, ecosystem science in Australia will oblige managers to continue to demand and be given instant answers to natural resource problems that, instead, require long-term investigation to underpin the development of truly long-term, sustainable management practices. There is a need to shift both science and management from reactionary problem solving to strategic problem solving, with sufficient knowledge to avoid problems or address them properly should they arise.

Accordingly, we advocate a new paradigm for land and water management in Australia – one that can capture the skills, knowledge and innovation of our research community and direct them toward a national programme of aquatic-ecosystem science and management, embedded in a common vision for the future of Australian landscapes and rivers and for their services to society. Specifically, we advocate the following:

(*i*) Establishing large-scale, long-term programmes based on ecosystem science in catchments and rivers of the nation to establish and compare the fundamentals of ecosystem structure and processes that play out across the full range of climatic and hydrological variability of the Australian continent.

(*ii*) Supporting this national research initiative with a more coordinated research funding policy and structure to foster collaborative ecosystem-science partnerships and interdisciplinary research, such as the Commonwealth Environmental Research Facilities (CERF) research Hubs linked to other major funding sources (e.g. Land & Water Australia, Australian Research Council, National Water Commission, Commonwealth Scientific Industrial Research Organisation).

(*iii*) Developing the interaction between scientists and managers whereby ecosystem science is integrated into policy setting, planning and management action by a combination of training and science-manager team building among all management agencies. We call on all agencies managing aquatic ecosystems to increase their support for, uptake and use of ecosystem science, and to drive a demand for it by formulating quantified, science-based management goals and monitoring of ecosystem responses.

(*iv*) Establishing national archives for long-term data and samples and clear custodial arrangements that will protect, update and facilitate ecosystem-knowledge transfer to other scientists, managers and the public.

(*v*) Reviewing and revamping educational opportunities and establishing a vastly more extensive and fully funded postgraduate and post-doctoral training programme to support the growth of river-ecosystem science and management across the nation.

The way forward

(*i*) Integrative ecosystem science should underpin water management and policy in Australia. Ecosystem science is essential for achieving the nation's goals of protecting and maintaining the ecological health of aquatic ecosystems, and for improving their biodiversity, functional processes and integrity (resistance and resilience).

(*ii*) There is a need to move beyond *multi*disciplinary approaches to develop an *inter*disciplinary approach for integrating understanding about the complexity of aquatic ecosystems in Australia into outcome-orientated management through integrated education, training, research and management-capacity building.

(*iii*) There is a need to think and to act at larger scales, over longer periods and in a way that integrates across disciplines. Ecosystem science is sufficiently broad to provide this framework for thinking about science, management and ethical behaviour.

(*iv*) There is an urgent need for aquatic environmental management to shift away from the aspirational culture of the past two decades into one in which the business of ecosystem management focuses on achievable and measureable outcomes underpinned by quality ecosystem science.

Acknowledgements

This paper stems from a meeting of this group of authors held in Bungendore, New South Wales, in April 2008. The meeting was convened by G. E. Likens and other authors are listed in random order. The meeting was facilitated by J. Olley. Financial support for the meeting and for a Flagship Fellowship to Likens was provided by CSIRO. We thank two anonymous reviewers for helpful comments.

References

Allan, J. D., and Castillo, M. M. (2007). 'Stream Ecology: Structure and Function of Running Waters.' (Springer: Dordrecht, The Netherlands.)

ANZECC (2000). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council/Agricultural Resource Management Council of Australia and New Zealand, Canberra.

Arthington, A. H., and Pusey, B. J. (2003). Flow restoration and protection in Australian rivers. *River Research and Applications* **19**, 377–395. doi:10.1002/RRA.745

Arthington, A. H., Balcombe, S. R., Wilson, G. A., Thoms, M. C., and Marshall, J. (2005). Spatial and temporal variation in fish assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone river, Cooper Creek, Australia. *Marine and Freshwater Research* **56**, 25–35. doi:10.1071/MF04111

Arthington, A. H., Bunn, S. E., Poff, N. L., and Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**, 1311–1318. doi:10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2

Australian Government (2008). 'Caring for Our Country.' Available at www.nrm.gov.au/funding/future.html [Verified April 2008].

Balcombe, S. R., Bunn, S. E., Arthington, A. H., Fawcett, J. H., McKenzie-Smith, F. J., and Wright, A. (2007). Fish larvae, growth and biomass relationships in an Australian arid zone river: links between floodplains and waterholes. *Freshwater Biology* **52**, 2385–2398. doi:10.1111/J.1365-2427.2007.01855.X

Beresford, Q., Bekle, H., Phillips, H., and Mulcock, J. (2001). 'The Salinity Crisis.' (University of Western Australia Press: Perth.)

Bond, N. R., Lake, P. S., and Arthington, A. H. (2008). The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia* **600**, 3–16. doi:10.1007/S10750-008-9326-Z

Bunn, S. E., and Arthington, A. H. (2002). Basic principles and consequences of altered hydrological regimes for aquatic biodiversity. *Environmental Management* **30**, 492–507. doi:10.1007/S00267-002-2737-0

Bunn, S. E., Balcombe, S. R., Davies, P. M., Fellows, C. S., and McKenzie-Smith, F. J. (2006*a*). Aquatic productivity and food webs of desert river ecosystems. In 'Ecology of Desert Rivers'. (Ed. R. T. Kingsford.) pp. 76–99. (Cambridge University Press: Melbourne.)

Bunn, S. E., Thoms, M. C., Hamilton, S. K., and Capon, S. J. (2006*b*). Flow variability in dryland rivers: boom, bust and the bits in between. *River Research and Applications* **22**, 179–186. doi:10.1002/RRA.904

COAG (2004). Intergovernmental agreement on a national water initiative. Council of Australian Governments. Available at www.nwc.gov.au/NWI/docs/iga_national_water_initiative.pdf [Verified April 2008].

COAG (2008). Forward Work Program on Water. Report to Council of Australian Governments prepared by the Working Group on Climate Change and Water. Available at www.coag.gov.au/meetings/260308/docs/CCWWG_water_report.doc [Verified April 2008].

Connell, D. (2007). 'Water Politics in the Murray-Darling Basin.' (The Federation Press: Sydney.)

CSIRO (2008). Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Canberra.

CSIRO and BoM (2007). Climate Change in Australia. CSIRO and the Australian Bureau of Meteorology, Clayton, Australia.

Cullen, P. (1990). The turbulent boundary between water science and water management. *Freshwater Biology* **24**, 201–209. doi:10.1111/J.1365-2427.1990.TB00319.X

Cullen, P. (2007). Adapting to water scarcity: a global challenge for the twenty-first century. Invited address. New Zealand Freshwater Sciences Society and Australian Society of Limnology Joint Conference, Queenstown, NZ, December 2007.

Cullen, P., Norris, R. H., Resh, V. H., Reynoldson, T. G., Rosenberg, D. M., and Barbour, M. T. (1999). Collaboration in scientific research: a critical need for freshwater ecology. *Freshwater Biology* **42**, 131–142. doi:10.1046/J.1365-2427.1999.00447.X

Davies, P. E., Harris, J., Hillman, T., and Walker, K. (2008). SRA Report 1. A report on the ecological health of rivers in the Murray-Darling Basin, 2004–2007. Independent Sustainable Rivers Audit Group. Murray-Darling Basin Commission, Canberra, Australia.

Davis, J. R. (1997). Managing algal blooms: outcomes from CSIRO's multi-divisional blue-green algal program. CSIRO Land and Water, Canberra.

Davis, J. R., and Koop, K. (2006). Eutrophication in Australian rivers, reservoirs and estuaries – a southern hemisphere perspective on the science and its implications. *Hydrobiologia* **559**, 23–76. doi:10.1007/S10750-005-4429-2

Dollar, E. S. J., James, C. S., Rogers, K. H., and Thoms, M. C. (2007). A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology* **89**, 147–162. doi:10.1016/J.GEOMORPH.2006.07.022

Harris, G. (2007). 'Seeking Sustainability in an Age of Complexity.' (Cambridge University Press: Melbourne.)

Hatton, T. J., Ruprecht, J., and George, R. J. (2003). Preclearing hydrology of the Western Australia wheatbelt: target for the future? *Plant and Soil* **257**, 341–356. doi:10.1023/A:1027310511299

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems* **4**, 390–405. doi:10.1007/S10021-001-0101-5

Lake, P. S. (2005). Perturbation, restoration and seeking ecological sustainability in Australian flowing waters. *Hydrobiologia* **552**, 109–120. doi:10.1007/S10750-005-1509-2

Lake, P. S. (2007). Flowing waters in the landscape. In 'Managing and Designing Landscapes for Conservation'. (Eds D. B. Lindenmayer and R. J. Hobbs.) pp. 445–457. (Blackwell Publishing and Zoological Society: London.)

Lake, P. S., and Bond, N. R. (2007). Australian futures: freshwater ecosystems and human water usage. *Futures* **39**, 288–305. doi:10.1016/J.FUTURES.2006.01.010

Lake, P. S., Bond, N., and Reich, P. (2007). Linking ecological theory with stream restoration. *Freshwater Biology* **52**, 597–615. doi:10.1111/J.1365-2427.2006.01709.X

Lawton, J. H. (2007). Ecology, politics and policy. *Journal of Applied Ecology* **44**, 465–474. doi:10.1111/J.1365-2664.2007.01315.X

LEBSAP (2008). State of the Basin 2008: rivers assessment. First Lake Eyre Basin Rivers Assessment. Scientific Advisory Panel to the Lake Eyre Basin Ministerial Forum, Canberra.

Levin, S. A. (1992). The problem of pattern and scale in ecology. *Ecology* **73**, 1943–1967. doi:10.2307/1941447

Likens, G. E. (1992). 'The Ecosystem Approach: Its Use and Abuse.' Excellence in Ecology, Vol. 3. (Ecology Institute: Oldendorf/Luhe, Germany.)

Likens, G. E. (2001). Ecosystems: energetics and biogeochemistry. In 'A New Century of Biology'. (Eds W. J. Kress and G. Barrett.) pp. 53–88. (Smithsonian Institution Press: London.)

Likens, G. E., Bormann, F. H., and Johnson, N. M. (1972). Acid rain. *Environment* **14**, 33–40.

Likens, G. E., Bormann, F. H., Pierce, R. S., and Reiners, W. A. (1978). Recovery of a deforested ecosystem. *Science* **199**, 492–496. doi:10.1126/SCIENCE.199.4328.492

Likens, G. E., Wright, R. F., Galloway, J. N., and Butler, T. J. (1979). Acid rain. *Scientific American* **241**, 43–51.

Lovett, S., Price, P., and Edgar, B. (Eds) (2007). Salt, nutrient, sediments and interactions: findings from the National River Contaminants Program. Land & Water Australia, Canberra.

Mackay, N., and Eastburn, D. (1990). 'The Murray.' (Murray-Darling Basin Commission: Canberra).

MDBC (2008). The Living Murray website. Murray-Darling Basin Commission. Available at http://www.thelivingmurray.mdbc.gov.au [Verified April 2008].

Murphy, B. F., and Timbal, B. (2007). A review of recent climate variability and climate change in south-eastern Australia. *International Journal of Climatology*.

NWC (2007). National Water Initiative. First biennial assessment of progress in implementation. National Water Commission, Canberra.

O'Neill, R. V., DeAngelis, D. L., Waide, J. B., and Allen, T. F. H. (1986). 'A Hierarchical Concept of Ecosystems.' (Princeton University Press: Princeton, NJ.)

Odum, E. P. (1971). 'Fundamentals of Ecology.' 3rd edn. (W. B. Saunders and Company: Philadelphia, PA.)

Oliver, R. L., and Merrick, C. (2006). Partitioning of river metabolism identifies phytoplankton as a major contributor in the regulated Murray River (Australia). *Freshwater Biology* **51**, 1131–1148. doi:10.1111/J.1365-2427.2006.01562.X

Parsons, M. E., and Thoms, M. C. (2007). Hierarchical patterns of large woody debris distribution and macroinvertebrate-environment associations in river ecosystems. *Geomorphology* **89**, 127–146. doi:10.1016/J.GEOMORPH.2006.07.016

Poff, N. L., Allan, J. D., Palmer, M. A., Hart, D. D., Richter, B. D., Arthington, A. H., Rogers, K. H., Meyer, J. L., and Stanford, J. A. (2003). River flows and water wars: Emerging science for environmental decision-making. *Frontiers in Ecology and the Environment* **1**, 298–306.

Schindler, D. W. (1977). Evolution of phosphorus limitation in lakes. *Science* **195**, 260–262. doi:10.1126/SCIENCE.195.4275.260

Schindler, D. W., Mills, K. H., Malley, D. F., Findlay, D. L., Shearer, J. A., Davies, I. J., Turner, M. A., Linsey, G. A., and Cruikshank, D. R. (1985). Long-term ecosystem stress: the effects of years of experimental acidification on a small lake. *Science* **228**, 1395–1401. doi:10.1126/SCIENCE.228.4706.1395

Schofield, N. J., Ruprecht, J. K., and Loh, I. C. (1988). The impact of agricultural development on the salinity of surface water resources of south-west Western Australia. Report WS27. Water Authority of Western Australia, Perth.

Slocombe, D. S. (1998). Defining goals and criteria for ecosystem-based management. *Environmental Management* **22**, 483–493. doi:10.1007/S002679900121

Smith, V. H. (1998). Cultural eutrophication of inland, estuarine and coastal waters. In 'Success, Limitations and Frontiers in Ecosystem Science'. (Eds M. L. Pace and P. M. Groffman.) pp. 7–49. (Springer: New York.)

SRP (2003). Ecological assessment of environmental flow reference points for the River Murray System. Interim Report prepared by the Scientific Reference Panel (SRP) for the Murray-Darling Basin Commission, Living Murray, Canberra.

Sykes, K. (2007). The quality of public dialog. *Science* **318**, 1349. doi:10.1126/SCIENCE.1151332

Thoms, M. C., Beyer, P., and Rogers, K. H. (2006). Variability, complexity and diversity – The geomorphology of river ecosystems in dryland regions. In ‘The Ecology of Desert Rivers’. (Ed. R. T. Kingsford.) pp. 47–75. (Cambridge University Press: Melbourne.)

Vollenweider, R. A. (1968). Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication, 182. Technical Report DAS/RS1/68.27. Water Management Research, Organization of Ecological Cooperative Development, Paris.

Walker, K. F., Puckridge, J. T., and Blanch, S. J. (1997). Irrigation development on Cooper, central Australia – prospects for a regulated economy in a boom-and-bust ecology. *Aquatic Conservation: Marine & Freshwater Ecosystems* **7**, 63–73. doi:10.1002/(SICI)1099-0755(199703)7:1<63::AID-AQC218>3.0.CO;2-5

Young, W. J., Scott, A. C., Cuddy, S. M., and Rennie, B. A. (2003). Murray flow assessment tool: a technical description. Report to the CRC for Freshwater Ecology from CSIRO Land and Water, Canberra.

Manuscript received 23 June 2008, accepted 23 November 2008