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The changing role of eco-hydrological science in guiding environmental flows

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Abstract The term environmental flows has become widely used to reflect the hydrological regime required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on them. The definition suggests a central role for eco-hydrological science to help determine a required flow regime for a target ecosystem condition. Indeed, many countries have established laws and policies to implement environmental flows with the expectation that science can deliver the answers. This paper provides an overview of recent developments and applications of environmental flow on six continents to explore the changing role of eco-hydrological sciences, recognising its limitations and the emerging needs of society, water resource managers and policy makers. Science has responded with new methods to link hydrology to ecosystem status, but these have also raised fundamental questions that go beyond eco-hydrology, such as who decides on the target condition of the ecosystem. Some environmental flow methods are based on the natural flow paradigm, which assumes the desired regime is the natural 'unmodified' condition. However, this may be unrealistic where flow regimes have been altered for many centuries and are likely to change with future climate change. Ecosystems are dynamic, so the adoption of environmental flows needs to have a similar dynamic basis. Furthermore, methodological developments have been made in two directions. First, broad-scale hydrological analysis of flow regimes (assuming ecological relevance of hydrograph components) and, second, analysis of ecological impacts of more than one stressor (e.g. flow, morphology, water quality). All methods retain a degree of uncertainty, which translates into risks, and raises questions regarding trust between scientists and the public. Communication between scientists, social scientists, practitioners, policy makers and the public is thus becoming as important as the quality of the science.

Key words Environmental flows, ecohydrology, hydroecology,

Introduction

The term environmental flows is now widely used to describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration http://www.eflownet.org/). The concept highlights the indirect benefits to people of providing water to ecosystems (such as food, recreation and cultural identity) in addition to the direct benefits of water used for drinking, growing food and supporting industry (Acreman, 1998). A key feature of this concept is the flow of water, hence it would seem evident that eco-hydrological science must occupy a central position in the concept. Furthermore, environmental flows are clearly concerned with sustaining ecosystems, hence requiring linkages with ecological sciences. The fact that one intended outcome is to maintain human livelihoods and well-being, also recognises the essential role of social sciences. Whilst hydrologists and ecologists may define the relationship between water flows and ecosystem state, questions arise concerning who decides the target condition of the ecosystem. This in turn raises issues of governance, stakeholder participation and communication of information. Thus, although hydrological science maybe at its heart, environmental flows is truly a cross-disciplinary issue. The inter-relationships can be complex.

Whilst eco-hydrological science has driven policy and highlighted previous policy weaknesses, attempts to implement environmental flows have raised fundamental scientific questions. Scientific advancements provide greater understanding of ecosystems, although much of our progress has been to acknowledge ecosystem complexity and to raise further questions. Key challenges include how to make recommendations on best evidence, build uncertainty into decision-making processes and explain this to stakeholders to optimise water benefits (Figure 1).

The past decade has witnessed a rapid expansion of methodological development and application of environmental flows. This Special Issue of Hydrological Science Journal draws-together some of the latest developments across six continents. Table 1 provides an overview of papers within the Special Issue based on key words and subject matter. This paper builds on this collection, but although these topics are wide ranging, reference to other past and recent publications is required to provide historical context of the changing role of eco-hydrological science in environmental flow assessments. A historical perspective recognizes limitations and encourages growth in new areas to address research gaps to support the emerging needs of managers and policy makers.

Historical context

The United Nations Conference on Environment and Development in Rio de Janeiro in 1992 was an important turning point in thinking, bringing to the global agenda the view that the lives of people and the environment are inter-related. Ecological processes maintain the planet's capacity to deliver goods and services, such as water, food and medicines and much of what we call "quality of life" (Acreman, 2001a). The Millennium Development Goals included the need for environmental sustainability, such as reducing the rate of loss of species threatened with extinction. The concept of ecosystem services (Barbier, 2009; Fischer *et al.* 2009) brought to prominence in the Millennium Ecosystem Assessment (2005) demonstrates that healthy freshwater ecosystems provides economic security, *e.g.* fish, medicines and timber (Emerton and Bos, 2004; Cowx and Portocarrero 2011); social security, *e.g.* protection from natural hazards, such as floods; and ethical security, *e.g.* upholding the rights of people and other species to water (Acreman, 2001a). Thus, water allocated for the environment also supports people by maintaining the ecosystem services on which we depend (Acreman, 1998; MEA, 2005). The Rio+20 meeting (http://www.uncsd2012.org/) called for action to protect and sustainably manage ecosystems (including maintaining water quantity and quality), and recognized that the global loss of biodiversity and the degradation of ecosystems undermines global development (Costanza and Daly, 1992), affecting food security and nutrition, the provision of and access to water and the health of the rural poor. Rio+20 also launched a process to develop a set of Sustainable Development Goals (SDGs), which will build upon the Millennium Development Goals and converge with the post 2015 development agenda.

Flow releases from reservoirs have been made since the 1800s, but these were to provide water for downstream riparian users and termed compensation flows (Gustard *et al*, 1987) and thus cannot be considered as environmental flows as we understand them today. The first flow management for ecosystems focused on the concept of a minimum flow for diluting polluted discharges, based on the notion that as long as the flow is maintained at or above a critical minimum, the river ecosystem will be conserved. The UK Water Resources Act 1963 required minimum acceptable flows to maintain natural beauty and fisheries. The US Clean Water Act in 1972 set the objective of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters. Water allocations for ecosystem maintenance have been incorporated into Integrated Water Resources Management (IWRM; Falkenmark, 2003), environmental impact assessment (Wathern, 1998), and the Ecosystem Approach (Maltby *et al.,* 1999). Recognising the importance of water for the environment is now part of the policies and laws of many countries (le Quesne *et al*., 2010). This development has required the involvement of an increasingly larger number of disciplines in environmental assessments (Figure 2); although these individual disciplines may encapsulate several sub-disciplines and the nature of research interests may have changed over time.

The concept of environmental flows is now a key element in many international policies (such as the Convention on Biological Diversity signed by 168 countries and the International Convention on Wetlands signed by 132 countries) and integrated into the water laws in many other countries e.g. Costa Rica (Jiménez Ramón *et al.,* 2005), Tanzania (Acreman *et al*., 2006), Australia (Kildea and Williams, 2007) and the European Union (Acreman and Ferguson, 2010). South Africa's water law recognises that water for the maintenance of the environment should be accorded the highest priority (Rowlston and Palmer, 2002; King and Pienaar, 2011) along with that for basic human needs. Environmental flows has also become a central part of the policies of major institutions, including the World Bank (Hirji and Davis, 2009) and IUCN (Dyson *et al*., 2003). Science has driven and highlighted weaknesses in national/regional policies and attempts to implement environmental flows have raised fundamental questions concerning the elements of the ecosystem for which we may wish to make provisions. In particular issues regarding who decides on ecosystem objectives, what flow regime is required to achieve the agreed ecosystem conditions, how to implement agreed flows and whether they can achieve the agreed conditions are all sources of debate or investigation.

It is now recognised that all elements of the flow regime influence the freshwater ecosystem, including seasonally and annually varying high, average and low flows (Junk *et al.,* 1989; King and Tharme, 1994; Richter *et al.,* 1996; Poff *et al*., 1997). Understanding of environmental flows has developed from being focused on river channels to embracing groundwater and the freshwater needs of other systems, such as lakes, estuaries and wetlands. In the Rufiji basin, Duvail *et al*. (this volume) found that lakes fed by the river during floods would dry-out if a proposed dam was built at Stiegler's gorge upstream. Adams (*this volume*) concluded that some initial determinations of environmental flow needs for estuaries were mistaken in assuming that the minimum flow from a river was sufficient. Defining water needs for wetlands is challenging because the term wetlands embraces many different ecosystem types that may have very different hydrological characteristics even when they are geographically close to each other (de la Hera and Murillo, *this volume*). Aldous *et al*. (*this volume*) found that for fens in Oregon, USA water table depth is the critical issue than river flow, with a required water table within 35 cm of the surface. Hendriks *et al.* (*this volume*) reported that drainage and groundwater abstraction in sandy catchments in the Netherlands meant that low flows were reduced below the environmental flow criterion, whilst Kennen *et al*. (*this volume*) found groundwater abstraction led to a 20% reduction in intolerant macroinvertebrates in New Jersey, USA due to reduced river flow. Streetley et al. (*this volume),* working in the midlands of England, also found that flow reductions caused by groundwater abstraction altered ecological conditions (as measured by relevant biotic indices). New terms have emerged, such as Ecological Water Requirements, to address the water needs for systems such as wetlands, lakes and groundwaters where 'flow' might not be the appropriate term. Some assessment methods have been developed in temperate Europe and USA (Acreman and Dunbar, 2003), some were developed in semi-arid areas such as South Africa and Australia (Arthington *et al.,* 1992; Arthington, 2012; King *et al*., 2000; 2004; King and Pienaar, 2011) and others address all kinds of rivers from ephemeral to flood pulse monsoon systems (King *et al.*, *this volume*). More environmental flow methods are currently being developed for urban rivers where flow augmentation can provide improved aesthetics and aquatic habitat (Lawrence *et al.*, *this volume*) and colder environments (Peters *et al.*, *this volume*) where new ecologically relevant hydrological indices are required including annual ice on/off dates, ice cover duration, spring freshet initiation and peak water level during river ice break-up. This has posed new challenges in dealing with river flow interactions with tidal processes, salinity, ice and groundwater.

More recently, assessment and implementation have progressed from individual river reaches to large geographic areas to enable integrated river basin management and policy implementation, posing new challenges for regionalizing environmental flow science (King and Brown, 2010; Poff *et al.,* 2010; Kendy *et al.,* 2012; King et al., *this volume*).

The term hydro-ecology has been used to describe the science defining the freshwater needs for aquatic ecosystems (Acreman, 2001b). Another term, eco-hydrology, was initially focused on sustainable water resource management and improving water quality of freshwater ecosystems (e.g. Zalewski *et al.*, 1997). However, eco-hydrology has developed a much broader scope, covering the interactions between water and the ecosystems, and the term encompasses the concept of environmental flows (Hannah *et al.*, 2007).

Setting objectives

Clarity of water management objectives is a crucial part of defining environmental flows. However, setting objectives is only partly a scientific issue. Science can provide advice on the nature and condition of ecosystems that will be supported by different management options, but agreeing on the desired state or condition of an ecosystem is a societal issue.

Setting the objective for the desired future condition of an aquatic ecosystem can take many pathways and involve multiple processes. The European Water Framework Directive (WFD; Acreman and Ferguson, 2010) specifies a generic target of Good Ecological Status (GES), with slight alteration from reference conditions (e.g. Schmutz *et al*., 2007). Although GES is defined in biological terms, eco-hydrological science plays a clear role defining the water needs to meet GES. Where hydrology and morphology of rivers performs economically essential functions, an alternative objective of Good Ecological Potential (GEP) can be followed providing other criteria are met. In many developing countries, there is a more explicit link between the ecological benefits of environmental flows and the livelihoods of rural subsistence users of the river, such as in the Okavango Basin (King *et al*., *this volume*), Mara River (McClain *et al*., *this volume*), Rufiji River (Duvail *et al*., *this volume*) and River Mekong (Thompson *et al*., *this volume*).

Sometimes environmental objectives are determined for individual rivers, rather than generic targets for all rivers. In Connecticut, USA, every river reach will be assigned a condition class ranging from 1 to 4. Streams in Class 1 support habitat conditions and biological communities typical of free-flowing streams. Class 2 and 3 streams support "minimally altered" and "moderately altered" biological communities, respectively, compared to free-flowing streams of similar types and Class 4 streams are recognized as being substantially modified - a recognised current condition, but not an objective for any rivers (Kendy *et al.,* 2012). A similar procedure is followed in South Africa, where every river is assigned a management class through a process of research, stakeholder consultation and negotiation: Class 1 (Minimally used), Class 2 (Moderately used) or Class 3 (Heavily used). In these instances, the role of science is two-fold: (1) providing stakeholders with scientific information to help make a class recommendation, with the final decision also taking other political, social or economic issues into consideration; and (2) defining environmental flow needs to meet the objectives once set (King and Pienaar, 2011).

Most policy makers now recognise that different rivers will need to meet different social, economic and ecological aspirations. Kendy *et al.* (2012) concluded that agreeing upfront to a hierarchy of river condition goals and associated environmental flow criteria de-fuses fear and encourages participation of water users in the process of enacting environmental flow policies.

State of the science

Rather than classify methods into discrete categories, the evolution of environmental flow methods can be mapped along five principle axes: (1) simple indices to whole hydrograph analysis; (2) rules of thumb to complex models; (3) hydrological to eco-hydrological methods; (4) species-centred to whole-ecosystem methods; and (5) site-specific to regional assessments.

Some rules of thumb are very simple; for example, in Australia it was suggested that the probability of having a healthy river falls from high to moderate when river flows are less than two-thirds natural (Jones, 2002). Tennant (1976) defined minimum river flows to protect fish habitat in selected regions of western USA: 10% of the annual mean flow for poor quality habitat (survival), 30% for moderate habitat (satisfactory) and 60% for excellent habitat. Yet these rules do not take into account the natural variability of the hydrological regime and the differences in river systems, focusing only on mean flows or total water volumes.

A major conceptual step took place through recognition that river habitat is in part defined by hydraulics, including water depth and velocity (Waters, 1976) rather than flow *per se* (i.e. discharge m^3s^{-1}). This led to models, such as the Physical Habitat Simulation (PHABSIM; Bovee, 1982) system, which describes relationships between discharge and physical habitat (such as depth, velocity and substrate type and cover). The importance of physical habitat is demonstrated by the rapid expansion of the sub-discipline of eco-hydraulics (James and King, 2010; Maddock *et al.*, 2013). For example, Turner and Stewardson (*this volume*) developed hydrological indicators of hydraulic conditions that control flow-biota relationships The science of environmental flows has also benefited from closer links with other aspects of hydrological science. For example, groundwater modelling assists with understanding groundwater-fed ecosystems (Streetly *et al*, *this volume*; Kennen *et al.*, *this volume*) including those in permeable sandy substrata (Hendriks *et al.*, *this volume*).

Another significant advance in the field was the formulation of the natural flow paradigm (Ferrar, 1989; Richter *et al.,* 1996; Poff *et al.*, 1997; King *et al.*, 2000), which highlighted that all aspects of the river flow regime, including floods and droughts, are important for river species and communities (Lytle and Poff, 2004). The natural flow regime is explicit in the regional Ecological Limits of Hydrologic Alteration (ELOHA) environmental flows framework (Poff *et al.*, 2010) which has been developed further in Australia (Arthington et al. *this volume*). It is also explicit in many local methods, such as in-stream flow standards in Texas (Opdyke *et al., this volume*) in which flow component statistics are coupled with biology, water quality, and geomorphology overlays and with implementation rules applied to example large-scale water supply projects. The application of this concept is most evident in areas where the objective is to conserve natural river ecosystems. It is also useful for assessing retrospectively or forecasting forward in time the degree to which our actions have altered (or may alter) freshwater ecosystems due to human population growth, land use or climate change (Laize *et al.*, 2013; Piniewski *et al.*, *this volume*). In the WFD, rivers with a target of High Ecological Status should not have flows reduced from natural by more than 10% at Q_{95} (the flow equalled or exceeded 95% of the time) and by not more than 5% for lower flows (UKTAG, 2008). However, it is increasingly recognised that WFD reference hydrological conditions will alter under climate change (Wilby *et al.*, 2010). Perhaps the most useful aspect of the natural flow paradigm is the ‘flow regime’ phrase, since the concept that the ecosystem is adapted to and dependent on the flow regime is valid in altered rivers and not restricted to natural river environments. Overton *et al*. (2010) used the flow regime concept to model changes to riparian vegetation on the River Murray in Australia over the last 100 years and likely future outcomes under climate change.

With the completion of an increasing number of environmental flow studies, it has been possible to undertake a meta-analysis of the results and produce some simple rules. Rapid desktop methods have been developed to provide initial estimates of environmental flow needs for rivers in South Africa (Hughes and Kennart, 2003; Hughes *et al*., *this volume*) based on applications of the Building Block Methodology (King et al., 2000) or Downstream Response to Imposed Flow Transformation (DRIFT, King *et al*., 2003, 2010). Similarly, statistical summary methods have been based on amalgamating multiple physical habitat studies (Booker and Acreman, 2007) and New Zealand (Lamouroux and Jowett, 2005). These desktop approaches provide the basis of screening tools to undertake broad-scale assessments, which need to be part of a tool kit with different tools used at finer scales of assessment.

Many river systems around the world have been heavily managed for many decades (e.g., the Orange River, South Africa and the River Murray, Australia) or even centuries (e.g. Yangtze River, China; River Thames, UK). These managed systems are essential to the contemporary economies and a return to a natural flow regime is not economically feasible (Overton *et al*.; *this volume*). Under the WFD, such river reaches are declared Heavily Modified Water Bodies and have an objective of reaching GEP. Some managed river systems, such as the River Itchen, UK, have modified habitats that support endangered or economically-important species (e.g. salmon *Salmo salar*). It may be more effective to build an appropriate flow regime that delivers specific objectives, rather than aim for a natural flow regime, particularly where large dams have a major influence on the hydrology. This philosophy can be served by both the Building Block Methodology (BBM; King *et al*., 2000) developed in South Africa, recommended in the UK (Acreman *et al*., 2009; UKTAG, 2013) and proposed for application in Norway (Alfredsen *et al*., 2012) and DRIFT (King *et al*., 2004), which has been applied to a range of river types in Africa, South America and Asia (King and Brown, 2006). The approach can be targeted towards conservation of ecosystem functioning, rather than species, or services defined by society. Environmental flows can help improve water quality, such as diluting effluent and maintaining oxygen levels and water temperature as well as addressing quantity issues. Both methods allow optimum flow regimes to be defined from agreed total environmental water allocations. The draw-back of the BBM is that we have limited knowledge of which building blocks of flow are required and may fail to include some that are essential.

The methods employed vary greatly in the degree to which they are based on objective scientific evidence or professional judgement. Expert panel methods rely on the consensus of specialists interpreting past research or field-based ecological observations of different trial flow releases. At the regional scale, expert panels in the Susquehanna River basin, Pennsylvania, USA, prescribed environmental flow regimes for different types of rivers, filling in biological data gaps with testable flow-ecology hypotheses (Kendy *et al.,* 2012). By contrast, most physical habitat models are based on physical deterministic principles. However, there may equally be large differences in results depending on the approach taken to analyse the same raw. The dilemma in method selection is whether to focus purely on quantitative relationships, which may restrict analysis to certain flow elements and species, or to take a more holistic approach that may require a mix of data and expert opinion to describe seasonal and annual flow variations needed to support diverse, dynamic ecosystems.

Flow/ecology relationships

Extremes of flow and patterns of flow variability can directly influence local community structure of fish, invertebrates and vegetation (Poff and Allan 1995; Merrit and Poff, 2010; Cowx *et al*. 2012). Wilding *et al*. (*this volume*) reported a strong relationship between flood flows and cottonwood abundance in Colorado, USA. In the UK, Streetly *et al.* (*this volume*) found a relationship between flow reductions caused by groundwater abstraction and ecological conditions. In Japan, Sui *et al*. (this volume) identified positive effects of natural flows and the negative effects of dams and weirs, on the occurrence probability of most fish species. Changes in flow are often coincident with changes in temperature (Lawrence *et al*., *this volume*), channel morphology and water quality (Norris and Thoms, 1999; Moss, 2010), such that independent impacts of flow can be hard to distinguish and quantify. In an analysis of rivers in South Queensland, Australia, Arthington *et al.* (*this volume*) found that flow variables alone explained only 5-6.5 % of the variation in fish assemblages. Likewise, Worrall *et al*. (*this volume*) found that hydrological variables account for less than 10% of ecological variability (typically <10%), with a range of other factors, including anthropogenic modification of instream habitats and community structure being important. There is also some evidence that river channels with naturally diverse morphology and habitats tend to be less sensitive to changes in flow than engineered or anthropogenically modified channels in which diversity has been reduced (Dunbar *et al*., 2010a, b). Furthermore, Paredes-Arquiola *et al*. (*this volume*) combined water quality, water resources management and habitat analysis tools within a Decision Support System at basin scale to deliver environmental flows in the Tormes River, Spain (where agricultural demands jeopardize environmental flows needs). Water quality assessment included developing a model to represent the relationship between chemical determinands (such as dissolved oxygen and BOD and ammonium) and flow.

Relationships have been defined between river flow data and in-stream benthic macro-invertebrate communities (Monk *et al.,* 2006; 2008) and fish diversity (Muneepeerakul *et al*. 2008) and broader ecosystem function. However, many flow-ecology relationships are based on statistical associations between biotic response measures and multiple candidate descriptors of antecedent flows. Such relationships may not necessarily represent causal mechanisms and rarely correct for multiple comparison effects. Nevertheless, biotic responses relationships motivate policy makers to enact protective environmental flow regimes (Kendy *et al.,* 2012). So we remain uncertain about some fundamental issues, such how does sensitivity to flow vary along major environmental gradients (e.g. large vs. small, ephemeral vs perennial, flashy vs baseflow). Biological traits and life history strategies suited to arid conditions are evident in some species living in ephemeral rivers, such as having a dormant stage that remains viable in sediments during extended periods of low or no flow (Danks, 2000) or rapid re-colonisation ability (Perrow *et al.,* 2007; 2008). Analysis of 80 BBM studies in South Africa suggested that rivers with naturally highly variable flow regimes required a smaller proportion of total flow to maintain the river ecosystem than rivers with more stable regimes (Hughes and Kennart, 2003). This was indirectly supported by (Dunbar *et al*., 2010a, b) who found that using current standard sampling methods, the macroinvertebrate community in upland rivers (compared with lowland rivers) appeared less sensitive to antecedent low flow. These issues of generalisation across regions require further study.

The majority of eco-hydrological studies are undertaken at specific river sites or reaches. We have begun to assess connectivity upstream/downstream under the river continuum concept (Vannote *et al.,* 1980), which can be important, for example, for input, transport and deposition of sediments and propagules in riparian environments (Moggridge *et al*., 2009) and utilisation of different habitats through a life-cycle (Fausch *et al*., 2002). Moreover, integrated operation of multiple dams to optimize ecosystem services throughout a large basin requires regional eco-hydrological assessment, as the US Army Corps of Engineers and others are demonstrating in the Connecticut River basin, USA (Kendy *et al*., 2012). DRIFT also addresses river connectivity (Brown *et al*., 2013).

The allocation of water between abstractors and ecosystems ideally requires quantitative threshold values that can be used by water managers (Acreman, 2005). This has prompted the search for thresholds of hydrological alteration that cause significant ecological change, such as minimum flow determination. Such relationships have been developed in many countries, including Australia (Arthington *et al. this volume*), Japan (Sui *et al.*, *this volume*) and New Zealand (Snelder *et al.*, *this volume*). Richter *et al.* (2011) suggested a precautionary standard of 10% alteration in any flow variable from natural flows to afford a high level of ecological protection, in the absence of detailed site-specific data. Many flow-ecology relationships are smooth curves (e.g. Extence *et al.*, 1999) and do not have obvious break-points (e.g. Dunbar *et al.*, 2010a, b) as data are collected over a limited flow range. In such cases a threshold becomes a management concept and political decision, not a scientific conclusion (Acreman, 2005). An example of a threshold is bank-full flow at which flow the river becomes connected with the floodplain and stimulates exchange of species, nutrients and carbon between the two systems (Naiman *et al.,* 2005). This is part of the challenge is to identify the parameters driving population and aquatic community abundance and structure, and to identify or develop appropriate indices (Worrall *et al.*, *this volume*). There is a large number of available metrics and these are a synthetic measure of a multi-dimensional flow regime. Stewart-Koster and Olden (*this volume*) used functional linear methods to model the relationship between fish density and community composition and the flow regime, since this approach overcomes some of the limitations associated with using hydrological metrics.

For many environmental flow studies, no ecological data are available. To overcome this limitation, the concept that the flow regime is major determinant of the river ecosystem is invoked (Poff *et al.*, 1997) which assumes that if ecologically-relevant flow regime characteristics (number of floods, duration of low flows) do not vary significantly from reference conditions (usually the natural flow), then the river ecosystem will not be impacted

(Richter *et al.,* 1996). Hydrologic metrics have been used widely as surrogates of river ecosystem condition (Thompson *et al*., *this volume*; Tavassoli *et al*, *this volume*).

Evidence and uncertainty

Environmental flow setting ideally requires good hydrological and ecological knowledge based on long-term data. Even at river gauging stations, discharge is rarely measured to an accuracy of 10% or better, especially at extreme high and low flows (Hershey, 1978). Furthermore, estimates of flow at un-gauged sites can be considerably less accurate (Booker and Snelder, 2012). Defining environmental flow targets to a greater resolution than flow accuracy could be un-necessary. Additionally, many river flow records begin in the late 20th Century (Rodda, 1998), which provides less than a 50 year period of record as a baseline. Globally hydrometric networks are in decline (Hannah *et al.,* 2011). Long records, such as for the Thames (since 1850) show that runoff and low flows in the UK since the early 1960s have been generally stable and not representative of longer time periods of greater variability (Hannaford and Marsh, 2006). This questions the representativeness of other datasets, such as for fish, which for the UK start in the 1970s (Nunn *et al*., 2010). In some cases where environmental flows need to be set, there may be limited or no data available for some locations within catchments. Some new methods are being developed specifically to assess environmental flows under limited data availability, such as in the Acheloos River, Greece (Efstratiadis *et al*., *this volume*) where simple hydraulics and wetted perimeter measurements are used and in mountainous river basins in India (Jain, *this volume*) where hydropower is being developed.

We may consider that river communities are in equilibrium with long-term flow regimes, but we know little about resilience to short term hydrological fluctuations and inter-annual and intra-annual variability. The natural environment may be too complex for us to understand fully and to define thresholds, scientifically or otherwise. However, decisions on water allocation still need to be made. Whilst we should seek to improve our scientific understanding and to base methods on best science/practice, we need to provide guidance acknowledging uncertainty, such as provided for climate change uncertainty when defining environmental flows for the Mekong (Thompson *et al*., *this volume*).

It is important to recognise that scientific understanding not only comes from scientific studies, but is often plentiful in the knowledge and experience of local people, such as indigenous knowledge of fish (Baird *et al*., 2005). Local and scientific knowledge regarding the floodplains and lakes on the Lower Rufiji, Tanzania, for instance, was critical to environmental flow assessment for that river (Duvail *et al*., *this volume*). Likewise, integrating science, expert knowledge and stakeholder participation has been fundamental to assessing environmental flows for the Mara River Basin of East Africa (McClain *et al*., *this volume*) and assessing them for the Okavango River system (King *et al*., *this volume*).

Lack of data has given rise to the need for expert judgement, where river scientists extrapolate from evidence to provide advice and recommendation. Although this may appear subjective, structured expert consensus can provide practical environmental flow estimates (Richter *et al*., 2006; Kendy *et al.,* 2012). To implement to European Water Framework Directive, flow standards for UK rivers were derived by an expert panel of river scientists (Acreman *et al.,* 2008), although they emphasised that the results were very uncertain due to lack of knowledge of eco-hydrological relationships. Uncertainty may be perceived negatively amongst some stakeholders, promoting fear of action. Such situations gave rise to the precautionary approach (Arrow and Fischer, 1974), in which lack of full scientific certainty cannot be used as a reason for postponing cost-effective measures to prevent environmental degradation.

One way forward is to employ adaptive management strategies, where initial estimates of environmental flows are implemented and the response of the ecosystem is monitored, and subsequently adaptations or changes to flows made, if objectives are not met. For example, abstractions may be initially restricted, then increased if no ecosystem degradation is recorded. Likewise, reservoir releases can be managed adaptively to achieve ecological outcomes. Warner *et al.* (*this volume*) documented the experience in the USA that focused on eight demonstration basins containing 36 dams, from which the collective experience will help guide operational changes for as many as 600 dams.

A risk-based approach links appropriate regulatory actions with corresponding levels of certainty regarding the ecological impacts of flow alteration. In Michigan, USA, government action on proposed new water withdrawals ranges from immediate registration to intensive agency review and possible mitigation requirements, depending on the level of certainty that the withdrawal would adversely impact fish communities (Kendy *et al.*, 2012).

Implementing environmental flows

The implementation of environmental flows adds a further challenge to our limited eco-hydrological knowledge. There may be many technical, legal, social and economic issues with which science must interface. A key issue is that different parts of the environment are often managed by different sectors, making it challenging, for example, to coordinate environmental flows from rivers to estuaries (Adams, *this volume*). Perhaps the greatest challenge is making the decision to allocate water to the environment rather than to an alternative use, such as irrigation. Pang *et al.* (*this volume*) suggested there would be no economic loss by allocating more water from agriculture to the Yellow River ecosystem in China. The trade-off in water between uses will inevitably have winners and losers (Figure 3). The Manantali Dam in Mali was constructed to supply hydro-electricity to cities in Senegal, Mauritania and Mali, thus benefiting the urban elite, commerce and industry. This was largely at the expense of the rural poor downstream who had little electrification and who lost ecosystem benefits from floodplain inundation including fisheries and flood recession agriculture (Acreman, 1996), and who suffered increased levels of water-related diseases. The dam also led to major species changes, with loss of floodplain fish and a gain in lake fish (in the reservoir). Water allocation is a highly emotive subject, with the future of local economies and communities at stake. The public burning of copies of the Murray-Darling Basin Plan in Australia in 2011 highlights the potential disputes that can arise where plans to cap abstraction are proposed (ABC, 2012).

In an attempt to demonstrate the wider benefits of functioning ecosystems to decision-makers - who have traditionally worked within an economic framework - economic valuation of environmental flows is being increasingly addressed (Cowx and Portocarrero, 2011), such as in Chile (Wagnitz *et al*., *this volume*), the Mekong (King and Brown, 2010); and the Okavango (King *et al*., *this volume*). The ecosystem services approach has also been followed in Australia (Plant *et al*., 2012) since incorporation of the concept in the Water Act 2007. However, the limitation of the ecosystem services approach, particularly its simplification of ecological complexity, is now recognised (Norgaard, 2010). While some environmental flow benefits, such as fisheries, have a market value and are included within traditional economic analysis, other benefits, such as maintenance of biodiversity or cultural services, including human community cohesion, cannot be readily assigned financial values. Nevertheless, decisions are rarely made on economic grounds alone and decision-makers are used to judging a range of political, social, economic and environmental issues. Thus appropriate multi-criteria frameworks to facilitate decision making and implementation are required.

Models can be useful for predicting ecological outcomes of basin-wide water planning, such as in the Yanga National Park, Australia (Wen and Saintilan, *this volume*) where increased floods and floodplain inundation are predicted to support the health of red gum trees and frogs. Irrespective of the complexity of scientifically-based environmental flows methods, they must be integrated into basin water management plans (Overton *et al*., *this volume*) and encompass legal issues and governance aspects. Banks and Docker (*this volume*) reported that institutional arrangement for flow releases from dams in the Murray-Darling Basin, Australia, are organized for irrigation and it is difficult to respond to environmental flow needs. Snelder *et al.* (*this volume*) argued that the uptake of scientific tools in New Zealand has enabled improvements in the clarity of water management objectives and the transparency of limits defined by regional water management plans. Even when environmental flows have been implemented there must be appropriate monitoring and assessment of compliance. Methods to assess compliance with environmental water allocation decisions have been developed in South Africa (Riddell *et al*., *this volume*) and used on the Crocodile (East) River, where non-compliance was found to be high.

The implementation of environmental flows may also face technical issues. For example, existing dams may not have the valves or gates to release sufficient water at the right time to create the environmental flow regime required (Acreman *et al.,* 2009). Furthermore, releases may need to be made to coincide with augmentation or to simulate real-time natural flow events within the catchment. This requires extensive flow monitoring or estimating current flows at un-measured locations (now-casting) on reference rivers (Alfredsen *et al*., 2012) and forecasts are being used to optimise scheduling of environmental flow releases from some structures, such as the Itezhi-tezhi dam upstream of the Kafue Flats in Zambia.

An essential pre-requisite for implementing environmental flows is the existence of appropriate institutions with sufficient expertise. River basin authorities are particularly important to address transboundary issues. These may concern international issues, such as in the Okavango basin, where Okavango River Basin Water Commission (OKACOM) undertook a transboundary diagnostic analysis between the countries of Angola, Botswana and Namibia, which included an environment flow assessment of the Okavango River system (King et al., *this volume*). Transboundary issues may also occur between states within a federation. For example, in Australia, the Murray-Darling Basin Ministerial Council (MDBMC), which oversees the Basin Authority, includes ministers from each of the basin states (Queensland, New South Wales, Victoria, and South Australia) and the Australian Capital Territory (Overton *et al. this volume*). Engagement and partnerships between the Basin Authority and state jurisdictions is seen as essential for managing the Basin (Banks and Docker, *this volume*).

Linking scientists and policy makers

A key recommendation from the process of defining environmental flows for UK rivers was that the research scientists be involved on an on-going basis to improve interactions between scientific advancements and policy development (Acreman *et al*., 2008). In this way, scientific research, resource management and conservation objectives can be adapted to finding solutions to real issues, and policy can be amended to best use available evidence.

In South Africa and Australia, academics have been more closely involved with environmental flow assessments than in the UK. Much of the early South African research on environmental flow requirements was undertaken in academic and government research organizations, but now most is done by consultants. They access knowledge widely including data specific to the water body, global understanding of how such water bodies functions and local wisdom. In South Africa the Department of Water Affairs has had very strong support from the national Water Research Commission to fund multi-year research programmes and post-graduate studies on environmental flows feeding into under-graduate and post-graduate teaching and a range of professional training courses. After twenty years of experience, South Africa has an excellent national network of informed water professionals who have produced a large body of scientific output while working hands-on in major water resource development projects (King and Pienaar, 2011). In the USA, regulatory agencies have considerable scientific expertise and have developed their own environmental flow methods in-house. Environmental flow methods tend to be developed by consultants and academics, with other organizations, such as NGOs, playing intermediate developmental roles (Kendy *et al.*, 2012). In Australia, research on environmental flows in the Murray-Darling Basin Australia has benefitted strongly from using scientific evidence to support environmental water use decisions (Banks and Docker, *this volume*). However, whilst interactions with scientists is essential, decision-makers need expertise within their organizations to interpret science into policy, thus institutional capacity building is an important aspect of environmental flows development (Richter *et al.*, 2006).

Communications

Environmental flows is just one of the various terms used to convey the concept of ecosystem water requirements, in addition to environmental water allocations, environmental reserve and ecological water demand (Moore, 2004). Some of these actually have different meanings. For example, environmental flow requirements can show how different amounts of water achieve different ecological status, while environmental flow allocations refer to the final decision regarding how much water would be assigned to the environment.

As described above, the underpinning science has been known variously as eco-hydrology or hydro-ecology, which incorporates eco-hydraulics. Whilst the rise and fall of paradigms is a key part of academic debate, intended to help communicate science, such debates can lead to confusion and dis-engagement with policy-makers and agencies responsible for implementing legislation. Clear and honest results are particularly important when the public is sceptical of scientific messages.

A major issue regarding scientific communications is dealing with uncertainty. Environmental flow science is uncertain (although not necessarily more so than other disciplines, such as economic assessment) and scientists need to demonstrate the utility of research outputs rather than stressing challenges of system complexity. The audience for awareness building is very wide and includes all relevant sectors such as water users, politicians, lawyers, engineers, NGOs and the general public. The environmental flows web site http://www.eflownet.org/ provides useful general information. Part of the challenge for effective communication is that target groups have their own language and values and trying to explain new ideas can be interpreted as imposing. Whilst ecologists may understand an ecosystem approach, water engineers may be more comfortable with what they understand as IWRM. During environmental flow training in Tanzania participants were most receptive when the subject was described as a component of environmental impact assessment, which was very familiar to them (Acreman *at al*., 2006).

When people understand the issue of environmental flows, they not only support the idea, but can be actively involved in assessments. In the lower Refiji basin, Tanzania, a participatory monitoring system was established with village-based observers collecting water level, rainfall, fisheries and food data (Duvail *et al*., *this volume*).

Most conferences concerning environmental flows have been attended primarily by hydrologists and those representing other environmental sciences, with an element of preaching to the converted. Some ecologists feel that basic ecological concepts, such as population dynamics have not been included in environmental flow studies (Shenton *et al*., 2010). Engagement with other sectors, such as planning, engineering and policy development has too often been restricted to inviting them to hydro-ecologically-based events. There is a clear need to re-think the message of environmental flows in terms of the language that target what other groups understand and to meet them on their own terms, thus offering environmental flow science as a potential solution to their problems.

Future Research

Hydro-ecological science is still arguably in its infancy and requires future investment in research to expand and fulfil the challenges of delivering knowledge and tools for policy development and delivery in sustainable water allocation. Examples of research needs that may significantly enhance the impact, relevance and wider understanding (and ultimately acceptance) of our scientific endeavours are outlined below.

<u>Multiple stresses</u>. We recognise that changes in external forces on ecosystems tend to occur in synchrony rather than as individual pressures (Ormerod *et al.,* 2010). There is a need to improve our knowledge of the links between changes in flow, channel morphology and water quality and to assess whether impacts are additive, synergistic or antagonistic. One approach is to extend field data collection to incorporate more sites where single and multiple pressures exist and to quantify pressures at individual sites, even when certain pressures are not thought to be limiting. These large data sets provide input to statistical tools to explore and elucidate relationships between multiple pressures. The limitation is that it is often difficult to be certain of cause and effect. A second approach is to undertake manipulative experiments where single variables, such as flow, are changed whilst other variables are held constant (or vary naturally). These manipulative experiments can be real-world scale (such as releases from a dam) or scale models, such as undertaken in laboratory flumes.

<u>Ecosystem function and species interactions</u>. Even multiple pressure research only focuses on external drivers. In addition, ecosystems have internal processes, such as biotic interaction and trophic relationships that govern flows of energy and carbon and thus also control ecosystem type, health and status. Alterations to single external pressures, such as flow, may interact in complex ways with these internal processes. There is a need for

biologists and ecologists to work more closely with hydro-ecologists to address the challenges of combining flow effects with internal ecosystem dynamics.

Groundwater surface water interactions. Much environmental flows science has focused on surface waters in river channels. However, the concept is equally valid in studying flows of groundwater to groundwater-dependent aquatic or terrestrial ecosystems, such as wetlands. Collaborative working between surface and groundwater scientists has occurred for many years to understand flows in groundwater-dominated rivers. This work needs to be extended to improve knowledge of the links between groundwater characteristics (flow, pH, temperature) and the ecology of receiving systems.

Paradigms and approaches. Most environmental flow approaches come under one of two paradigms: (1) the natural flow paradigm based on minimising flow regime alterations from a natural condition to conserve biodiversity and (2) a management-based paradigm where environmental flows are targeted towards achieving specific outcomes, such as ecosystem services. These alternatives could be brought together to providing a unified paradigm to environmental flows. Conceptual frameworks are important for high-level management of ideas and scientific findings. Environmental flows can sit within many possible frameworks, such as integrated water resources management (IWRM), environmental impact assessment (EIA), ecological benefits of flood (Ecoflood) or the ecosystem approach (Overton *et al.*, *this volume*). More work is required to develop links with appropriate frameworks and to assess their utility for managing, communicating and delivering environmental flow science.

Dealing with uncertainty. Like many areas of science, our understanding of environmental flows is limited and progress is slow. Certainty regarding flow-ecosystem relationships remains elusive our understanding needs to be enhanced through careful monitoring of environmental flows that are being implemented. We need to develop methods of dealing with uncertainty, which may include risk-based approaches or use of expert opinion through structured teams within workshops, so that the evidence we have can be used effectively despite its limitations.

Conclusions

The science of environmental flows has made a significant contribution to the understanding and appreciation of the links between rivers flows, environmental processes and ecosystem services. It has brought together a community of previously disparate groups (encompassing all stakeholders from governments through academics to local residents) to work together as teams to address common goals. The science of environmental flows has advanced and influenced policy, although policy is asking new questions of the science. Our results have increasingly highlighted gaps in our knowledge and defined new research needs. It is likely that we will never have perfect answers and so we need to present our scientific outputs in a clear and easily comprehensible manner that acknowledges uncertainties. In the meantime, we need to improve our management of uncertainty and the use of scientific judgement, such as through risk-based approaches and adaptive management.

Some questions can be answered by the science of environmental flows because they are scientific questions, such as the flow needed to support and maintain a certain species or communities in a defined condition. By contrast, we cannot address questions regarding the desired state or condition of an ecosystem since these are social questions, although science can help by providing advice regarding the nature of ecosystems and ecosystem services that will be supported by specific flow regimes. The science of environmental flows aims to define relationships between flow and ecosystem state, while the political process defines society’s preferred position on the relationship curve.

It is therefore essential that the science of environmental flows is set in the wider context of water and ecosystem management. The science of environmental flows can contribute to the assessment of water management trade-offs, including trajectories of change and development space (King and Brown, 2010), but fundamentally cannot address human rights for water, the un-even distribution of economic benefits or provide answers where local versus national (or international cross-border) objectives are at odds.

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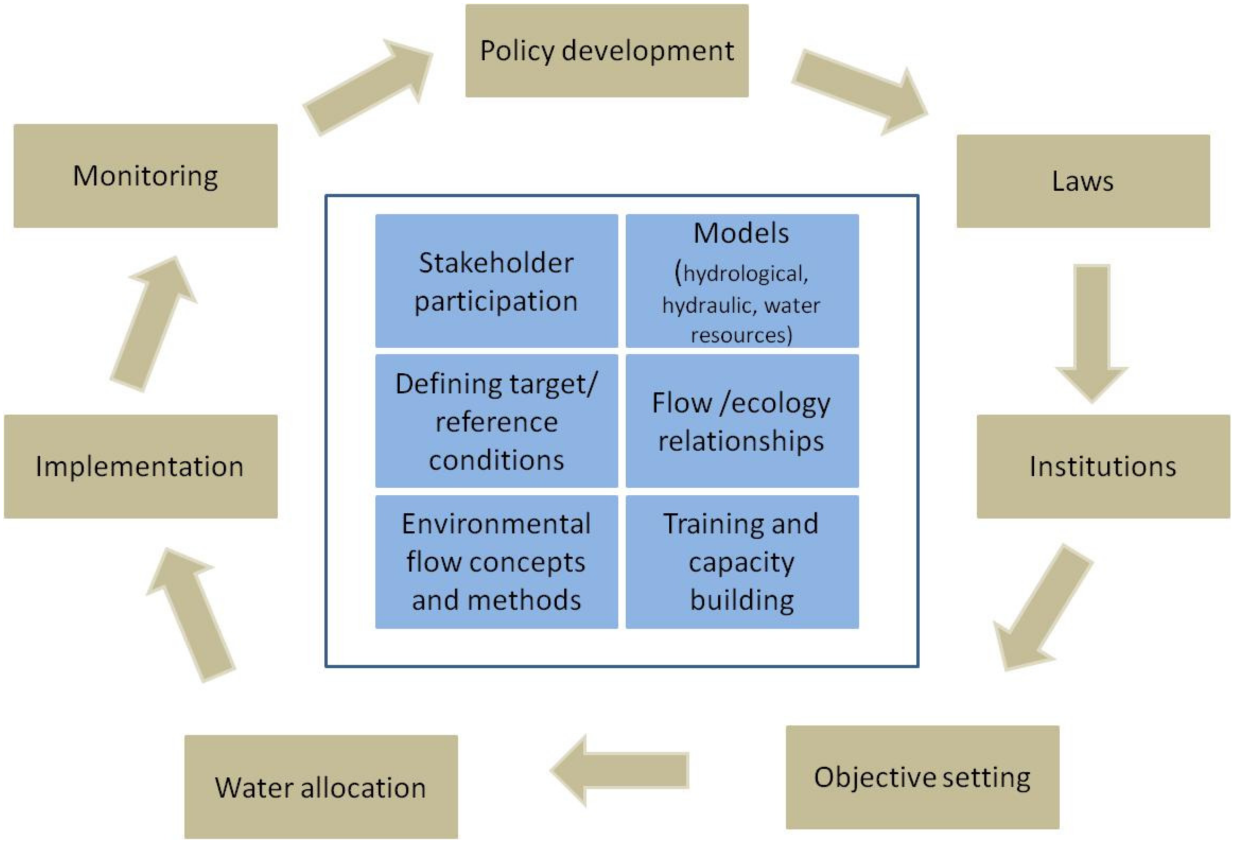

Figure 1 Science supporting policies. Science (blue) provides inputs to all aspects of the policy cycle (brown).

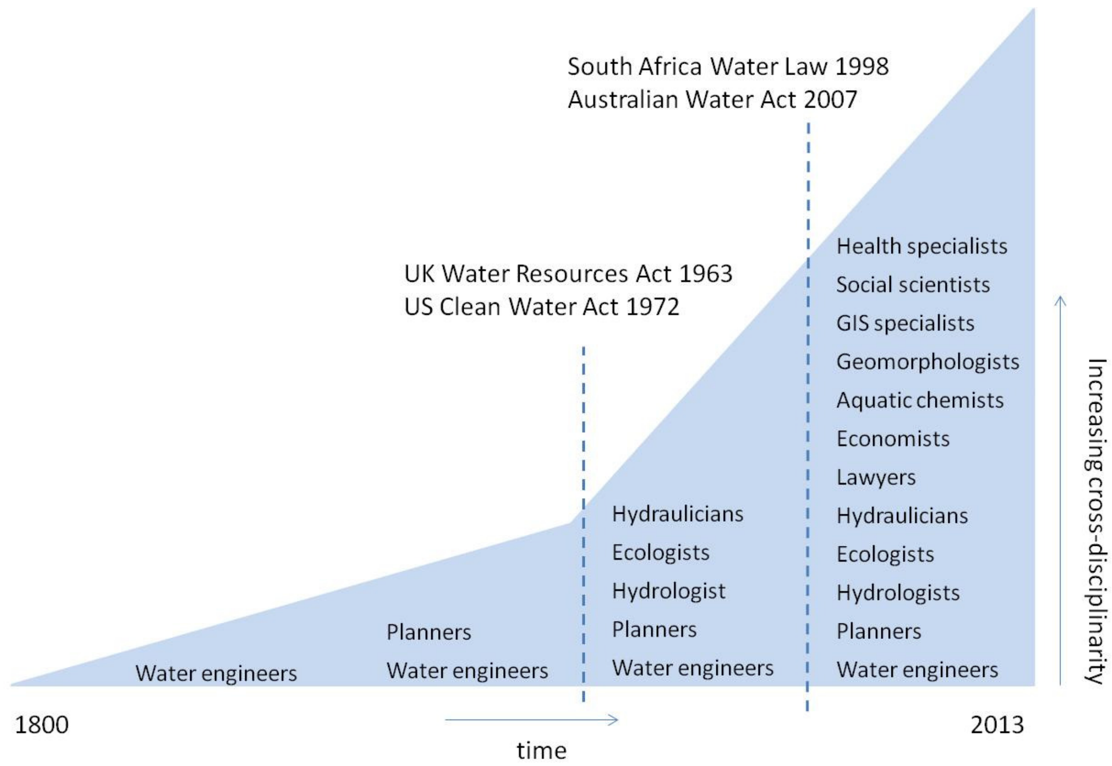

Figure 2 Increase in cross-disciplinarity in environmental flows with time

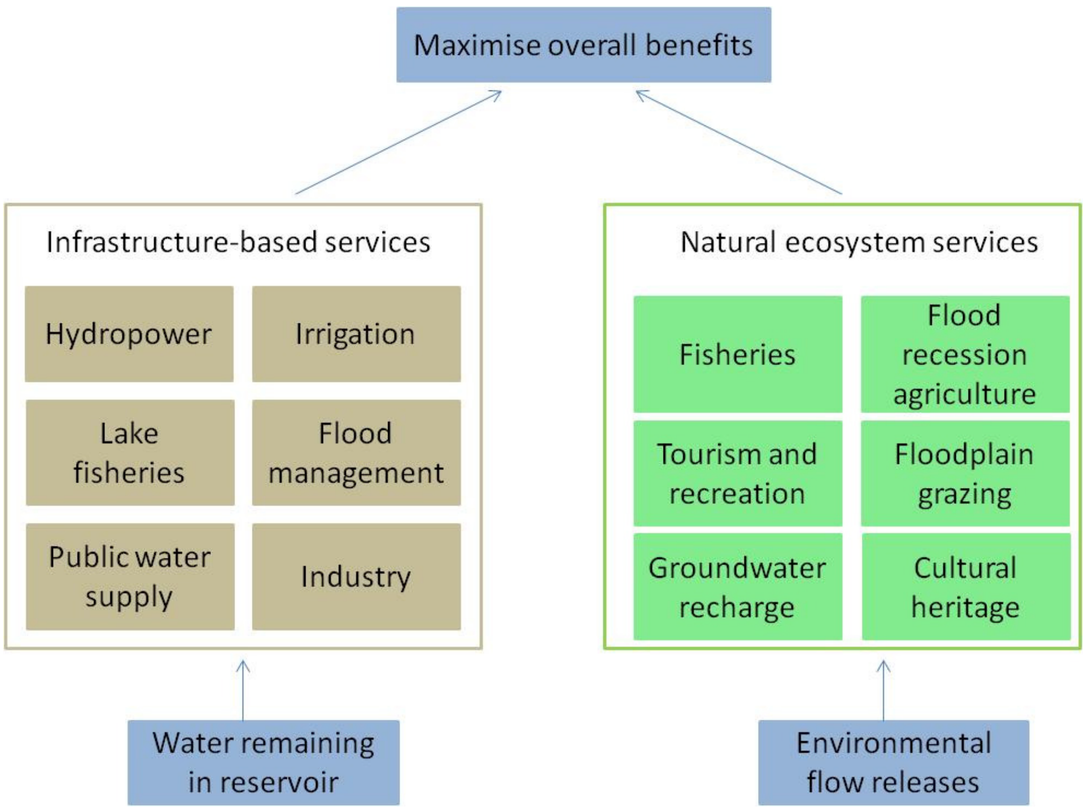

Figure 3 Trade-offs in reservoir management (after Acreman and McCartney, 2000)

Table 1. Areas of science covered by the papers in this Special Issue

Key science areas	Authors	Title
Novel environments: estuaries, wetlands, cold regions, urban streams, arid regions	Adams	A review of methods and frameworks used to determine the environmental water requirements of estuaries
	de la Hera & Murillo	Groundwater flow system in small scale inland wetlands: Miguel Ibáñez case study (Segovia, Spain)
	Lawrence et al.	Recycled water for augmentating urban streams in Mediterranean-climate regions: a potential approach for riparian ecosystem enhancement
	Peters et al	Cold-regions Hydrological Indicators of Change (CHIC) for ecological flow needs assessments
	Tavassoli et al.	Classification of natural flow regimes in Iran to support environmental flow assessment
Groundwater-dependent ecosystems	Aldous & Bach	Hydro-Ecology of Groundwater Dependent Ecosystems: Applying Basic Science to Groundwater Management
	Kennen et al.	Effects of streamflow reductions on aquatic macroinvertebrates: Linking groundwater withdrawals and assemblage response in southern New Jersey Streams, USA
	Hendriks et al.	Groundwater impact on environmental flow needs of streams in sandy catchments in the Netherlands
	Streetly et al.	Using empirical relationships and model results to assess the hydroecological effectiveness of water resources management options
Ecological response to flow change, including ecohydraulics and physical habitat, multiple stresses	Arthington et al.	Multi-variate hydro-ecological relationships for fish from an Australian field trial of ELOHA (Ecological Limits of Hydrologic Alteration)
	Sanderson et al.	Riparian responses to reduced flood flows: comparing and contrasting narrowleaf and broadleaf Cottonwoods
	Sui et al.	Modelling basin-scale distribution of fish occurrence probability for assessment of flow and habitat conditions in rivers
	Stewart-Koster et al.	Quantifying flow-ecology relationships with functional linear models
	Worrall et al.	The identification of hydrological indices for the characterisation of macroinvertebrate community response to flow regime variability
	Turner & Stewardson	Hydrologic indicators of hydraulic conditions that drive flow-biota relationships
Regional environmental flow assessments	Hughes et al.	A new approach to rapid, desktop level, environmental flow assessments for rivers in southern Africa
Legal and governance	Banks & Docker	Delivering environmental flows in the Murray-Darling Basin – legal and governance aspects
Economic analysis	Wagnitz et al.	Cost of environmental flow during water scarcities in the arid Huasco River Basin, northern Chile
Local participation	Duvail et al.	Jointly thinking the post-dam future: exchange of local and scientific knowledge on the lakes of the Lower Rufiji, Tanzania
Methods for limited data	Efstratiadis et al.	Assessment of environmental flows under limited data availability - case study of Acheloos River, Greece
Dam management	Jain	Assessment of environmental flows requirements for hydropower projects
	Warner et al.	Restoring environmental flows through adaptive reservoir management: planning, science, and implementation through the Sustainable Rivers Project
Transboundary rivers	King et al.	Proactive management: the role of environmental flows in transboundary cooperative planning for the Okavango River system
Ecological response to flow change	McClain et al.	Comparing flow regime, channel hydraulics and biological communities to infer flow-ecology relationships in the Mara River of Kenya and Tanzania
Policy, regulation, standards and compliance	Opdyke et al.,	Texas Environmental Flow Standards and Hydrology-based Environmental Flow Regimes (USA)
	Riddell et al.	A methodology for historical assessment of compliance with environmental water allocations: Lessons from the Crocodile (East) River, South Africa
	Snelder et al.	The role of science in setting water resource use limits: a case

		study from New Zealand
Water resources and river basin management	Overton et al..	Implementing environmental flows in Integrated Water Resources Management and the Ecosystem Approach (global)
	Paredes-Arquiola et al.	Integrating water management, habitat modelling and water quality in the environmental flow assessment at basin scale – Tormes River (Spain)
	Pang et al.	A framework for determining recommended environmental flows for balancing agricultural and ecosystem water demands (China)
	Wen & Saintilan	Linking local ecological outcomes with basin-wide water planning: case study of an inland wetland complex
Environmental change: climate and land use	Piniewski et al.	Un-anticipated environmental flow projections under future climate and catchment change in the Narew River Basin, Poland.
	Thompson et al.	Climate change uncertainty in environmental flows for the Mekong River