# EMERGING TRENDS IN ENVIRONMENTAL FLOW SCIENCE

Paul M. Leonard

AUTHOR: Cardno ENTRIX, 50 Glenlake Parkway, Suite 600, Atlanta, GA 30328.
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## ABSTRACT

The past decade has brought wide recognition of the importance of natural flow regimes as the conceptual underpinning of sustainable environmental flows and an expanding attention to a framework for developing regional flow standards. This article summarizes and highlights some of the most relevant developments in environmental flow science nationally and their ongoing application in the Eastern and Southeastern United States, with a focus on approaches for basinwide environmental flows based on hydrologic and geomorphic classification, flow alteration, and flow-biological responses.

## INTRODUCTION

Over the past two decades, droughts, water shortages and disputes, and the development of regional and state water plans in the Southeastern United States have brought water quantity and quality issues into sharp focus. One of the most important, yet challenging and elusive, issues has been the development of science-based environmental flow approaches that can be applied broadly in the water planning and permitting process for the protection of aquatic resources. The rate of development and use of water resource and accelerated water planning initiatives are straining the traditional approach to addressing environmental flow needs – a case-by-case, permit-by-permit approach. The shortfalls of this approach are now being realized – overtaxed agency resources, lack of integrated flow protection for streams and basins, and failure to consider basinwide flow needs. These same issues are challenging the water planning and allocation process, because while current and future water demand may be adequately understood, allocations of flow for ecological values are poorly understood at the basin level. The pace and intensity of flow alteration in rivers are exceeding the ability of scientists to conduct holistic assessments on a river-by-river basis (Tharme 2003; Acreman and Dunbar 2004; Annear et al. 2004; Arthington et al. 2006).

The purpose of this paper is to summarize and highlight some of the more relevant developments in environmental flow science nationally and their application in the Eastern and Southeastern United States, with a focus on approaches for regional and basinwide environmental flows. I point to examples of where and how new approaches are being used. We touch on regional efforts towards environmental flow standards, and recent developments that may change the trajectory for how environmental flows may evolve in water planning processes and in the regulatory context of the Clean Water Act.

## A PARADIGM SHIFT – NATURAL FLOW REGIME

The most significant new concept in the science of environmental flow management has been the natural flow paradigm; the recognition that aquatic and water-dependent ecosystems have evolved with, and depend upon, naturally variable flows of high-quality fresh water. The convention of instream flow science has changed from applying a single, minimum flow or “flat-line” flow (Stalnaker 1990) to a range of flows that account for seasonal and inter-annual variation, magnitude, timing, frequency, and rate of change (IFC, 2002; Poff et al., 1997; Postel and Richter, 2003; National Academy of Science, 2005; Poff et al., 2010). These hydrologic attributes translate into different levels of flow that together constitute a flow regime – subsistence flows, base flows, high flow pulses, and over bank flows. It is now widely accepted that a naturally variable regime of flow, rather than just a minimum low flow, is required to sustain the integrity of freshwater ecosystems (Poff et al. 1997; Bunn & Arthington 2002; Postel and Richter 2003; Annear et al. 2004; Biggs, Nikora & Snelder 2005; Poff 2010).

The outcome of this paradigm shift is that by the early 2000s, scientific approaches had been expanded to a framework for environmental flows that could be more broadly applied. However from a management perspective, major challenges remains to educate politicians and the public about the importance of variability in sustaining riverine ecosystems.

## DEVELOPMENT OF REGIONAL OR BASINWIDE APPROACHES

Increasingly, a gap has been widening between the rate of water resource development, allocation, and overuse, and the application of the advancing environmental flow science. In most cases, environmental flows established to date have been dominated by site- and often species-specific empirical studies (Petts, 2006) performed for specific licenses and permits. While these studies may adequately address flow needs on a segment or river reach scale, they typically do not address flow needs at larger scales within the river basin, especially for migratory species (e.g., shad, sturgeon, suckers, striped bass) and their co-dependent species (e.g., freshwater mussels), or for downstream needs. That is, multiple site-specific requirements may not add up to flows that are sufficient basinwide. As a result, a patchwork of environmental flow requirements ranging from none at all to considerable can exist within a basin, considerably complicating existing and future environmental flow management at the basin scale.

These pressures have led to approaches designed to address regional and basinwide flow needs based on hydrologic and geomorphic classification, flow alteration, and flow-biological responses. This most recent phase of innovation has been driven by a need to establish environmental flow standards for many streams and rivers, and by a lack of data on many rivers to determine empirical or more sophisticated mathematical models of river flow and ecological status (Petts, 2006). It is also driven by the need to develop instream flow standards quickly, as water allocation decisions continue to be made with or without a sound scientific basis. Defining environmental flow standards for many rivers simultaneously, including those for which little hydrologic or ecological information exists, is necessary for water managers to effectively integrate human and ecosystem water needs in a timely and comprehensive manner (Arthington et al., 2006).

## ECOLOGICAL LIMITS OF HYDROLOGIC ALTERATION: A FRAMEWORK

Although a number of approaches have been proposed for establishing regional environmental flow standards, one approach seems to have gained broad attention and acceptance on the basis of its strong ecological underpinnings and synthesis of the strong points of previous methods. The Ecological Limits of Hydrologic Alteration (ELOHA) (Poff et al. 2010), is a framework for developing regional environmental flow standards. Previously outlined in 2006 by Arthington et al. (2006), the approach is a synthesis of a number of existing hydrologic techniques and environmental flow methods that are currently being used to various degrees and that can support comprehensive regional flow management. This approach represents a consensus view from a group of international scientists. Five core elements in the ELOHA process are shown in Table 1. Although there are few states or basins in which ELOHA is being applied exactly as formulated, there are many examples of the use of the concepts and components that are being added to the growing base of example applications.

**Table 1. Five key steps in the development of regional environmental flow standards using the Ecological Limits of Hydrologic Alteration approach (Poff et al. 2010)**

1. Build a hydrologic foundation
2. Classify rivers according to flow regimes and geomorphic features
3. Characterize degree of hydrologic alteration
4. Define flow alteration-ecological response relationships
5. Use flow alteration – ecological response relationships to manage environmental flows through an informed social process

## BUILDING HYDROLOGIC FOUNDATIONS

Over the past decade there has been increasing attention directed to methods and approaches for characterizing the historic "unaltered" or "unregulated" flow regime, including in ungaged basins (Armstrong et al. 2008; Aguilar 2009; Kennard et al. 2010; NCDWR 2011). The use of unimpaired flows, as opposed to historical observed flows, allows resource assessments to be founded on the "natural" hydrology of the stream network. Many of the early applications were completed for relicensing of Federal Energy Regulatory Commission (FERC) licensed hydroelectric projects (e.g., Catawba Wateree Project; Yadkin Pee Dee Hydroelectric Projects), but increasingly unimpaired flow regimes are being applied in basinwide water planning studies. Examples of efforts to build hydrologic foundations for states and basins include Georgia (e.g., Georgia EPD Draft Unimpaired Flow Report), North Carolina (http://www.ncwater.org/Data_and_Modeling/eflows/), the Delaware River Basin (Apse et al. 2008), Potomac River Basin (http://www.potomacriver.org/cms/index.php?option=com_content&view=article&id=162&Itemid=117), New Jersey (Kennen et al. 2007), and Texas (Hersch and Maidment 2007).

For the past 10 years, North Carolina has been taking a systematic approach to quantifying unaltered flow regimes as part of the states' hydrologic modeling foundation. North Carolina has synthesized data sets that describe unaltered hydrology based on basinwide mass balance and applied basin hydrologic simulation models on a watershed-by-watershed basis (NCDWR, 2011). The North Carolina General Assembly enacted legislation in 2010 directing the Department of Environment and Natural Resources to develop hydrologic models for each river basin in the state.

Increasingly, the need to simulate future hydrologic conditions has led to research about potential changes in historical flow regimes due to climate variability and change, watershed land development, and urbanization. As described by Leonard et al (2010), consensus-based climate change models downscaled to produce consensus-based projections of likely future baseline precipitation and runoff (streamflows) are urgently needed to begin to build a hydrologic basis for future environmental flow standards.

## STREAM FLOW REGIME CLASSIFICATION (ECO-HYDROLOGIC CLASSIFICATION)

A critical step in the process of developing the regional approach is to classify streams and rivers by similarity in hydrologic regime, using flow statistics computed from the baseline hydrographs. The purpose is to define a manageable set of distinct hydroecological classes or types whose flow regimes are generally similar within the class but which can be differentiated from other classes, using flow metrics that are (1) ecologically relevant (Arthington et al., 2006; Monk et al., 2007), and (2) amenable to management, so that water managers can establish environmental flow standards using these same hydrologic metrics (Poff et al., 2010). This one of the important first steps in defining practical stream management units (Arthington at al. 2006).

New Jersey was one of the first states to classifying river types according to their hydrologic characteristics, using the U.S. Geological Survey's Hydroecological Integrity Assessment Process (HIP) (Henriksen et al, 2006; Kennen et al 2007a). North Carolina is just completing the North Carolina Stream Classification for streams statewide based on hydrologic regimes and other considerations (Mead, 2010). http://www.ncwater.org/Data_and_Modeling/eflows/files. A number of other states have initiated and/or completed efforts for hydroecological classification of their rivers, including Texas (Hersch et al. 2007), Pennsylvania (Apse et al., 2008), and Missouri (Kennen et al. 2009).

## COMPUTING HYDROLOGIC ALTERATION

The ELOHA approach is based on the premise that increasing degrees of flow alteration from baseline or unaltered condition are associated with increasing ecological change. There has been a rapid expansion of the number of methods and software packages available to perform hydrologic alteration analysis and stream classification throughout the Eastern United States and nationally. These include the Hydrologic Assessment Tool (HAT) within the Hydroecological Integrity Process (HIP) (Henriksen et al., 2006), the Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996), and the River Analysis Package (Marsh, http://www. toolkit.net.au/rap) to name just a few. There has also been considerable research into defining which hydrologic statistics appear to be best for future hydroecology studies (Harris et al. 2000; Olden and Poff, 2003; Monk et al. 2007; Kennard 2010).

## FLOW – ECOLOGY RESPONSE RELATIONSHIPS

A key challenge in regional environmental flow standards is developing quantitative relationships between flow alteration and ecological response. Such understanding is essential to support scientifically defensible guidelines for flow standards for broad application to streams and rivers. Over the past decade, there has been accelerated attention and interest in developing a general, quantitative understanding of aquatic ecosystem response to various types and degrees of flow alteration. A growing number of example flow-ecology relationships are being reported in the literature in the Southeast (Freeman and Marcinek 2006; Taylor et al. 2008; Knight et al. 2008; Roy et al. 2008; Rypel et al. 2009; Vokoun and Kanno 2009); and elsewhere (Konrad et al. 2008; Yang et al. 2008).

There has been a rapid expansion in research and focus on the ecological response to hydrologic alteration, including a number of special symposia (e.g., North American Benthological Society 2009 Special Session on Developing Flow-Ecology Response Relations to Support Regional Streamflow Management), publications (Freshwater Biology, Special Issue, Environmental Flows: Science and Management), and sessions (Ecological Flows and Biological Indicators; https://www.benthos.org/Annual-Meeting/2011-Providence/Special-Sessions.aspx).

However, in a recent review of 165 papers that report flow alteration and ecological responses, Poff and Zimmerman (2010) concluded that the existing global literature did not fully support the use of general, transferable quantitative relationships between flow alteration and ecological response. But their results did support the inference that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration. In the absence of explicit flow-ecology relationships, practitioners must use existing literature, models, and existing data to infer these relationships, and this remains as one of the fundamental needs for defensible environmental flow standards.

## MANAGE ENVIRONMENTAL FLOWS THROUGH INFORMED SOCIAL PROCESSES

The science of sustainable flow management can inform flow standards by illustrating the expected ecological consequences of flow alteration. This provides or supports a more explicit understanding of the potential consequences of flow alteration, but decisions about environmental flow standards must then enter the realm of a political decision that is based on a variety of technical, policy, legal, and economic considerations.

Stakeholders and the public must be provided with the information and opportunity to understand and make societal judgments about the desired ecological condition for a river or class of rivers. Like any decision, the final flow standard must be one that is a balance that ideally follows a collaborative public review process and which is made in consideration of local stakeholders' opinions and interests.

## TEXAS AND FLORIDA

Texas and Florida are worthy of particular mention in regards to their programmatic approaches to environmental flow science, though their full description is beyond the scope of this article. Florida is unique because of its minimum flows and levels (MFLs) program started in 1997. MFLs are established for individual waterbodies to protect water resources from significant harm resulting from permitted water withdrawals and to identify a range of water levels and/or flows above which water may be permitted for consumptive use. The technical approaches to MFLs were established during the past decade, and although these approaches used many of the concepts described above, especially the natural flow regime paradigm, they take a different approach (see Neubauer et al. 2008).

Texas in particularly noteworthy for their programmatic approach to determination of basin environmental flows that incorporate many of the concepts described in this article (See http://www.twdb.state.tx.us/instreamflows/pdfs/TIFP_Presentation_final.pdf.).

In 2001, Senate Bill 2 (SB 2) established the Texas Instream Flow Program and set the stage for comprehensive sub-basin level studies to identify instream flow conditions needed to maintain a sound ecological environment in Texas rivers and streams. In 2007, SB 3 established a statewide scientific and stakeholder process for identifying environmental flow needs, including both instream flow needs and freshwater inflow needs for bays and estuaries. After scientific peer review, the Texas Instream Flow Program released a framework calling for multidisciplinary assessments of subsistence flows, base flows, high flow pulses, and overbanking flows. The disciplines included biology, hydrology, geomorphology, water quality, and connectivity. An adaptive management component allows for refinement of flow recommendations at least every 10 years.

## ENVIRONMENTAL FLOWS AND THE CLEAN WATER ACT

The Clean Water Act (CWA) is the principal environmental law that affects state water law. The sole objective of the Clean Water Act (CWA) is to restore and maintain the chemical, physical and biological integrity of the Nation's waters; the CWA requires that states maintain instream water quality standards. Natural variability in river flows plays a vital role in defining ecological communities (Poff and Allan, 1995; Poff et al., 1997; Richter et al., 1997; Biggs et al., 2005), yet to date the CWA has not been widely explicitly used as a basis for setting environmental flow standards. Notable examples of where the CWA has been used include the licensing of some hydroelectric projects where flows for water quality, habitat, or recreation have been mandated through the CWA Section § 401 water quality certification process. In PUD No. 1 of Jefferson County v. Washington Dept. of Ecology, 511 U.S. 700 (1994), the Supreme Court found that States may include minimum stream flow requirements in a water quality certification issued pursuant to § 401 of the CWA insofar as such flows are necessary to enforce a designated use contained in a state water quality standard. As another example, the State of Tennessee uses the CWA and its Aquatic Resource Alternation Permit (ARAP) process as its basis for evaluating alteration of the physical, chemical, radiological, biological, or bacteriological properties of any waters of the State; a definition that includes water withdrawals. The States rules grant to TDEC authority to consider the rate of flow of state waters and loss of stream length or water levels.

Although existing water quality standards implicitly protect flow through narratives for the protection of aquatic life and other measures, recent developments point to the potential for increased involvement of the CWA with environmental flows. EPA Region 4 is moving towards building flow criteria into water quality standards as an explicit standard. In recent letters to Region 4 states, the EPA is encouraging "…all of our states and tribes to consider explicit expression of flow as a water quality standard, either through a narrative standard (i.e., such as that used by Tennessee "…flow shall support the aquatic criteria"), or through a numeric standard (i.e., such as used by Vermont, "no more than 5% 7Q10 change from natural flow regime…"). EPA Region 4 has asked that that these suggested changes be addressed during their 2011-2014 triennial reviews.

## CONCLUSIONS

Increased demands on limited water resources, water shortages, and state water planning and allocation processes highlight the needs for regional environmental flow standards and the limitations of the permit-by-permit approach to setting instream flows. The past decade has brought wide recognition of the importance of natural flow regimes as the conceptual underpinning of sustainable environmental flows and an expanding attention to a framework for developing regional flow standards. Implementation of scientifically credible and defensible regional flow guidelines is a critical step in developing a positive approach to sustainable river management. Additional research and attention is needed to better understand flow-ecological responses, calibrate basin and regional ecological flow guidelines, and improve the corresponding stakeholder and social processes so that environmental flows can be more effectively integrated into riverine system management.

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