Primer

Environmental flows—basics for novices

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The term environmental flows has become widely used to define the hydrological regime required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on them. A large range of frameworks and methods has been developed to assess environmental flow needs and many authors have identified subtleties in the approaches needed for different situations and required outcomes. This article summaries some basic concepts that can assist those new to environmental flows to navigate the rapidly expanding plethora of information. It briefly covers key areas of setting objectives for river ecosystems, examining pressures that constrain reaching these objectives, the level of detail needed, implementation, and how future changes affect environmental flow assessments.

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PROLOGUE

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[1]). An underpinning concept is that people benefit indirectly from water provided to ecosystems—such as recreation and cultural identity and much of what we call 'quality of life'[2]—in addition to the direct benefit of water used for drinking, growing food, and supporting industry.[3] Implementing environmental flows frequency concerns a trade-off in the allocation of water between direct and indirect use.[4] A principle assumption is that river flow and water quality are major determinants of river ecosystem condition[5] and the resulting benefits, along with other factors such as light, temperature, channel morphology and species interactions.[6] Furthermore, because river systems evolved under a natural river flow and quality regime, this provides the baseline for determining what is required[7] and the greater the departure from the natural regime, for example caused by water use, the greater the loss of ecosystem benefits.[8] There may be flow thresholds at which abrupt changes in ecosystem condition occur,[9] such as at bankfull flow (above which the river is connected to its floodplain) or at very low flows (when the river fragments into disconnected pools and dry riffles), but the river is not a binary (dichotomous) system, i.e., either in good (full services) or bad (no services) condition. The relationship between flow and ecosystem condition will also altered by structural changes to the river, such as straightened and deepened, so that the appropriate flow to give best ecosystem condition is not the natural flow. In addition, dams, embankments, and others structures may fragment the river system into separate parts that preclude certain processes and hence species, regardless of the flow.[10]

A prerequisite for setting environmental flows is to decide what sort of river is desired and can be achieved.[11] Whilst science can inform us of how flow, morphology, plants, and so on make up habitat templates for species and communities and the social benefits that will be delivered by different types of ecosystem in different condition, the selection of the 'desired ecosystem' (the management objective) is a matter of social choice.[12] It needs to be recognized that many rivers have undergone centuries of water

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and land management and thus the natural flow regime is not a realistic objective, it may not be appropriate due to channel alterations and it may not be achievable due to climate change, so future targets will need to be adapted to accommodate emerging ecosystem characteristics and social aspirations.[13]

An additional consideration is that different human interventions (direct abstraction of water, diversions and dams) alter the flow regime in different ways and thus require different management responses. Some attributes of environmental flow methods are consistent with these different interventions and can help guide method selection. Methods also vary in the detail to which they consider eco-hydrological processes and different levels of detail are appropriate for different environmental flow applications. This article briefly explores five fundamental questions that must be addressed when defining environmental flow requirements: (1) What are the objectives for a river ecosystem? (2) What pressures currently constrain reaching these objectives? (3) What level of detail is needed? (4) What are the key issues in implementation? (5) How will changing climate and land/water management make a different in the future? The paper gives a list of references that provide further details of specific issues. More comprehensive coverage of all issues in a single document can be found in Arthington's Environmental flow book.[1]

SETTING OBJECTIVES

Defining the desired future condition of an ecosystem is a societal issue that should be guided by science in terms of what is achievable.[14] Setting objectives can take many pathways and involve multiple processes. Nevertheless, two principle approaches are common; objective-based setting and scenario-based setting.[15] Objective-based setting takes place where predefined legal or policy targets exist. These may be to restore or conserve certain desired species or communities (such as fish or birds[16]), to elimination unwanted species such as algae[17] or terrestrial vegetation[18] or more generally to enhance river condition. For example, in the European Union, member states are required to implement the Water Framework Directive (WFD[19]), which specifies a generic target for rivers of at least Good Ecological Status (GES), defined as slight alteration from reference biological conditions.[20] Where it is economically unrealistic to achieve GES, an alternative objective of Good Ecological Potential (GEP) may be adopted. Sometimes environmental objectives vary for individual rivers within a generic framework to meet specific local requirements such as recreation, esthetic value, water supply or biodiversity, each of which may need different environmental flows. In Connecticut, USA, e.g., every river reach is 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, though this is not an objective for any river.[21]

In scenario-based decision-making, the objectives are not pre-set, but result from an assessment of a range of potential water allocations. Decisions may be based on economic, social, ecological, and/or cultural consideration and may involve negotiations amongst a wide range of stakeholders.[22] In India, historical water allocations have given a priority to diversions for agriculture, but this has conflicted with the high spiritual value of its rivers, such as the Ganges, and now water allocation to achieve religious objectives is being explicitly considered in allocation decisions.[23] Objective setting in South Africa follows a hybrid of objective and scenario-based decision-making, in which potential management classes are defined by government agencies—class 1 (Minimally used), class 2 (Moderately used), or class 3 (Heavily used)—but every river is assigned a management class through a process of research, stakeholder consultation, and negotiation.[24]

PRESSURES ON RIVERS

All direct uses of water disturb the natural hydrological regime of rivers, but the nature of the alteration depends on the type of exploitation. A constant direct water abstraction from a river, such as for power station cooling or public water supply may reduce discharge uniformly across the entire flow hydrograph, but does not alter flow variability so the pattern of floods and low flows remains (e.g., Figure 1). In this case, environmental flow management involves restricting abstraction (and thus deviation of the flow regime from a pre-abstraction baseline) to achieve an altered flow regime that still maintains the desired ecosystem. Methods that quantify departure of the altered regime from the baseline[7,25] are well-suited to this issue (Figure 2). In contrast, large dams have the potential to store much of the flow of the river, thus the downstream flow regime may be dominated by pulses of flow during

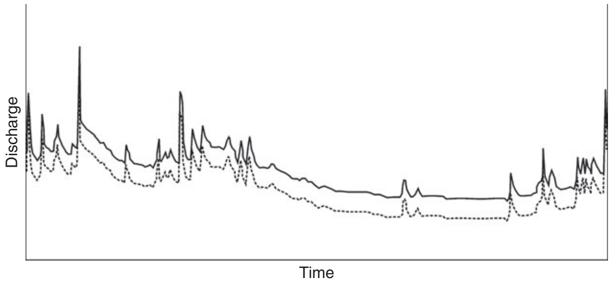

FIGURE 1 | Natural flow regime (solid) and the flow require altered by a constant abstraction (dashed).

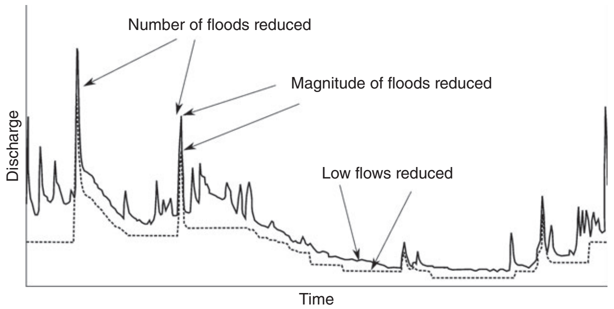

FIGURE 2 | Hydro-ecological impacts can be quantified by recording the difference between a natural (solid) and altered (dashed) flow regime as a set of indices that capture changes in key hydrograph components.

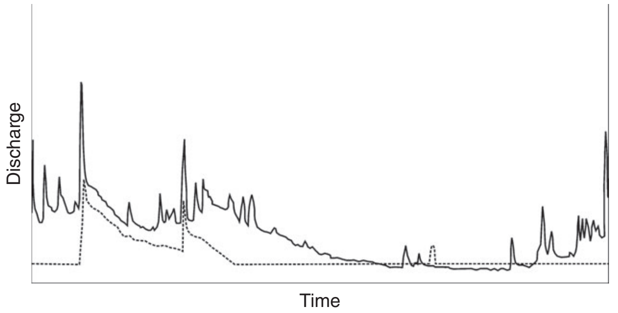

FIGURE 3 | Natural flow regime (solid) and the flow require produced by a constant dam release and occasional flows over the spillway (dashed).

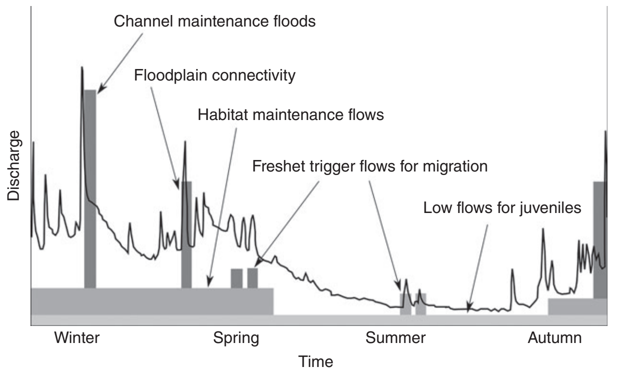

FIGURE 4 | Environmental flows releases from dams can be achieved by building a flow regime from a zero flow baseline using hydrograph components (gray blocks) that support particular parts of the river ecosystem. (Reprinted with permission from Ref 27. Copyright 2009)

extreme floods when water bypasses the dam via the spillway, plus any release from the dam, such as water passing through turbines (e.g., Figure 3). In such cases, environmental flow management involves making releases to build a flow regime from a zero flow baseline that is designed to produce the desired ecosystem[26,27] (Figure 4).

Although the environmental flow management processes might begin at opposite extremes (a natural flow hydrograph or no flow below a dam), we will see a convergence to a common end if the ecological objectives are the same.[13] For the abstraction case, characteristics of the baseline flow regime may be lost but if the remaining flow regime remains within limits desired ecosystem conditions can be maintained. For the dam case, the environmental flow releases will need to build-up a flow regime with basic elements sufficient to produce the desired ecosystem conditions. The resulting flow regime may be much the same in the two cases.

DETAIL IN ENVIRONMENTAL FLOW METHODS

In 2003, Tharme[28] suggested there were 250 methods of assessing environmental flows and the number has certainly risen significantly in the past 13 years. All methods have their own advantages and disadvantages, so none is right or wrong. One way to classify methods is to consider the data required and the outputs that result. Hydrological methods rely on analysis of indices of the river flow regime, such as magnitude and frequency of floods, duration of low flows and rates of flow change.[7,24] If the natural flow regime concept[7] is accepted (i.e., that all aspects of the flow hydrograph are important to some organism life stage or biological community), by maintaining key characteristics of the hydrograph all biological niches are conserved, suggesting there is no need to consider individual species. Indeed, as the flow regime needs of all species and communities are not known, focusing on a few target organisms may mean that flow requirements of vital, but poorly understood, components of the ecosystem are not met. Hydrological methods are used frequently with existing flow time series data. However, data do not always exist pre- and postalteration, so it may be necessary to hind-cast the baseline (natural flow) or forecast the impacts of a dam or abstraction using a hydrological model. Hydraulic methods are based on the notion that flow itself does not determine river ecosystem condition, but rather it is the interaction between flow, channel geometry, and aquatic plants that produces a mosaic of different widths, depths, and velocities in the river, which define physical habitat.[29] Hydraulic methods are particularly useful for rivers with channels modified by dredging or straightening, where the natural relationships between flow and hydraulics have been disturbed. Many such methods require repeat measurements of hydraulic variables at different flows, although more rapid methods are being developed.[30,31] Biological response models consider the relationships between hydrology (whether as flow or hydraulic variables) and organism traits.[32,33] For example, depth and velocity requirements have been prescribed for certain species and life stages (such as spawning or migration). Such relationships may be formulated for different river types.[34] A team of global environmental flow experts achieved consensus around the form of this approach and produced the ELOHA framework.[35] These methods are applicable particularly where flows are set to conserve particular species that might be rare or provide an ecosystem services, such as a fishery or recreation. They provide the ideal method for environmental flow assessment, by definition, but most require significant biological data and the flow needs of some underlying aspect may be unknown or ignored. Focus is often on the most sensitive species with the idea that if the flow is appropriate for them, or it should suit other species or communities. Great care must be taken in applying the results of environmental flow methods generated in one eco-hydrological region directly to another; recalibration using local data is always recommended.[35]

IMPLEMENTATION

Once an environmental flow method has been develop and applied to a river, the results need to be implemented, which creates an additional set of issues. A technical issue is that environmental flows are often specified in terms of the natural flow that would be in the river. For example, making flood releases from a dam as part of environmental flow implementation should be undertaken when there would have been a flood on that river, requiring flow monitoring on a reference natural river and real-time data transfer to a control center.[36]

The flow regimes of many rivers of the world are already heavily modified through major water use.[37] So implementing environmental flows is likely to involve recovering water currently being used for other important purposes, such as agriculture, industry, or public supply, with consequential economic and social impacts. In 2010, angry farmers burned copies of the Murray-Darling basin plan in front of the press to show their opposition to environmental flow proposals that would mean less water for their irrigated crops. Ideally involving stakeholders in environmental flow assessment can help build awareness of the issues and prepare water users for the likely outcomes, but considerable political will and potentially financial compensation is often needed when water allocations are altered. In many cases, current water uses have legal rights. In the UK, releases from dams are restricted by individual Acts of Parliament,[14] so these would need to be repealed to implement environmental flows. Our eco-hydrological knowledge is limited and studies often highlight gaps and defined new research imperatives. We will never have perfect answers for complex river ecosystem challenges and so we need to present our scientific outputs in a clear and easily comprehensible manner that acknowledges uncertainties. One approach is to employ adaptive management,[7] where initial environmental flows are implemented, the ecological and human response is monitored, and environmental flow regime is altered if required.

FUTURE CHANGE

Analysis of past climate fluctuations and recognition of man's increasing influence[38] suggest that our environment is not stationary and will be different in the future. By 2050, annual average river runoff and water availability are projected to increase by 10–40% at high latitudes and in some wet tropical areas. In contrast, they are expected to decrease by 10–30% over some dry regions at mid-latitudes and in the dry tropics. Drought-affected areas will most likely become larger and heavy precipitation events are very likely to become more common, increasing flood risk.[39] How each river ecosystem will respond depends on the new climate, the potentially altered response of the catchment and the resilience of its biological communities to change. It is likely that our current ideas of baseline conditions, e.g., natural or semi-natural/recent, will need to be adjusted for the future.[13] Furthermore, the spread of alien invasive species into new areas or range shifts of native species ecosystems will result in different species composition and ecological functions.[40] Some changes will result in hybrid systems that retain some original characteristics, with novel elements, for which there are no current analogues.[41]

It is important that environmental flow assessments consider changes in external forces of climate, land use, and water management, with a succession from natural, though managed or hybrid to novel ecosystems as these forces change from their original patterns of water, quantity, quality, and variability. Additionally, in many areas such changes are likely to continue in the future, and may be substantial,[42] whilst in other regions new 'natural' flow regimes will emerge and be stable at least temporarily. As a result, new forms of hybrid and novel ecosystems that deliver different sets of ecosystem services will also be likely to emerge as each ecosystem adjusts to both the changing climate and management drivers. The 'new' natural flow regime in a relatively pristine area may still provide the basis for environmental flow assessment using a natural flow framework.[13] Overall, it will become increasingly important to consider future altered flow regime scenarios that project the risk to current river ecosystems.[24]

EPILOGUE

This study has addressed five major questions facing water managers in assessing environmental flow needs for river ecosystems. Environmental flow methods to date have focused on water quantity, primarily in rivers of good water quality. Separate methods are often used to assess water quality, in which threshold levels of various nutrients and pollutants are employed to determine ecological condition related to eutrophication or risk of algal blooms or direct human use, such as suitability for drinking water for crop irrigation. But even in rivers of poor quality, inappropriate water quantity can be a major limiting factor. Ecosystem condition also depends on other factors including species mobility and interactions, such as food web dynamics. As yet, there are few methods that integrate these with environmental flows.[43] Ideally all pressures on the ecosystem should be assessed together as one may affect the other; e.g, high levels of copper in rivers have been shown to reduce the swimming ability of fish and so the flows that are suitable for them.[44] Such interactions maybe synergistic such that the resulting overall effects that are greater than the sum of individual effects. The flow regime thus provides a template defining potential for a range of riverine species and ecological communities.

Emerging topics that have not featured significantly in past environmental flow assessments are species interactions,[45] water temperature,[46] and sediment dynamics.[47] For example, dams trap sediment and starve the downstream river reach, often leading to erosion and morphological change. Releasing sediment-free water through a dam to generate an appropriate flow regime may be ineffective if it does not restore the natural downstream sediment regime.[48] Finally, no environmental flow assessment can be considered successful unless its outcomes can be implemented. For example, elaborate details of a flow release from a reservoir can be defined but this is academic if the dam is in a remote location and its outlet structures cannot be readily manipulated.

The concept of environmental flows is becoming globally accepted as efforts are made to restore and maintain river ecosystems that provide human livelihoods and well-being. A multitude of frameworks and methods have been developed, each with their own advantages in particular situations. However, this article has summarized basic concepts that can assist those new to environmental flows to navigate the rapidly expanding information available.

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