Wounded rivers, thirsty land: getting water management right

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INTRODUCTION

Water! What a remarkable molecule. It can assume three different states - liquid, solid and gas - and can penetrate the most minute of apertures. It is universally life-giving. Water not only supports all life, it is life! 60% of the human body is water, 90% of a jellyfish. The biosphere is dependent upon water, but for many organisms and all humans it must be fresh water.

Most (97%) of the world's total water supply is saline - the seas and estuaries and some salty inland lakes. The remaining 3% is fresh water, representing a total of about 35 million km$^3$. If we could spread this water evenly over the surface of the earth it would form a layer 70 m deep. However, close to 70% of this fresh water is unavailable to humans - it is stored in the ice caps of the polar regions and in deep underground aquifers. Only 0.3% of the total freshwater reserves on earth is found in the rivers, lakes and aquifers that provide the bulk of our useable supply.

This makes fresh water a very scarce resource, and it is also a finite resource. The total quantity can only be increased slightly by processes such as desalinisation, and at a tremendous energy cost. We can dream of towing icebergs from the Antarctic and tapping into deep groundwater but in reality such reserves of fresh water are technologically and economically out of human reach.

The quantity of freshwater available for human use is critical. Humans use around 550 litres of freshwater per person per day, the average industrial consumption is 1500 litres of freshwater per person per day in developed countries, and agriculture uses up several thousand litres of freshwater per person per day in hot dry climates.

Unfortunately, freshwater is frequently not available to humans in sufficient quantity in the right place at the right time, especially in arid and semi-arid countries like Australia. We live in the world's driest inhabited continent; only the Antarctic has less surface fresh water. Australia has the lowest percentage of rainfall as runoff, the lowest amount of runoff, the least amount of water in rivers and the smallest area of permanent wetlands (Australia SOE 1996). Thirsty land characterises much of our continent.

In Australia, rainfall and runoff distributions are also very patchy and so, therefore, is the distribution of fresh water. Coupled with the small amount and patchy distribution of water resources in Australia is the problem of temporal variability. Rainfall, runoff, storms and flooding
are all natural events with a substantial random component. They vary from decade to decade, year to year as well as from month to month, with the level of variation changing from one part of the country to another.

This means that some parts of Australia have an extremely unpredictable supply of surface fresh water, and humans demand predictability. We take it for granted that clean water will always pour abundantly from our taps, we expect to be able to water our lawns and gardens on a regular basis, and seldom question the role of water in keeping our cities and industries running. Agricultural systems are also dependent upon a regular and predictable supply of fresh water. In Australia about 70% of water use goes to agriculture, compared to 21% for urban and industrial supply and 9% for rural supply (Australia SOE 1996). Again, we take it for granted that there will be a predictable, although seasonal, supply of fresh vegetables and fruit in the supermarket.

**RIVER MODIFICATIONS**

To achieve reliable supplies of water for human use, we have changed freshwater systems as much as, possibly more than, any other part of the planet\(^4\). Around the world, heroic engineering feats have produced a multitude of large dams to store water when it is plentiful and release it in dry times, and to control potentially devastating floodwaters. Vast networks of man-made waterways distribute water to dry regions and sustain life where otherwise it would not survive. Underground aquifers have been tapped and their vast reserves of fresh water marshalled for human use.

The statistics on large dams alone are awesome. Each year 500 high dams (>15m) are built and in Europe alone large dams >150m high are being built at a rate of one every 1.65 years\(^5\). In 1989, worldwide, there were 28 dams over 200m high and by 1992 as many were planned or under construction\(^6\). The Nurek Dam in the former USSR is over 300m high and the Three Gorges Project on the Yangtze River in China will be the world’s largest dam (rising 185 metres above bedrock, full crest length of 1,893 metres) with total generating capacity of 17,680 mega-watts\(^7\). The truly damming statistic is that by the year 2000, more than 60% of the total volume of river flow in the world will be regulated\(^8\).

Australia’s record in dam-building is impressive. We have the highest per capita water storage of all countries, a direct result of the dryness and variability of our climate (Australia SOE 1996). Most of this water is stored in a few large reservoirs, with the 10 largest holding about 50% of the capacity. However, in NSW, the 10 largest reservoirs hold 90% of
the State’s storage volume (NSW SOE 1993). These large storages are located primarily in the south-east of Australia along the Great Dividing Range and in Tasmania, with a few very large impoundments in Queensland and one in Western Australia (Lake Argyle).

Have we benefited by building large dams and regulating river flows? From one perspective, essentially a human one, the answer can only be “yes”. Large dams hold back devastating flood waters, while others generate hydroelectricity for industrial and urban use. Man-made lakes behind large dams support major recreational fisheries and provide for many other forms of recreational activity. By regulating and abstracting river flows in Australia we have achieved security of food supplies and generated billions of export dollars. For example, in the Murray-Darling Basin, irrigation uses about 90% of annual water consumption and returns more than A$10 billion in annual production, much of it dependent upon regulated river flows: the river also supplies 16 cities and provides more than 40% of the water needs of South Australia.

Viewed in this way, many dams have been worthwhile, indeed essential to the development of Australia and other arid countries with their vast tracts of thirsty land. But with these benefits have come social and environmental costs. Many of these costs are familiar to us - such as flooded valleys and displaced farmers, water quality problems and algal blooms in water-supply reservoirs, and the disruption of fish migrations by barriers.

These obvious environmental costs have been recognised and addressed to some degree at least in the developed countries of the world. Many dams now incorporate a fish ladder or bypass system so that fish can continue their upstream migrations; however many do not. Water quality problems in man-made lakes have been solved by ingenious water circulation systems designed to break down the natural thermal layering of stored water and disrupt algal populations before they reach bloom proportions.

Unfortunately, there is an additional environmental effect of dams which we have not fully appreciated until relatively recently - changes to the downstream river environment.

**DOWNSTREAM EFFECTS OF DAMS**

Dam construction and river regulation generally mean gross changes to the natural flow, sediment and thermal regimes of rivers and a cascade of biological and ecological responses will follow over various spatial and
temporal scales\textsuperscript{10,11}. As more rivers are studied, we gain greater insight into these responses, and a greater capacity to predict them.

The initial changes downstream from dams relate to the flow regime, the sediment load carried by flowing water and water temperature. Any change in the fluid discharge or the supply of sediment, either in magnitude or in distribution through time, will lead to adjustments in bed sediments and channel morphology\textsuperscript{12} and these adjustments are often very complex\textsuperscript{13}. Channel and bank erosion and down-cutting of the stream bed are possible consequences of extremely high flows, whereas sediments accumulate whenever flushing flows are eliminated\textsuperscript{14}. The results are altered channel morphology and a different array of aquatic habitats compared with the natural river. Biological systems adjust to these new conditions but the outcome is often a very different aquatic ecosystem.

A river's temperature regime is altered to varying degrees by impoundments, most markedly downstream from large reservoirs on temperate rivers. Provided that the reservoir has sufficient depth and residence time, thermal stratification will occur during warmer months, creating an upper, warmer layer and a deep, colder layer of water. Water released from this deeper layer during summer is thus much colder than normal for the stream, water released during winter is warmer, and the seasonal amplitude is usually reduced overall\textsuperscript{15}. These changes may be sufficient to cause the disruption of invertebrate and fish life cycles, which are often very sensitive to water temperature\textsuperscript{16}.

Changes to the flow regime depend upon the size and type of dam and the way it is operated. Any or all of the following features may be modified below a dam: the magnitude of river flow (or discharge), the seasonal pattern of flows, the timing, duration, frequency and rate of rise and fall of floods, the timing, duration, and frequency of low flows, and the overall predictability of the flow regime.

The magnitude of river flow at any given time determines the availability or suitability of habitat, and defines such in-stream habitat attributes as wetted perimeter area or habitat volume. In large floodplain rivers, lateral exchanges between the floodplain and river channel, and nutrient recycling within the floodplain, are key driving processes. The "flood pulse concept"\textsuperscript{17} proposes that the biota of large floodplain rivers is highly adapted to the conditions created during flooding. When flood flows or pulses are reduced, river channels become isolated from their alluvial floodplains, the area of floodplain habitat decreases and there are severe effects on biotic diversity and river productivity\textsuperscript{18}.
The timing of occurrence of particular flow conditions can determine whether certain life cycle requirements are met. Many native plants and animals depend upon periodic but not necessarily seasonal floods to cue reproduction and sustain recruitment\textsuperscript{19,20}. Regulation often interferes with the timing of the flooding regime and may cause a decline in these species. Other species breed when river flows are usually low and conditions are more favourable for development of early life history stages (e.g.\textsuperscript{21}). Seasonal inversions of the flow regime caused by the release of high flows when river flows would normally be low appear to disrupt fish life cycles\textsuperscript{22}.

The frequency of occurrence of particular flows such as flood flows may govern the frequency of reproductive events and hence influence the total population recruitment of a species. Many fish species have few breeding cycles in a lifetime, so that each season is important in maintaining populations of the species, especially in an environment that is already degraded. An increased frequency of occurrence of low flows may stress aquatic biota and cause high levels of mortality. When fish are confined to a series of disconnected pools in a river channel, mortality may be due to poor water quality, exposure to predators and competition for limited resources.

The duration of time over which specific flow conditions extend may determine whether a particular life history stage can be completed. The duration of floodplain inundation is generally thought to be important for many fish species using these shallow productive habitats as a nursery area\textsuperscript{23}. Conversely, the duration of very low flows will influence the degree of stress experienced by aquatic biota.

The rate of change in flow conditions is important in terms of both the rate of rise and rate of fall of flood hydrographs. The natural gradual rise in flood water levels in floodplain rivers has led to the concept of the ‘moving littoral’, the inshore edge of the aquatic environmental that slowly traverses the floodplain\textsuperscript{24}. A slow hydrograph rise allows sufficient time for processes such as nutrient release from sediments, stimulation of seed growth, production of phytoplankton and zooplankton, and migration of juvenile fishes into floodplain habitats\textsuperscript{25}. At the other extreme, a too rapid rate of fall may lead to stranding of aquatic organisms at the water’s edge, or prevent the return of fish from floodplain habitats to the main river channel.

The predictability of the overall flow regime over long periods of time (\textit{sensu} Colwell\textsuperscript{26}) is an important determinant of lotic community structure
and lifecycle processes. Large tropical rivers with predictable flow regimes are associated with a highly adapted biota\textsuperscript{27,28}. Conversely, where flow regimes are unpredictable, as in south-eastern Queensland rivers such as the Mary\textsuperscript{29} and Burnett, aquatic biota are more opportunistic in their use of resources, and they are likely to be more resilient in times of stress\textsuperscript{30}. Changes in the predictability of river flows in either direction have important consequences for riverine ecosystems\textsuperscript{31}. O'Keeffe and De Moore\textsuperscript{32} found that increasing the constancy of flow in a river with an unpredictable flow regime had a marked effect on the diversity of invertebrate communities.

It is clear from the discussion above that dam construction and regulation of free-flowing rivers brings about fundamental changes in their physical condition and the structure of biological communities. To assess the full environmental impact of flow regulation requires that we also consider effects on ecosystem functioning. Unaltered rivers are viewed by ecologists as a continuum of physical and biological conditions from headwaters to mouth, in which processes taking place upstream strongly influence downstream dynamics\textsuperscript{33}. Dams disrupt the vital connections, both longitudinal and lateral, that drive natural river ecosystems\textsuperscript{34}.

Nowhere is this more apparent than in large rivers with mainstream dams, where the Serial Discontinuity Concept explains the effects of longitudinal disruptions\textsuperscript{35}.

The Brisbane River, for example, no longer functions as a free-flowing river linked from its headwater areas to the tidal estuary and Moreton Bay by river flows and longitudinal, flow-dependent processes. It has suffered two large discontinuities in the main channel - Wivenhoe Dam and Somerset Dam - which effectively divide the river system into two major ecological components functioning more or less independently. As a result, the Brisbane River below Wivenhoe Dam has been isolated from its natural supplies of inorganic and organic materials originating in the upper Brisbane and Stanley catchments. Somerset and Wivenhoe Dams have become 'sinks' for these materials, and the tidal river and Moreton Bay are deprived of materials and flows which may perform critical ecological functions. Arthington and Mosisch\textsuperscript{36} suggest that flows from the Lockyer, Bremer and Oxley systems may have a disproportionate influence on the lower Brisbane River because they drain the most degraded catchments within the lower part of the river system, where flows are modified in terms of water quantity, temporal pattern and water quality.
HEALTH OF AUSTRALIAN RIVERS

If health is the metaphor, what can we say about the condition of Australian rivers in general? The 1996 State of Environment Report has checked our continent and rivers for vital signs and presented a diagnosis. It goes something like this. Rivers are the arteries of the landscape, fresh water is the blood of our land, carrying nourishment to our forests, wetlands and estuaries. Rivers and wetlands support biologically diverse aquatic ecosystems with high levels of endemcity, and they perform many important ecological functions. Yet after only 200 years of European settlement, many Australian rivers are seriously degraded, loaded with salt, sediment, nutrients and pesticides, clogged by introduced plants (aquatic cholesterol), and infested with alien fish species such as carp and mosquito fish (parasites of the circulatory system?). Perhaps worst of all, the Australian continent has been wounded by a thousand cuts to the arteries and capillaries of the landscape - large dams, small dams, weirs, road crossings, drained and filled wetlands and groundwater abstraction - all contribute to the modification of flow regimes, loss of riverine habitat and declining biodiversity.

The vital signs of failing river health have been obvious to scientists for at least two decades, and many diagnoses have been published and pronounced from lecterns. Yet treatment has been slow in coming, and isolated to a few very prominent and wealthy patients, most notably the Murray-Darling River system, a very sick river indeed. When a human turns bright green we know immediately that something is drastically wrong, and so it is with rivers. The massive blue-green algal blooms formed along the Darling River in the summer of 1991-92 have now entered the published record as the world’s largest, longest, and worst blooms (Australian Water Resources Council 1991). We are a big country, we like big things - cows, pineapples, bananas- but this was a record Australia could well do without!

The underlying causes of the Darling River blooms were high nutrient levels and perfect physical conditions for algal growth, i.e. no river flow hence limited turbulence, brought about by the drought and excessive water abstractions upstream. As well as these bottom-up controls on algal growth, the loss of top-down controls in the form of grazing zooplankton may have been a contributing factor. The point is that the major causes of blooms are well understood from research in lakes and reservoirs, and the conversion of a once free-flowing river into a series of enriched riverine ‘lakes’ was a recipe for disaster. Worse, the probability of such bloom formations had been predicted for at least 50 years. We failed to read the symptoms in time, our limited attempts at preventive medicine
were dismally unsuccessful and what followed was an expensive band-aid approach\textsuperscript{38}.

**ENVIRONMENTAL FLOWS RESEARCH**

Coming to terms with the whole panoply of environmental impacts due to flow regulation has been a slow and painful process, but it has led to the emergence of an exciting and challenging new field of endeavour for river ecologists and geomorphologists as well as hydrologists and water managers - the field of environmental flow management.

Environmental flows are those features of a river’s natural flow regime which are set aside to maintain the physical integrity of the watercourse, the species it supports and the functional riverine ecosystem. The early history of environmental flow management has been recounted by Stalnaker\textsuperscript{39} and others in Calow and Petts\textsuperscript{40} and Harper and Ferguson\textsuperscript{41}. Initially, the main focus was the maintenance of minimum flows to sustain important fisheries, especially salmonids in gravel-bed streams of the north-west of North America, where conflicts with hydropower development were frequent\textsuperscript{42}. In 1978, a simulation model (PHABSIM) was developed by the Cooperative Instream Flow Service Group of the US Fish and Wildlife Service. It formed the core of the Instream Flow Incremental Methodology (IFIM) developed by the group to solve problems of river flow allocation\textsuperscript{43}. IFIM developed into a library of models for performing hydraulic simulations of river reaches, habitat analyses and predictions of the amount of habitat useable by fish at various levels of stream discharge. The methodology and the simulation model PHABSIM were applied widely throughout the USA in licensing and flow adjudication decisions\textsuperscript{44}.

There were many criticisms of IFIM and PHABSIM, some addressed, others disregarded in subsequent refinements of the methodology. Nevertheless, its use spread beyond the USA and a more user-friendly version RHYHABSIM (River Hydraulic and Habitat Simulation) was eventually developed in New Zealand to assess the flow needs of fish and invertebrates\textsuperscript{45}.

My research on environmental flows had its beginnings in a field trial using RHYHABSIM to assess the flows required to sustain the stream fish assemblage of Barker-Barambah Creek, a tributary of the Burnett River, south-eastern Queensland. This was part of a larger environmental study which we began in 1987, shortly after the establishment of the Centre for Catchment and In-Stream Research (CCISR).
I invited the new CCISR Research Fellow, Brad Pusey, to join with me and other project staff (Diane Conrick and Brian Bycroft) in an assessment of RHYHABSIM, and we brought Ian Jowett over from the Ministry of Agriculture and Fisheries in Christchurch, New Zealand, to guide the trial. Brad took the lead in analysing the data and writing a report which we submitted to the Water Resources Commission, putting the case that RHYHABSIM could help to produce flow recommendations to sustain stream fishes (and possibly invertebrates) but it would require a much better understanding of habitat preferences than we had at that time. We also stressed that RHYHABSIM did not offer any methodology for evaluating seasonal flow requirements, or flows to achieve successful fish recruitment, or the needs of other aquatic biota. It was, in short, simply a tool to be used as appropriate within the broader context of stream flow management for all aquatic biota and the river as an ecosystem.

Our doubts about the utility and applicability of RHYHABSIM extended to interpretation of the outcomes in systems with highly variable flow regimes. We asked ourselves how one might establish levels of stream flow to protect stream ecosystems and biota during drought cycles, or to provide the opportunity for optimal fish production in wetter years. Under pressure to produce some generic guidelines for river flow management, I suggested that ranges of flow percentiles (extracted from stream discharge records to bracket channel maintenance flows and the needs of aquatic biota, as then understood) could be used as a guide to environmental flows in 'drought', 'normal' and 'wet' years. These ranges were much more reasonable in terms of demands on the water resources of the system than the outcomes from the RHYHABSIM analysis. I also recommended some so-called 'flushing flows' for particular water quality and ecological purposes. It was a germinal holistic approach.

At this time (late 1991), an opportunity arose for me to spend part of study leave in South Africa evaluating a large river research program in the Kruger National Park. During this visit I met an enlightened group of river ecologists grappling with the same issues of simplistic environmental flow methodologies developed in North America, inadequate information on the biology of even the most common aquatic species, and highly variable river flow regimes. On a long ramble through the heathlands of Table Mountain, Cape Town, exercising Jackie King's dogs, I found many parallels in our research and thoughts on river flow management. Back in Australia in late 1991, CCISR held a small workshop with Jackie and other South African river ecologists to discuss these topics, and we decided that the prime requirement was for an approach which could address the flows required to sustain the entire
riverine ecosystem, i.e. all of the constituent biota, the integrity of aquatic habitats (a function of channel morphology), water quality and key ecosystem processes. As I recall it, Stuart Bunn (as usual) made some penetrating comments about identifying particular features of the natural flow regime which would maintain particular biota etc, and from that point everyone chipped in to add their own ideas about important flow characteristics, and how to assemble them into a modified flow regime to protect the entire riverine ecosystem.

It so happened that most of us were headed the next day for an environmental flows conference in Armidale (run by the Centre for Water Policy Research, UNE) where I had a slot on the program. So Jackie King, Diana Day, Jay O’Keeffe and I collectively wrote and presented a paper about this new "Holistic Approach" to environmental flow assessments\textsuperscript{49}, dubbed by the conference the “Royal Flush” due to Jackie’s regal connections.

Development of this new approach proceeded in very different ways in South Africa and Australia. Jackie took the concept and worked on developing it into a practical methodology for immediate use because at that time enormous demands were being made on South Africa’s limited water supplies, and decisions about water allocations for the riverine environment had to be made regardless of the amount of ecological information available or the precision of the methodology applied. Jackie called it the "Building Block Methodology" (BBM) because it basically builds up a modified flow regime from blocks of water, each block included to achieve a particular geomorphological or ecological or water quality objective\textsuperscript{50}. The BBM has developed into a structured workshop methodology, fully endorsed by the Department of Water Affairs and Forestry, and is now being built into the new Water Law for South Africa (J. King, pers comm. 1996).

In Australia at this time (early 1992) there was limited institutional commitment to the concept/practice of water for the environment, although the Armidale conference certainly drew attention to the significance and complexity of the issue\textsuperscript{51}. In CCISR, our response was to identify key areas of research that would place the "Holistic Approach" on a sound scientific footing. Brad and I laid out a program of studies focusing initially on river fish assemblages and how they respond to different types of flow regime and to extremes of drought and flooding. Building on an earlier research project funded by the Australian Water Research Advisory Council (AWRAC), we conceived a second large project known locally as the 10-rivers study, generously funded for 5 years by the Land and Water Resources Research and Development
Corporation (LWRRDC) and the Queensland Departments of Natural Resources and Primary Industries. This work began in 1994, with the aim of developing predictive models relating fish assemblage structure to habitat structure and flow characteristics in a series of paired catchments running up the Queensland coast from the Albert/Logan and Mary rivers in south-eastern Queensland to rivers of the Wet Tropics. Our idea was that if rivers within a region are fairly similar in terms of flow regime, channel morphology, hydraulic habitat and fish assemblage structure, then we should be able to develop predictive models and sets of environmental flow rules that could apply to all rivers of a particular regional type. If not, then each river would have to be treated separately.

To date our research has established that, by and large, the rivers and fish assemblages of some regions (e.g. south-eastern Queensland, the Wet Tropics area) are similar. Moreover, we can predict fish assemblage structure at various points in a catchment in terms of species presence/absence from a suite of habitat variables (e.g. depth, substrate, velocity, in-stream and riparian cover) with 90-95% success. This gives us a powerful tool but nevertheless a limited one. We are working now on refining these models to predict fish abundances and biomass under different habitat and flow conditions. This project involves an experimental phase wherein the fidelity of the association of fish with particular types of habitat is being tested via defaunation experiments and manipulations of aquatic habitat structure. The final stage, just commencing, aims to relate fish life history strategies and patterns of recruitment to features of the flow regime and hydraulic habitat structure. Outcomes from this program will be a large database on the habitat and flow requirements of some 55 riverine fish species, predictive models for the study rivers, and practical guidance on how to collect similar data and construct predictive models for other river systems. The intention eventually is to publish this material as a practical manual and later as a book, illustrated by Brad's marvellous drawings of fish. Over 20 papers are planned from this research and they are coming out now in the published literature. Many CCISR staff have contributed to the project but I particularly wish to thank Brad Pusey, Mark Kennard, Steve Mackay, Jason Bird, Darren Renouf, Paul Close, Martin Read and Michael Arthur for their dedicated efforts.

The 10-rivers study relies on the natural variability of rivers flows along the Queensland coast to provide the 'treatments' in our experimental design. We are also conducting a 'natural experiment' in an impounded system (Barker-Barambah Creek) where the flow regime is altered by releases from a dam and by water abstraction for irrigation. Here our objective is to identify how particular patterns of flow modification affect
fish assemblages, reproduction and recruitment\textsuperscript{56}. We have established that fish assemblages in regulated stream reaches are different from those in unregulated reaches and are now exploring the roles of flow variation, habitat structure and patterns of recruitment in determining these differences. Our recent work in Barker-Barambah Creek has received support from the Department of Natural Resources and the LWRDDC, and the key project staff have been Chris Thompson, Darren Renouf, Celia Thompson, Dave Blühdorn, Sue Dunlop and Simon Hamlet, and before them, Diane Conrick, Brian Bycroft, Debbie Harrison and Rob Wager.

The Barker-Barambah study has proved useful in another context, that is, testing the concept of ‘capacity sharing’ developed by Professor Norm Dudley and his colleagues from the Centre for Water Policy Research, UNE, Armidale. Norm and Brad Scott have developed this approach to the stage where a combination of computer simulation and stochastic dynamic programming techniques is used to derive best water management decisions through time in a highly uncertain climatic environment. For irrigation, this means decisions to maximise net revenue through time, and for the riverine environment, to maximise some measure of environmental effectiveness, where environmental effectiveness means the degree of achievement of a particular target flow regime\textsuperscript{57}.

CCISR’s roles in this project have been several: firstly, to assist in defining the target flow regimes, using a combination of field data from the Barker-Barambah studies described above and more general principles about environmental flow allocations; to develop ways of expressing the target flow regime as an ‘objective function’ in the modelling process; to develop indices of environmental effectiveness for use in the trade-off curves; and lastly, to identify various statistical measures of flow characteristics which help to explain why any particular allocation of reservoir inflows, reservoir capacity and tributary flows is more effective than another. Our results to date show that a high level of environmental effectiveness can be achieved when a large proportion of tributary flows and a small share (20\%) of reservoir capacity are allocated to the environment. This is because the natural tributary flows achieve a good measure of flow quantity as well as desirable levels of flow variability, whereas the reservoir capacity share ‘tops up’ the tributary flows to the target level for environmental protection.

By the end of this study, we hope to have developed a multivariate measure of environmental effectiveness and used it to identify the water sharing arrangements which will maintain fish assemblage structure and
recruitment at various points along the stream, as well as other environmental objectives. The whole project was a completely new experience for me and I am grateful to Norm Dudley, Brad Scott and Jeanett van der Lee for the challenge and pleasure of our collaboration.

APPLICATION OF ENVIRONMENTAL FLOWS RESEARCH

Our first real opportunity to give practical advice on flow management for ecosystem protection concerned the Tully-Millstream Hydroelectric Scheme in the Wet Tropics region of north Queensland. This scheme as initially designed had the potential to disturb streams and their fauna through construction and operation of several new impoundments and inter-basin transfers, and by regulation of natural flow regimes. Several of the systems potentially affected by the scheme lie within the Wet Tropics World Heritage Area. We used a suite of methods incorporating some explored previously in the Barker-Barambah study to show that the proposed impoundments and inter-basin transfers would significantly modify river flow regimes, causing loss of stream habitat and disruption of biological systems.

The Tully-Millstream project was a challenge for a variety of reasons - the sensitivity of the environmental context, the contractual arrangements surrounding our work, and the pressure to produce outcomes compatible with plans for the scheme. What did we achieve for riverine environments in the Tully-Millstream area? Although our reports arising from this consultancy were the target of savage “editing” (which we rejected) and were suppressed for many years, they had an impact on decisions about the feasibility of the hydroelectric scheme, which did not proceed beyond the planning stage, and hopefully will never be resurrected! Recently, Stuart Bunn and I had the satisfaction of contributing to the development of a policy on environmental flows for the Wet Tropics Management Agency, using, amongst other things, key findings from the Tully-Millstream study. Several valuable publications on invertebrates and regional biodiversity have also been produced by Stuart’s group.

Between 1992 and 1994 our research group contributed to many meetings and conferences concerned with environmental flow assessment and management (eg. 58, 59, 60; and 61, 62, 63). A paper published by the Australian Institute of Biology following a joint ANZAAS/AIB Symposium reviewed some of the methods used in Australia to develop environmental flow recommendations, and commented on their deficiencies 64. We suggested that Australia needed a unified approach and suggested that a moratorium on further water use in some catchments
might be one step in the right direction whilst scientists and managers sorted out how to proceed with environmental flow management. This was greeted in some quarters as an “interesting” suggestion. By 1995, the Murray-Darling Basin Ministerial Council initiated a comprehensive audit of water use and water diversions throughout the Basin, and agreed to the introduction of a moratorium on further water abstraction.

In 1994 I made another trip to South Africa to participate in a workshop on river classification and river health. I travelled with a party of Australians and we started our trip at Kruger National Park, had some wonderful (distant) encounters with wildlife (including a very pregnant lion) and then set off for Cape Town. On this visit I renewed my friendship with Jackie King and we began to plan an Australian trial of the Building Block Methodology and comparison with the Holistic Approach. The LWRRDC and Department of Natural Resources (DNR) in Queensland agreed to fund the project. The first stage took me back to South Africa in October 1995 to participate in the Tugela River Environmental Flow study and observe the BBM first hand, with yet another wonderful visit to the Kruger Park. We duly ran the workshop in the Logan catchment in October 1996 and two reports from this study are in preparation. It was a long haul to collect all the necessary field data and prepare the background papers but everyone involved gave it their best and we had a very successful workshop, facilitated by Jackie King and Jay O’Keeffe, with Greg Long from the DNR keeping everyone organised and making sure that our evenings took us to all the exciting night spots that Beaudesert has to offer the unwary. On the last morning Greg hauled the more energetic souls out of bed at daybreak to watch Platypus over a chicken and champagne breakfast. After this the South Africans retired to Port Douglas to recover.

1996 brought two new opportunities to present our case for the importance of environmental flows. With Stuart Bunn, Thorsten Mosisch (CCISR Research Fellow) and Bill Dennison from the University of Queensland, I prepared the Ecology Foundation Paper for the Brisbane River Management Group (BRMG). Using conceptual models of river ecosystem functioning based on the dynamics of organic carbon, we attempted to show (and I believe we succeeded) that the future condition of the riverine ecosystem and quite possibly also the estuary would be governed by two key ‘drivers’, the flow of energy (carbon) and the river’s flow regime. At the same time I began a study commissioned by the South East Queensland Water Board to identify the environmental flow requirements of the Brisbane River below Wivenhoe Dam. One of the pleasures of this project has been the opportunity to work again with most of the team from the Logan River study, and with hydrologists from
the DNR, as well as renewing my acquaintance with Maureen Gubbelts, who read every word I wrote about Barker-Barambah Creek. This study provides an excellent opportunity to apply the latest environmental flow methods as well as findings from much of our previous river research.

Many different approaches to environmental flow assessment and management are being developed and applied in the states and territories and the LWRRDC together with the National Land Care Program have commissioned our Centre to conduct a review and develop guidelines for "best management practice" in this field. The project will also identify areas of research to underpin future environmental flow management, since it is widely recognised that there are large knowledge gaps inhibiting our capacity to give advice on the environmental flow requirements of the nation's rivers.

FUTURE DIRECTIONS

To a large extent, the agenda for the future has been set by the Council of Australian Governments (COAG), which in 1995 reviewed water resource policy in Australia and agreed to implement a strategic framework to achieve an efficient and sustainable water industry. As one of the major components of this framework, COAG recommended the introduction of comprehensive systems for water allocations. These include the determination of clearly specified water entitlements, the provision of water for the environment and water trading arrangements. In undertaking this review, Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) commissioned a set of National Principles for the Provision of Water for Ecosystems.

The Goal for the provision of water for the environment is "To sustain and where necessary restore ecological processes and biodiversity of water dependent ecosystems". The purpose of the National Principles is to provide policy direction on how the issue of water for the environment should be addressed in the general context of water allocation decisions.

In concluding this lecture, I wish to offer a final comment on several of the principles and their implications for water use and environmental protection in the future.

The basic premise behind the National Principles is that provision of water for consumptive uses will have impacts on ecological values. Yet the very first principle steps back from this basic premise with the statement:
"River regulation and/or consumptive use should be recognised as potentially impacting on ecological values".

State of the Environment and many other forms of reporting on Australian inland waters have established river regulation and water extraction as one of the greatest threats to Australian rivers and their floodplains. River regulation is directly implicated in many of the existing problems (e.g. degraded water quality, bank slumping, sedimentation, blue-green algal blooms, fish kills, loss of rare and endangered species, and declining biodiversity).

Principle 6 states:

"Further allocation of water for any use should only be on the basis that natural ecological processes and biodiversity are sustained (i.e. ecological values are sustained)".

Principles 1 and 6 can be taken to imply that further allocation of water for consumptive use should be very severely constrained in many areas of Australia. The evidence of ecological impacts is irrefutable. However, there is still a thrust for development of new water infrastructure in Australia (e.g. in Queensland) and abstraction systems in vulnerable regions of high environmental value (e.g. along Cooper Creek). As a nation, we must ask ourselves whether these new water infrastructure developments are consistent with the COAG principles, and how to balance them against the benefits they may confer.

The concern of our research group is that under the present system of conducting an individual environmental impact assessment and water allocation plan for each river and new project, each decision to harvest/allocate water in a particular fashion is potentially a local decision, even though regional and national conservation issues are taken into consideration. It seems obvious that a nationally coordinated bioregional planning system is needed to overcome the problems of ad hoc individual assessments and provide greater planning certainty for industry and other sectors.

To achieve this, three layers of information must be collated - existing levels of river regulation and flow modification, and other threatening processes in river basins throughout Australia, the environmental values and conservation significance of all river ecosystems, and the degree of protection afforded by existing national and local conservation reserves. Information sources could include the 1996 State of Environment reports, data on aquatic invertebrates arising from the National River Health
Initiative, other databases held by state agencies and research groups, the outcomes of the Wild Rivers Project (presently identifying wild rivers of high heritage value), and data bases on endangered species and the national network of conservation reserves (National Parks, wildlife refuges etc).

From this review a framework should be established to identify a priority system for river conservation and protection. It should rank river basins (and parts of basins) into suitable categories including (but not intended to be exhaustive):

(i) those of high conservation significance which should not be modified at all by water infrastructure developments, and consumptive use,

(ii) those that require restoration of water allocations and for environmental protection and/or extensive rehabilitation, and

(iii) those which are so severely modified that restoration efforts may be futile and would be better expended elsewhere.

Informed and supported by a nationally coordinated bioregional planning framework, plus a priority system for river conservation and protection, and with a strong commitment to the COAG National Principles on water for the environment, a firm research base and strong community support, I am convinced we will have a very good chance of getting water management right.

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Professor Angela Arthington was born in South Australia, and became a New Zealand Citizen in 1948. She was educated at Canterbury University and McGill University, Canada, joining the Dept of Entomology, University of Queensland, as a Lecturer in 1971. In 1976 she was appointed Lecturer in the School of Australian Environmental Studies at Griffith University, progressing to Senior Lecturer, Associate Professor and Professor (1994).

In 1987 Angela established the Centre for Catchment and In-Stream Research (CCISR), and served as Director of the Centre until 1996. CCISR was set up by the Australian Water Research Advisory Council (AWRAC) to develop research programs in aquatic ecology, ecotoxicology and integrated catchment management. Professor Arthington is currently involved in the Co-operative Research Centre for Tropical Rainforest Ecology and Management and the CRC for Sustainable Tourism. She has a career total of over 170 publications of which 92 are peer reviewed items. She was elected as a Fellow of the Australian Institute of Biology in 1991, and has delivered over 80 conference and workshop papers and invited lectures in Australia, New Zealand, the USA, Canada, England and Scotland, China, Hong Kong, Singapore, Malaysia, Thailand and South Africa.

Angela's favourite freshwater environments are the dune lakes and wetlands of Stradbroke, Moreton and Fraser Island and the Noosa River system. She loves old Queenslanders and renovating houses, is a keen gardener, reader and traveller and is also mad about cats. She lives in Chelmer, and has an extended family in Brisbane, New Zealand and California. She is godmother to Nina and looks forward to the marriage in December 1997 of her son, Mark, to Kerstie.