Environmental flows: ecological importance, methods and lessons from Australia

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INTRODUCTION

This paper presents an overview of the importance of the natural flow regime as a key ‘driver’ of river ecology and describes some ecological consequences of flow regulation. Major approaches to the determination of environmental flows for river systems are outlined. It is suggested that there is as yet no ideal environmental flow methodology for large floodplain rivers with extensive wetlands that could be "lifted" into the Mekong situation with all its unique complexities related to the reversing of flows in the Tonle Sap, the extensive floodplain wetlands and forests, and the Mekong Delta. Significant preparatory data collection as well as research will be needed to develop predictive models of relationships between flow characteristics and ecological response in the Mekong River Basin, if the goal is to protect the biodiversity and ecological functions of this critically important river system.

HYDROLOGY AND THE ECOLOGY OF RIVERS AND FLOODPLAINS

Around the world there is growing awareness of the pivotal role of the flow regime (hydrology) as a key ‘driver’ of the ecology of rivers and their associated floodplain wetlands (Poff et al. 1997). Every river system and often individual tributaries have a “signature” flow regime with particular characteristics relating to flow quantity and attributes such as seasonal pattern of flows, timing, frequency, predictability and duration of extreme events (floods, droughts and intermittent flows); measures of flow variability, and rates of change (e.g. rates of rise and fall in water levels; flood recession rate) (Olden and Poff 2002). Each of these signature characteristics has its own (as well as interactive) influences on the physical nature of stream channels, their biological diversity and key ecological processes sustaining the aquatic ecosystem and the ecosystem services the river provides to humans.

Water movement across the landscape influences the ecology of rivers and wetlands across a broad range of spatial and temporal scales (Bunn and Arthington 2002). Flow influences the shape, size and complexity of river channels, the distribution of riffle and pool habitats, the structure of aquatic habitat, the amount and type of food available, and the nature of the interactions between the main channel and the floodplain. The temporal pattern of rainfall and runoff is a major driver of population processes in rivers and wetlands, and the life cycles of many aquatic animals are strongly influenced by the timing and frequency of particular flow or inundation events. The “boom or bust” dynamics of the biota of arid zone rivers and wetlands are a spectacular example of this linkage. Other species, e.g. many small fishes, breed when river flows are usually low and conditions are more favourable for development of early life history stages (Milton and Arthington 1985; Pusey et al. 2001). Bunn and Arthington (2002) propose four guiding principles describing the influence of river flow regimes on aquatic biodiversity and illustrate the consequences of changing flow regimes in light of each principle.

As well as directly influencing the distribution and abundance of aquatic organisms, river flow regimes have a profound effect on key ecosystem processes. The transport and processing of energy and nutrients, both longitudinally through river channel networks (Vannote *et al.* 1980) and laterally between the channel, riparian zone and floodplain (Junk *et al.* 1989), are greatly influenced by flow. Large flow events help to maintain the health and productivity of floodplain ecosystems, stimulating recruitment of floodplain trees, connecting and flushing billabongs and backwaters, and stimulating the growth of microscopic organisms that fuel floodplain food webs. The natural gradual rise in floodwater levels allows sufficient time for processes such as nutrient release from sediments, stimulation of seed growth, invertebrate recruitment and migration of juvenile fishes into floodplain habitats. Slow rates of flood recession are equally important in allowing aquatic organisms to follow the retreating water rather than being stranded on the drying floodplain.

The influence of large flow events extends well beyond the limits of freshwater reaches in coastal rivers and the ecological roles of these events are only just beginning to be appreciated. Studies in eastern Australia have shown strong correlation between the magnitude of annual and/or seasonal discharge from rivers and fishing catches in estuaries and coastal waters (Bunn *et al.* 1998). Such relationships extend over very large spatial scales, even out into coral reef systems over 70 km offshore. Water flowing into the sea is certainly not ”wasted”.

EFFECTS OF ALTERED FLOW REGIMES

The alteration of flow regimes is often claimed to be the most serious and continuing threat to ecological sustainability of rivers and their associated floodplain wetlands (Naiman et al. 1995; Ward et al. 1999). Dams, weirs and flow regulation have changed water volumes and patterns of variability in major world rivers on three temporal sales - the flood pulse (days to weeks), flow history (weeks to years) and the long-term statistical pattern of flows, or flow regime (decades or longer). Flow regulation is widely acknowledged to be a major cause of deteriorating conditions in many Australian river and floodplain ecosystems (Walker, 1985; Kingsford, 2000; Bunn and Arthington, 2002). Ecological changes in regulated river systems include the following:

- massive loss of wetlands - 90% of floodplain wetlands in Murray-Darling Basin, 50% of coastal wetlands in New South Wales and 75% of wetlands on the Swan Coastal Plain in south-west Western Australia .
- associated with these changes have been reductions in the abundance and species richness of colonially-nesting water birds in the northern part of the Macquarie Marshes and in the Barmah-Millewa Forest on the River Murray.
- major changes in aquatic plant and invertebrate community structure have occurred in regulated river reaches, dams and weirs, e.g. along the lower Murray River. This has affected the distribution of the Murray Crayfish (*Euastacus armatus*), now close to extinction, and several species of riverine and wetland snails have declined to low abundance levels. Seven lacustrine invertebrates disappeared when Lake Pedder in Tasmania was flooded for a hydropower scheme.

- regulated river reaches below hydroelectric dams with rapid diurnal changes in flow and erratic flow patterns are typically characterized by low diversity macro-invertebrate communities. Sudden increases in flow can cause catastrophic downstream drift to the extent that as much as 14% of the biomass of benthic biota is lost.
- pulsed reservoir discharges limit the quality and quantity of habitat below dams and stream fish can become stranded on gravel bars or trapped in off-channel habitats during rapid flow decreases.
- critical life-history events of fish are linked to flow regime (e.g. seasonal timing of reproduction, spawning behaviour, larval survival, growth patterns and recruitment). Many of these life events are synchronized with temperature and day-length to the extent that changes in flow regime that are not in natural harmony with these seasonal cycles may have a severe impact on reproduction and recruitment.
- fish species migrating long distances within the main channels and larger tributaries of rivers are very sensitive to barriers such as dams and large weirs because obstruction of their migrations may prevent completion of the life cycle. The disappearance or decline of the major migratory fish species often follows river impoundment and the blocking of fish passage.
- in large floodplain rivers, many aquatic species ranging from benthic microorganisms, phytoplankton, zooplankton, to fish cue their activities to rising flood levels, emerging from resting stages or spawning in response to the stimuli of rising water levels and wetland inundation. River regulation to prevent flooding has seriously affected such recruitment in Australian rivers with increasingly regulated river flows
- mortality of fish trapped in dry season refugia on the floodplain of Australian arid zone rivers may be increased when water is abstracted, due to deteriorating water quality conditions, limited food and lack of shelter from predatory fish and birds.
- flow regulation has contributed to massive blooms of toxic cyanobacteria in storages and rivers, most notably the 1000 km long bloom in the Barwon-Darling River in 1991/91, so severe as to necessitate the declaration of a state of emergency.
- regulated rivers frequently experience invasions of exotic species of plants such as water hyacinth (*Eichhornia crassipes*), Sth American pasra grass, *Hymenachne* and willows (*Salix* spp.). With its free-floating habit and rapid growth rate, the water hyacinth can form dense surface growths covering large areas of open water, interfering with flow and water transport, disrupting recreation, impeding the access of stock to water, and blocking light penetration.
- regulation of flows has favored exotic fish species such as carp *Cyprinus carpio* and mosquitofish (Pusey et al. 1989, Gehrke et al. 1995). Conversion of rivers to lentic habitat has led to the proliferation of the exotic tilapia *Oreochromis mossambicus* in large dams in Australia, Africa and Sri Lanka (Arthington and Blühdorn 1994). However, conversion to lake-like habitat is not always perceived to be bad news; it can contribute to fisheries production and vital human food supplies.
- inter-basin transfers can alter natural distribution patterns of native aquatic biota and enhance the spread of exotic pests and diseases (as well as presenting serious problems in terms of water balance, water quality and the disruption of significant ecological processes). Such schemes are increasing in popularity as the number of sites suitable for dam construction and the scale of individual schemes declines (Boon 1992).

ENVIRONMENTAL FLOW METHODS

Ecologists emphasise the need to partially or fully maintain or restore the range of natural variation of hydrologic regimes in order to protect native biodiversity and sustain the evolutionary potential of aquatic, riparian and wetland ecosystems (Arthington et al. 1992; Poff et al. 1997; Olden and Poff 2002). This natural flow paradigm forms the basis of most ecological frameworks for recommending environmental flows. In the last five decades, over 200 different approaches have been described for advising on environmental flows and they are applied in at least 50 countries (Tharme 1996). A 3-level hierarchy of methods has been suggested to accommodate the management contexts, ecological objectives and resource factors affecting environmental flow assessments.

Level 1: The first level of assessment often involves simple hydrological and other precautionary environmental flow assessment methods. These may be used in country-wide water resource planning activities; catchment-wide reconnaissance of development options; preliminary identification of opportunities for restoration of regulated systems, and low resolution, interim assessments of environmental flows at various spatial scales. Examples of such methods are the Montana Method and the more complex Range of Hydrological Variability Approach (Richter *et al.*, 1997). The scientific foundations of hydrological methods are very limited and there is a high risk of failing to provide the flow requirements of all aquatic biota and the processes sustaining the aquatic/floodplain ecosystem. Hydrological methods should only be when the time frame, resources, expertise, and/or knowledge of hydrology-ecology relationships are very constrained.

Level 2: At the second level are methods termed “holistic” scientific panel approaches (Arthington *et al*. 1992). These are used in catchment and sub-catchment scale assessments of environmental flow requirements at the planning stage of new developments (e.g. new dam, increased water allocation from dam, or from unregulated rivers); assessment of opportunities for restoration of regulated or abstracted river systems. They involve moderate resolution, multi-disciplinary, expert assessments of environmental flows at various spatial scales, and are applicable when the time frame, resources, expertise, and/or knowledge of hydrology-ecology relationships are moderately constrained. Examples are the Benchmarking Methodology (Brizga 2000; a risk assessment framework) and DRIFT (Downstream Response to Imposed Flow Transformations), a scenario-based methodology used to predict the type, direction and severity of ecological responses to alterations of river flow regimes (King *et al*. 2002). These methods vary in scientific rigor and their use can lead to low, moderate or high risk of error in environmental flow allocations.

Level 3: This represents flow assessments with much more sound scientific foundations ideally involving the development and application of river-specific predictive flow-biological and flow-ecological response models. Predictive models can be used for environmental flow assessments at any spatial scale. Environmental flow recommendations based on sound predictive models have the lowest risk of error in allocating water for ecosystem protection.

There is as yet no ideal environmental flow methodology for large floodplain rivers with extensive wetlands that could be "lifted" into the Mekong situation with all its unique complexities related to the reversing of flows in the Tonle Sap, the extensive floodplain wetlands and forests, and the Mekong Delta (see Smakhtin 2002). Ongoing environmental flow studies in the Murray-Darling Basin may produce useful frameworks and even guidelines for adaptation to the Mekong situation. However, each river system, hydrological regime, biogeographic setting and environmental flow study is unique. It may well be that a river such as the Mekong with such predictable annual flood pulses is more vulnerable to flow regime change that the Murray-Darling, where the flow regime can be described as highly variable and unpredictable, especially in relation to the timing and frequency of flooding and dry spells. Therefore, significant preparatory data collection as well as research will be needed to develop predictive models of relationships between flow characteristics and ecological response in the Mekong River Basin, if the goal is to protect the biodiversity, ecological functions and ecosystem services of this critically important river system.

The comments of Bunn and Arthington (2002) about the certainty of the science underlying provision of environmental flows are worth noting:

"Ecologists still have much to learn about the ecological significance of individual flow events and sequences of events, and descriptive science can take us only so far in unraveling these linkages. The advice from aquatic ecologists on environmental flows might be regarded at this point in time as a series of largely untested hypotheses about the flows that aquatic organisms need and how rivers function in relation to flow regime. To overcome these problems aquatic science needs to move into a manipulative or experimental phase, either by restoring flows, or taking away flows, and measuring ecosystem response. Hopefully, flow restoration experiments will dominate over flow regulation experiments!"

LESSONS FROM AUSTRALIA

For large and important river systems such as the Murray-Darling and the Mekong, with such profound social and economic implications of providing (and not providing) water for environmental objectives, it is essential to have sound science on environmental flows on the negotiating table. Developing a predictive capacity (i.e. working at Level 3 of the hierarchy described above) will allow scientists to describe confidently and in detail the changes that are likely to occur in a river with any contemplated water management strategy. Without this information scientists can only deliver their best estimates of water requirements rather than the quantitative predictions that decision-makers so urgently require.

Worldwide, just 1% of the cost of most major water-resource developments would generate a substantial amount of the new scientific information needed on river ecology in relation to flow regime and flow events. With so much at stake, it is surprising to observe that this small proportional cost is everywhere seen as too expensive, and inexplicable that managers remain content with advice based only on available (usually quite inadequate) knowledge rather than sound science. The same stringent standards for conduct of baseline studies and development of simulation models that underpin dam construction projects should also apply to the ecological investigations for environmental flows.

The cost of not being able to describe the ecological condition of a river nor predict the ecological outcomes of river flow management can be very high, as witnessed recently in Australia in relation to the Condamine-Balonne system. Here disagreement about the quality of the science and the "correct" environmental flow regime may prove very costly for all concerned. For cotton farmers, immense profits are threatened by lack of water allocations, whereas for graziers further down the river, production systems are dependent upon overland flooding and a healthy floodplain ecosystem. Also at risk are important terminal wetlands (the Narran Lakes) listed on the Register of the National Estate, and since 1999, under the RAMSAR Convention. With better science, or at least application of precautionary principles while the knowledge base improves, and structured negotiations framed around community needs and visions for the river, such costs and social disruptions can be avoided.

In the past, most river engineering schemes went ahead without consideration of their probable environmental impacts because the objective was to tame and divert the water resources of large rivers for the benefit of settlements and irrigated agriculture. Degraded rivers and loss of ecosystem services (e.g. fish production) are now unacceptable to societies the world over and many rivers are being targeted for restoration of their regulated flow regimes and diminished aquatic communities. The Snowy River in Australia is an example of the costs involved for even limited restoration of the flow regime. Restoring 28% of mean annual flow is expected to achieve improvements in thermal regime, channel structure, longitudinal connectivity, dispersal and migration of biota, triggers for fish spawning and the aesthetics of the currently degraded riverine environment. This flow target will be achieved through water efficiency savings, supported by a 10 year funding assistance package to farmers of $300 million. Economists estimate that it will cost at least $643 million to achieve total quantifiable benefits of $61 million representing enhanced opportunities for recreational fishing, canoeing and rafting (note that the full value of ecosystem services has not been included in any way in these estimates of benefits).

The lesson from world experience is very clear - flow restorations (out of necessity to sustain production that is underpinned by a healthy ecosystem, or arising from public pressure) involve enormous costs and investments in re-engineered infrastructure and compensation, as well as significant social disharmony. New dams and massive water diversion projects still being constructed today are likely to become the river restoration projects of the future. Far better that we learn to conserve water, develop and promote alternative water management systems, avoid major water infrastructure projects unless absolutely necessary, and invest more in fundamental science to underpin river management for productive, amenity and conservation purposes. The alternative to such sensible investments now is to face ever increasing water shortages in the future and pay the immense price of reversing bad decisions, re-engineering infrastructure, restoring river ecosystems and compensating communities for their legitimate losses.

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