Environmental flows science to save rivers in the face of uncertainty

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ANGELA: Thank you very much, Brian, and thank you to the In-stream Flow Council for inviting me to join this stimulating workshop. Many thanks also to the Council for my “Making a Difference Award”. I was really delighted. It is beautifully prepared, and Hal gave a great summary of my contributions to in-stream flows and river ecology.

My talk is about improving the science underlying in-stream (environmental) flow assessment and management (SLIDE 2). The first section is about what we have achieved and some of the limitations of our knowledge of flow regimes and their importance for biodiversity and healthy rivers. I will present some lessons from the framework known as ELOHA (Ecological Limits of Hydrologic Alteration, Poff *et al*. 2010) drawn from experiences in Australia and applications in other places. Then I switch into a conversation about restoring environmental flows to the Murray-Darling Basin in Australia, how concepts from ELOHA are being applied with variations around the original framework, and some results from delivery of environmental flows to icon sites along the River Murray. After this ‘gee-whiz’ presentation about environmental flow science, methods and outcomes, I will address the ‘so-what’ issues around improving the science, enhancing monitoring of environmental flows and coping with uncertainty.

Firstly, here is a definition of environmental flows (SLIDE 3). In-stream flows and environmental flows are terms for the same concepts. In Australia we always talk about environmental flows because people said to us years ago “You’re only talking about what’s happening in the stream. What about the flows that leave the channel and flow into floodplain wetlands?” These comments led to a shift in terminology to embrace out of channel flows. This slide presents the definition developed during the International River Symposium and Environmental Flows Conference held in Brisbane, Australia in 2007. I think Brian Richter of the TNC had a lot to do with formulating this definition and the Brisbane Declaration 2007 on environmental flows (http://www.eflownet.org/) developed by delegates.

I think this is a really good definition for several reasons. I like it because it starts with flow quantity, the first element of environmental flows for rivers, but also considers timing issues like seasonality, variability and daily patterns of water flows. Water quality also has to be integrated into environmental flow prescriptions, as in the past water quality issues have been somewhat neglected in environmental flow assessments. The Brisbane definition then links the water flows required to sustain freshwater and estuarine ecosystems to the human livelihoods that depend upon these ecosystems. Ecological goods and services of valuable to people, human livelihoods and well-being are increasingly embraced into the field of environmental flows (King and Brown 2010). I think this development is strengthening the political uptake of the concept of environmental flows (Arthington 2015).

SLIDE 4 presents flow-ecology principles proposed by Bunn and Arthington (2002). This publication has been mentioned several times during this workshop and I am glad to hear that the principles and the literature review that underpins them have proved useful. In addition to the Bunn and Arthington literature review, three scientific summaries and meta-analysis of existing published data have been added over the past decade (SLIDE 5). The first one by Lytle and Poff (2004) is an excellent summary of ecological adaptations to natural flow regimes. In 2010, Poff and Zimmerman searched through the literature on ecological responses to altered flow regimes, in an attempt to identify quantitative relationships that could inform environmental flow practitioners about the risk of modifying flow quantities and temporal patterns (e.g. below dams). Although they found many relationships, these were not consistent across studies and rivers, for a number of reasons. In a similar effort, Gillespie and colleagues (2014) published a critical analysis of the ecological responses of river species and communities to environmental flows released below dams. All three literature reviews found it difficult to assemble the published data into quantitative 'rules' to guide environmental flow implementation and management. Published studies have been done at different spatial scales, using different methodologies and indicators, and variable lengths and quality of hydrological records relevant to river study sites. Another common observation from these literature reviews is that the field studies were done in different climatic regions where the rivers have different kinds of flow regime. In each case there were too few studies to stratify the data according to climatic zones and particular types of flow regime.

This is where ELOHA comes into play in such a potent way as a means to understand how rivers in different climatic zones and with different kinds of flow regime respond to flow alteration, and how they might respond when we try to restore flows through an environmental flow program (Arthington *et al*. 2006).

SLIDE 6 presents the ELOHA framework developed by a group of rivers scientists and environmental flow practitioners at a workshop held in Half Moon Bay, California, and published in 2010 (Poff *et al*. 2010). The framework is designed to be employed at a regional scale, i.e. a large geographic region defined by the users (and the budget). The idea is that the rivers of the chosen study region can be classified into groups distinguished by their flow regime type (e.g. ephemeral, intermittent, perennial), and within each flow regime type (class) we should be able to find locations to study the response of rivers of that type to particular kinds of flow regime alteration. If strong relationships between flow regime alteration and ecological responses can be derived from a field or published data for each river type, it may be feasible to extrapolate those relationships to other rivers of that same type. The ELOHA framework represents a structured process to understand and define the common features of rivers of each hydrological class and how they respond to alterations of the flow regime. It is complex and demanding to apply, as many of you here have experienced.

Now I want to make a few comments about some of the developments with ELOHA applications in Australia and elsewhere. I will not discuss developments in the US because you are familiar with those (see Kendy *et al*. 2010, McManamay *et al*. 2013). The first phase of every ELOHA application is development of the 'hydrologic foundation', and a flow regime classification for the chosen study region. The classification component of ELOHA has received the most attention to date. For example, SLIDE 7 presents the results of a classification of flow regime types in Australia (Kennard et al. 2010). It is based on Bayesian classification of 120 hydrological metrics describing the natural flow regime at 830 stream gauges where there was no flow regime regulation by dams and minimal effects of land use on natural flow patterns. You can see the great gap in the distribution of gauges in the middle of Australia, where rivers are poorly gauged. The distribution of gauging stations and the lack of representation across the chosen study region can be an issue for developing these flow regime classifications. Poff et al. (2010) present some options to address this issue.

The Australian classification of flow regimes types produced 12 different kinds illustrated by the example hydrographs in SLIDE 8. A bit later on I will demonstrate how I built flow-ecology relationships around this way of representing the main characteristics of a flow regime.

Now I want to outline other aspects of ELOHA applications in Australia. A research program called TRACK (Tropical Rivers and Coastal Knowledge) has used the ELOHA framework as a means of assembling information about the rivers of five different flow regime types across northern Australia (SLIDE 9). My colleague Brad Pusey has called this Web-based system for knowledge collation and interrogation NEWT (Northern Environmental Water Tools). NEWT provides a framework for recording knowledge relevant to all components of the ELOHA process. Searching NEWT on the Web reveals what has been achieved in the TRaCK program in relation to environmental flows science and management in Northern Australia. I think it offers a great way to summarize existing knowledge through all the steps of the ELOHA process and show where data are available or new information is needed.

In SLIDE 10 I have opened a couple of examples of the ELOHA components in NEWT to show some recent publications. For instance, in the flow-ecology component of the ELOHA framework (represented by the green box in the middle of the figure), I have given the details of a paper by Warfe and colleagues 2011 (The “wet-dry” in the wet-dry tropics drives river ecosystem structure and processes in northern Australia. *Freshwater Biology* 56). In the Social process component of ELOHA (blue in SLIDE 10) Jackson and colleagues (2012) describe principles and guidelines for good practice in indigenous engagement in water planning. Finn and Jackson (2011) have added a new component to the ELOHA framework requiring of the ecologists and hydrologists that they specify the aboriginal and cultural values related to water and flow regimes, and address them in the social decision making process.

I have completed an ELOHA trial in south-eastern Queensland (SLIDE 12). My study sites are shown in red for locations with an upstream dam and in green for reference sites, spread across five classes of flow regime type (varying from intermittent to perennial flows). Across the study region there is a strong climatic gradient from east (the coast) to west (foothills), with drier conditions in the west, and another gradient of drier conditions in the north and wetter regimes in the south. We sampled riparian and aquatic vegetation and fish at each 40 sites on four occasions over two years.

SLIDE 13 demonstrates a way of presenting information about how the flow regimes of the study region have been altered by dams and other factors (e.g. land-use change). This image is called a 'heat' diagram and seems to be rather like a Raster diagram. It shows the percentage change in a range of flow metrics for every gauged stream and river location with good flow records across the study region. The flow metrics represent the magnitude, timing, frequency, duration and variability of flows (from Poff *et al*. 1997). At a glance you can see where all the highly regulated sites are located. One of the discoveries of this study was that almost every site considered as a 'reference' site for comparison against regulated sites (with altered flow regimes) had some degree of flow regime change compared to modeled pre-development flow patterns (Mackay *et al*. 2014). This was an issue in terms of our desire to identify strong ecological relationships with degrees and types of flow regime alteration using a referential approach.

SLIDE 14 presents a summary of the strong hydro-ecological relationships derived during this study, for riparian vegetation, aquatic vegetation, and fish. The first block of these hydrographs represents inter-annual variability and predictability of flows. The second block shows low flows, low flow duration, timing, seasonal timing, flood frequency, and the third block presents the characteristics of a large flood, the rate of rise and fall, and flood duration. Some really nice relationships came out, but unfortunately not as many as I had expected. However, some of them might be worth pursuing in other places. For instance, the riparian ecologist related a number of metrics about the riparian vegetation growing along creeks to the coefficient of variation of daily flows during the dry season. She was interested in evidence of stress during the dry season when channel water flows are low and variable and the vegetation is increasingly dependent on groundwater rather than channel flows. Total species richness, species richness per hectare, basal area, late successional species, et cetera, all decreased as the CV of daily flow increased. In another mechanistic relationship, the aquatic vegetation ecologist reasoned that plants rooted in the substrate in a stream are vulnerable to being disturbed and uprooted by the velocity and sheer stress associated with particular flows. He found that the number of days over a 12-month period when discharge was above the threshold that disturbs stream substrates (of median substrate size) is related to decreasing vegetation cover. Relationships like these seem plausible and, even though they come from this part of Australia, are testable anywhere.

I was asked to talk about environmental flows and experiences from efforts to restore the ecological health of the Murray-Darling Basin. I have sat on a number of committees working on Murray-Darling Basin environmental flows as well as reviewing reports and workshops. SLIDE 15 presents the geography of the basin which covers 1,062,025 km^2 - about one-seventh the area of Australia. There are 77 or so thousand kilometers of rivers, creeks, and water courses, and 30,000 wetlands. Wetlands are very important, especially the wetland forests supported by flows from the river channel. There has been a long history of concern about how to manage the river system, which is now very well developed to supply water for irrigation, small towns and a large city. Managing the river system has always been a challenge (see history in SLIDE 15). From about 1970 onwards it became very apparent that there were a number of critical issues in the health of the river. Salinity was rising, the mouth of the Murray was not opening as frequently as it used to, riparian vegetation was dying or not regenerating. There were major problems with fish passage and so on.

Gradually, over time, voices from the science and the community sector convinced the federal government to undertake an audit of how much water was being taken out of all the sub-catchments of the basin, and that led eventually to a cap on water abstractions. The National Water Commission was set up to develop and apply the principles of ecologically sustainable development to the management of water in the entire M-D Basin, a new Water Act was promulgated and a Basin Plan produced in 2012. An entity called the Commonwealth Environmental Water Holder was set up to purchase water from license holders who were willing to sell their rights, and an $AUD 9 billion was allocated for e-water purchases and water improvements to water infrastructure to restore the ecological health of the Murray-Darling Basin. Through a demanding process, ecologists used existing data to come up with a recommendation on how much water should be restored to this river system to restore its ecological health. The figures started at 4,000 or so gigaliters but this was seen to present too much of a conflict with the needs of irrigators and other users of the water and was whittled down to 2,750 gigaliters, and that has been whittled further by using infrastructure arrangements to increase irrigation efficiency and to deliver water to stressed floodplain wetlands.

The first stage of the river restoration program was called the Living Murray, with 500 gigaliters per year allocated to icon sites (SLIDE 16). The original icon sites (typically large floodplain wetlands) are now being called ecological umbrella sites, and the idea is that if water can be provided to these wetlands in a number of critical places, then large areas of wetland and channel upstream and downstream would also receive water flowing through the system. The objectives of this early stage of the Murray- Darling Basin plan were to restore aquatic vegetation, riparian vegetation, red gum forests, and recruitment of water birds and fish, and also address the problem of rising salinity and acid sulphate soils in the lower basin.

Activities at icon site can be seen on the Web by searching entries showing ecological objectives, photographs, a record of the amount of water allocated to each of those sites, and the ecological outcomes to date in terms of those objectives (e.g. SLIDE 17, Barmah–Millewa Forest).

Several tools are being used in the Murray-Darling Basin flow restoration program A center for ecological research in Australia called e-Water has produced a raft of hydrological and associated ecological computer programs to support environmental flow management (SLIDE 18). A program called EcoModeler (very like the original IFIM in concept) uses components such as habitat preference curves for selected species to estimate the amount of water, the timing of flows and their duration. Using this program you can cost what a number of environmental flow scenarios would mean for other users of water in the basin.

Recently a large research program has been undertaken by a group of university researchers and CSIRO (Commonwealth Scientific and Industrial Research Organization) working together in a research ‘cluster’. The CSIRO Cluster “Ecological responses to altered flow regimes’ was designed to support the Murray-Darling Basin Plan and the environmental watering plan (SLIDE 19). It has adopted all of the main components of the ELOHA framework and built on them is several important ways. The project has developed a basin-scale classification and mapping of ecological assets including rivers, lakes, wetlands and flood plains (SLIDES 20, 21), and mapped flow-related to non-flow-related threats to the ecological condition of those assets, such as on-channel and off-channel water storages, bores and irrigation channels (SLIDE 22).

A major component of this program was the development of flow-ecology response models based on the literature, field research and expert opinion. The expression of uncertainty in flow-ecology response relationships adopted language from the IPCC (Mastrandrea *et al*. 2010), in terms of ‘confidence’ and ‘likelihood’ (SLIDE 23). Confidence is a measure of the amount of data, the quality, and the consistency of the evidence, and the degree of agreement expressed simply as low, medium, and high. Likelihood is expressed in probabilistic terms ranging from unlikely to almost certain. SLIDE 24 describes some of the flow-ecology response relationships for different components of the flow regime. In this basin, as in many river basins with very large dams, the large wet-season flows are captured and stored, to be released in the dry season, inverting the normal seasonal flow pattern. There are serious implications for life history processes that are dependent on certain signals and triggers in water levels and flows (e.g. King et al. 2010).

Flow management strategies in Murray-Darling Basin are summarized in SLIDE 25. A mapping analysis demonstrates that 45% of the floodplains, 46% of lakes and 61% of wetlands could be watered by water releases from large dams. Flow management strategies also include water shepherding, water buy-backs to reduce water extraction or interception and groundwater management. This Cluster research program also addressed how to optimize the allocation of environmental water across the basin, and development of methods for monitoring and assessment of the outcomes of environmental flows (SLIDE 26). These aspects go beyond the scope of my presentation but can be reviewed on the Web.

Moving on from the ‘gee-whiz’ parts of this presentation I turn now to the ‘so what’ question set for us by Tom in his introduction to this Workshop. My response is a scientific summary of the progress I have recounted today (SLIDE 27).

Firstly, I think ELOHA offers a robust and systematic process to assess the risk of altering the flow regimes of rivers of different hydrological character in particular ways. Its authors have argued that if we understand those relationships within one type (hydrological class) of river then we may be able to apply them to other members of that river class. The framework aims to get around the demands of undertaking an environmental flow assessment for every single individual river, by extrapolating knowledge from a sample of rivers to other rivers of the same hydrological character. If that hypothesis does not hold up, and every single river is different and individual, where does that leave us? It leaves us with the need to go back to conducting individual studies of each river we wish to conserve or restore by implementing individualistic (tailored) environmental flows.

Applications of the ELOHA framework are increasing and there has been a great deal of innovation around the original framework, with new ideas about classification methods becoming more impressive and inclusive, as seen in the Murray-Darling Basin research cluster program (SLIDES 20-22) and other studies. The framework, as applied in the Murray-Darling Basin, allows multiple stressors on aquatic ecosystems to be incorporated into the classification of systems at risk. It is an unfortunate reality that rivers and wetlands in many developed landscapes suffer the impacts of multiple stressors (Davis *et al*. 2015). The noise they create in efforts to relate ecological condition to flow regime change has to be addressed.

Frameworks such as ELOHA have helped to improve the development of hydro-ecological relationships in data-limited and data-rich circumstances and in developing and developed economies alike. Flow ecology models emerging out of scientific studies and environmental flow assessments can be used to predict any kind of scenario by whatever cause, whether it is a new dam, irrigation withdrawals, inter-basin water transfers, or climate change. Developments around the ELOHA framework have also expanded the spatial scale, socio-economic dimensions, and governance contexts of environmental flow assessments and management (Arthington 2015).

Delivery of environmental flows has to be optimized. Recent developments in optimization theory and practice are helping to choose the most beneficial places to deliver environmental water in terms of biodiversity and ecosystem processes, connectivity to other systems and protection of source populations to replenish disturbed systems. Systematic conservation planning is a burgeoning field with great potential to support environmental flow management (e.g. Nel *et al*. 2011).

Finally, environmental flows and any other conservation or restoration actions must be treated as experiments with careful monitoring of ecological outcomes according to a robust experimental design (Poff *et al*. 2003, Arthington 2012). At this point in time when so much is changing in our landscapes (changes due to human use of water, more dams, extensive water grids connecting wet to dry landscapes, and climate shifts slowly, inexorably changing ecosystems), we have the responsibility to make a record of those changes, so that the scientists and managers who come after us have a solid scientific background and greater certainty about the ecological roles of flow and ecosystem resilience to change.

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