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Alternative Environmental Flow Management Schemes

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OVERVIEW: As demand on fresh water increases, water and environmental managers must trade off potentially conflicting uses of this resource, one of which is the maintenance of aquatic ecosystem integrity (Baron et al. 2002, Postel and Richter 2003, Arthington et al. 2006). In some cases, the process of analyzing trade-offs can identify solutions where numerous outcomes benefit (i.e., win-win scenarios, King and Brown 2010). Although the importance of "environmental" or "instream" flows is widely acknowledged, challenges arise in specifically identifying the flow regime needed to obtain a desired ecological state (Richter et al. 1997). Historically, environmental objectives were treated as a constraint whereby a minimum flow level for a given river is identified and used to maintain low flow conditions for critical needs. Although this provides some benefit, a minimum flow approach only addresses a single portion of a river's flow regime (low flows). This approach omits the magnitude, frequency, duration, timing, and rate of change of a river's entire hydrograph and the ecological significance of those parameters both individually and in combination (Poff et al. 1997). This technical note reviews multiple techniques aimed at managing water for environmental and ecological objectives. Review of these techniques is followed by a brief discussion of key considerations in selecting an environmental flow management scheme.

INTRODUCTION: A river hydrograph is a time series of volumetric discharge (i.e., flow rate in cubic feet per second) or stage (i.e., river level). Different portions of a hydrograph may be of interest depending upon the objectives of a particular hydrologic analysis. For instance, a flood risk management project is likely interested in high-stage events, whereas a municipal water supply may be interested in low-flow conditions caused by drought. Likewise, ecological objectives are differentially addressed by a hydrograph, and there is extensive scientific documentation of the ecological importance of all components of a river's flow from natural low flows to floods (Bunn and Arthington 2002). For example, high-velocity conditions may increase physical abrasion and breakdown of organic matter, while low-velocity conditions are critical for residence times governing nutrient uptake. Conflicting social and environmental objectives have led to challenges in defining what is (and is not) an "environmental flow." To overcome this confusion, more than 750 scientists from 50 countries (including scientists from the US Army Corps of Engineers (USACE)) presented a consensus definition as:

> *Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.*
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> Brisbane Declaration (2007)

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This definition highlights the complexity associated with managing water quantity as well as quality. **Provision of water quantity is the focus of this document, but the crucial role of water quality (and its tightly-coupled relationship with quantity) cannot be overstated.**

A common method for conceptualizing a hydrograph is to break down the "flow regime" into its constituent parts, namely: magnitude, frequency, duration, timing, and rate of change (Poff et al. 1997). Although these five components are well-acknowledged in the literature and over 170 hydrologic indices exist (Olden and Poff 2003), a recent examination of 165 peer-reviewed studies found that measurements of ecological responses often remain focused solely on flow magnitude (Poff and Zimmerman 2010). Framing a hydrograph in terms of all five components often assists managers with identifying the portion of the hydrograph most relevant to their objectives. Importantly, these are highly interdependent variables, and many hydrologic metrics combine multiple elements into a single value (e.g., average annual 7-day low flow incorporates magnitude, frequency, and duration). An alternative breakdown of environmental flow components (EFCs) conceptualizes a flow regime as: extreme low flows, low flows, high flow pulses, small floods, and large floods (Matthews and Richter 2007).

Although environmental flow management is often thought of as a purely hydrologic action, the elements of a flow regime may be manipulated using multiple restoration actions influencing hydrology or geomorphology. A common application of environmental flow methods is releasing water from an upstream reservoir. However, a hydrograph could also be manipulated through changes in withdrawal patterns (e.g., by purchasing water rights) or land uses (e.g., stormwater infiltration through installation of pervious pavement, Walsh et al. 2012). Conversely, channel alteration may also be applied to induce a similar effect without changing hydrologic conditions. By modifying channel geometry, a restoration project could change the frequency of floodplain access, depth, or hydraulic radius at baseflow. Generally speaking, Corps planners require techniques to identify ecological response to the changes in hydrographs that result from restoration projects.

ENVIRONMENTAL FLOW ALTERNATIVES: Development of environmental flow alternatives often requires equal parts of social, physical, and life science due to the complex trade-offs involved in water management. As a testament to this complexity, over 200 techniques have been used to develop environmental flows in more than 44 countries (Tharme 2003). **Here, environmental flow alternatives are defined in the general sense of any scheme or rubric for managing water for environmental objectives**. These alternatives may vary from setting a minimum river flow (e.g., Tennant 1976) to identifying thresholds in ecological process from incremental investigation of discharge (e.g., Bovee and Milhous 1978) to expert panel recommendations (e.g., Richter et al. 2006).

Although methods vary widely, six general categories of alternatives have emerged: (1) hydrologic methods, (2) hydraulic rating, (3) habitat analysis, (4) holistic methodologies, (5) optimization, and (6) regionalization. Categories 1 through 4 are well-established in the literature (Jowett 1997, Tharme 2003, Arthington et al. 2003a, Acreman and Dunbar 2004, Kilgour et al. 2005, de Freitas 2008, Navarro and Schmidt 2012). Optimization and regionalization have been added to this list based on recent trends in environmental flow science and literature. The following sections describe each general class of alternatives, discuss techniques within that class, and provide references for further investigation.

Hydrologic methods. The most commonly applied methods for environmental flow management have historically been simple hydrologic rules (Tharme 2003, Acreman and Dunbar 2004). These rules are typically based on hydrologic indices calculated from historically observed discharge data at daily, monthly, or annual time-scales (e.g., Tennant 1976). Often these methods are manifested in a minimum flow level such as the 10-year frequency, 7-day averaged low flow (7Q10; Evans and England 1995), the 2-year frequency, 30-day averaged low flow (30Q2; Peterson et al. 2011), a percentage of mean annual flow (Tennant 1976), a percentage of a flow duration curve (Acreman and Dunbar 2004), or other criteria (Tharme 2003). In some cases, these minimum flows are specified for monthly, rather than annual, periods. However, minimum flows only regulate low flow and do not address high flow, which is broadly acknowledged as a significant short-coming.

Minimum flows are by far the most common hydrologic method, but other simple operational rules are possible. For instance, a "peak shaving" approach encourages water withdrawal during high flows, when withdrawal is a smaller percentage of total river discharge. Alternatively, Richter (2010) and Richter et al. (2011) propose a simple, "sustainability boundary" approach where discharge is allowed to fluctuate within a specified boundary, expressed as a percentage of the natural flow.

Figure 1 provides an example of the impact of two alternative hydrologic methods on an annual hydrograph. Daily discharge data from the Middle Oconee River in Athens, Georgia were obtained from the U.S. Geological Survey (USGS) for 2008 (USGS 2012). Two hydrologic rules were applied: (1) water withdrawal by a 60-million-gallon-per-day pump down to a minimum flow associated with the 7Q10 of 45 cfs (Carter and Putnam 1978), and (2) withdrawal of 29.5% of river discharge each day of the year. While these scenarios withdraw nearly identical volumes of water (1.63 and $1.64 * 10^9$ ft^3, respectively), their impacts on hydrologic variability and low flows are very different. Importantly, these are overly dramatic scenarios not representative of existing conditions, and the hydrograph labeled as "unaltered" actually shows the effects of existing water withdrawals. As such, this example merely demonstrates the type of effect a hydrologic method can have on a hydrograph.

Hydrologic methods are generally intended to provide a desktop technique for rapid application when extensive ecological data collection or analyses are not feasible. These methods are often used in conjunction with existing hydrologic and ecological data to understand the natural range of variability within the flow regime (Richter et al. 1997, 1998; Poff et al. 1997). The ecological significance of these rules should be well-established prior to application throughout a region (Tharme 2003, The Nature Conservancy (TNC) 2009). Methods targeting multiple components of the flow regime (low flows, high flow pulses, floods, etc.) are generally preferred to those setting only minimum flows (Navarro and Schmidt 2012).

Hydraulic rating. Hydrologic data may be translated into hydraulic parameters such as wetted perimeter, wetted cross-sectional area, hydraulic radius, velocity, depth, or shear stress using channel cross-sectional data and hydraulic analyses (e.g., Saint Venant equations). When using hydraulic methods for environmental flows, these parameters are an implicit surrogate for overall habitat provision (Navarro and Schmidt 2012). The relationship between discharge and a hydraulic variable is often examined for critical thresholds or breakpoints, which become minimum flow recommendations (e.g., Figure 2; Gippel and Stewardson 1998). These hydraulic methods may also be used to examine sediment movement, water quality, or other hydraulically mediated processes of interest (Navarro and Schmidt 2012). Although these methods are well-established, Tharme (2003) points out that these methods have shown few recent advances and are largely being used in conjunction with similar, yet more specific, habitat-based methods.

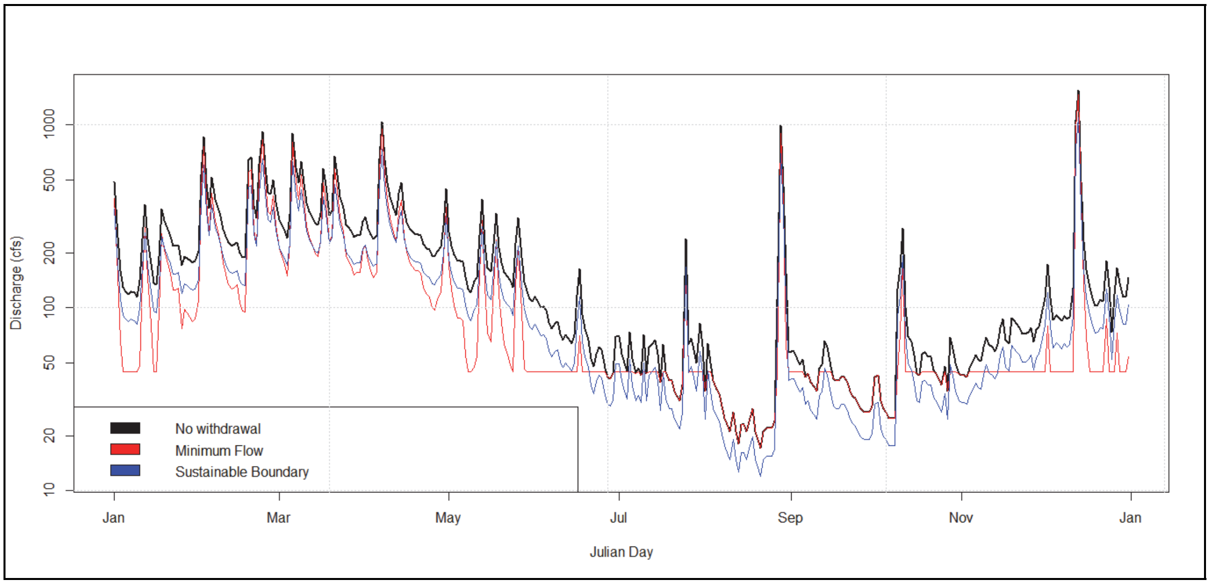

Figure1. Sample hydrograph from the Middle Oconee River near Athens, Georgia (USGS Gage # 02217500) in 2008 showing hypothetical water withdrawal alternatives: a minimum flow standard at the 7-day low flow with 10-year recurrence (7Q10 in red) and a “sustainability boundary” of 29.5% of river discharge (blue).

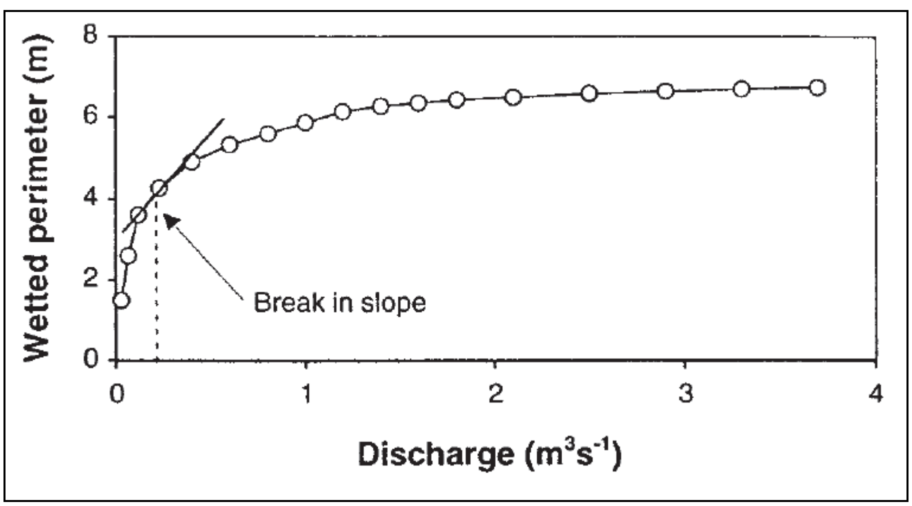

Figure 2. Hypothetical wetted perimeter–discharge relationship (from Gippel and Stewardson 1998).

Habitat analysis. Hydraulic analyses may be used in conjunction with the physical conditions required by key plant or animal species to develop detailed discharge-habitat relationships. These relationships may be developed for a variety of focal taxa for a given study and are often considered in terms of "weighted useable area" (Acreman and Dunbar 2004). This suite of techniques includes the Physical Habitat Simulation (PHABSIM; Gore and Nestler 1998) module of the Instream Flow Incremental Methodology (IFIM; Bovee and Milhous 1978, Nestler 1993), the Riverine Community Habitat Assessment and Restoration Concept (RCHARC; Peters et al. 1995), and a variety of other methods. Habitat analyses have utilized a variety of output formats from steady-state techniques to flow-duration approaches to times series of habitat availability. Furthermore, habitat models have become more precise as resolution of hydraulic models has increased to two and three dimensions and spatial data have become finer in scale. A number of numerical tools exist to facilitate these analyses by importing data from hydraulic programs such as the spatiallyexplicit Ecosystem Functions Model (HEC-EFM shown in Figure 3; Hickey and Fields 2009). Because of the structured analytical approach, these techniques are often more repeatable than other methods (Acreman and Dunbar 2004). Implicit in these methods is the assumption that changes in habitat are directly correlated to changes in a population (e.g., survival and recruitment rates). These analyses are often a critical part of evaluating the feasibility of environmental flows and planning for associated actions such as acquiring floodplain easements or moving levees.

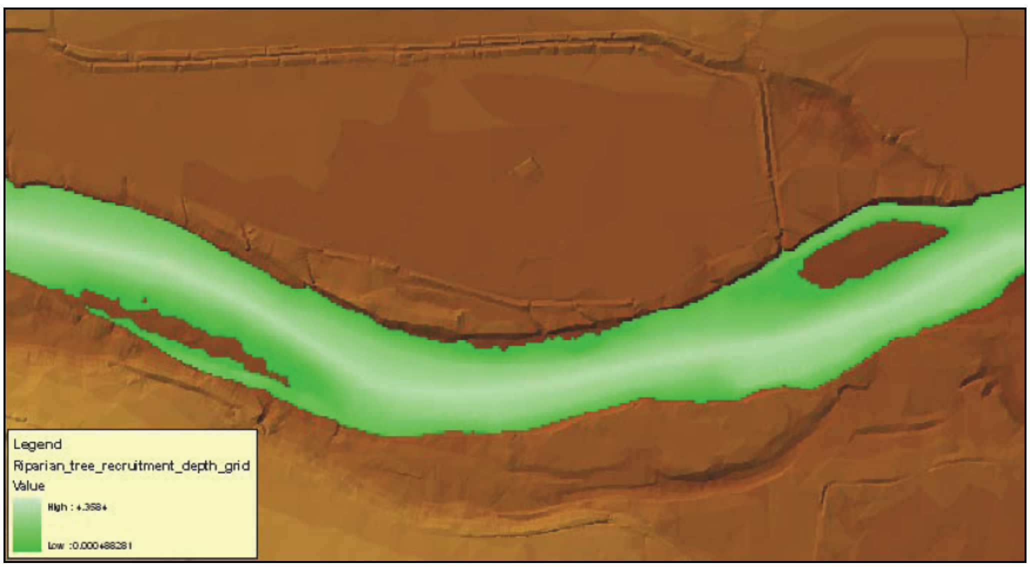

Figure 3. Example of habitat analysis output using HEC-EFM (from Hickey and Fields 2009). The green area shows where hydraulic conditions are suitable for riparian tree recruitment.

Holistic methods. The methods described thus far have focused primarily on general hydrologic and hydraulic conditions as well as habitat for a specific set of target or focal taxa. However, many authors recommend a broader (i.e., more holistic) perspective of the aquatic ecosystem as a whole, and numerous structured approaches have been developed to address ecosystem-wide environmental flow recommendations. Tharme (2003) and Arthington et al. (2003a) provide a thorough review of these methods.

Holistic methods typically consider many components of an aquatic ecosystem including geomorphology, hydraulic habitat, water quality, invertebrates, vertebrates (e.g., fish, mammals, amphibians, birds, and reptiles), adjacent riparian or floodplain vegetation communities, downstream estuarine communities in coastal rivers, and adjacent human settlements. Because many ecological endpoints may be involved, alternative analytical methods may be used varying from empirical methods such as field studies to theoretical methods such as desktop modeling (Arthington et al. 2003a).

When considering multiple ecological outcomes, environmental flow recommendations are typically constructed in one of two logical frameworks (Arthington et al. 2003a). "Bottom-up" construction begins with a null scenario of zero river discharge and adds elements to the flow regime for each ecological process of interest (i.e., a restoration of flow). "Top-down" methods begin with the null scenario of an unaltered hydrograph and remove discharge until undesirable ecological outcomes are reached (i.e., a restriction management threshold). Top-down methods are similar to using a reference ecosystem in restoration design projects (Miller et al. 2012). Some of the most common bottom-up and top-down holistic methods are summarized in Table 1 along with key references associated with each method.

Table 1. Several commonly applied holistic environmental flow management schemes. Modified from Arthington et al. (2003a).

Methodology	Construction	Region of Origin	Key Reference
Building Block Methodology (BBM)	Bottom-up	South Africa	King and Louw (1998), King et al. (2008)
Flow Restoration Methodology (FLOWRESM)	Bottom-up	Australia	Arthington et al. (1999)
River Babingley (Wissey) Method	Bottom-up	England	Petts et al. (1999)
Benchmarking Method	Top-down	Australia	Brizga et al. (2001)
Adapted BBM-DRIFT Method	Top-down	Zimbabwe	Steward et al. (2002)
Downstream Response to Imposed Flow Transformations (DRIFT)	Top-down	Southern Africa	King et al. (2003), Arthington et al. (2003b)
Flow Events Method (FEM)	Top-down	Australia	Stewardson and Gippel (2003)
Ecologically Sustainable Water Management (ESWM)	Top-down & Bottom-up	United States	Richter et al. (2003)
Savannah Process	Top down	United States	Richter et al. (2006)
Integrate Basin Flow Assessment (IBFA)	Top-down & Bottom-up	Africa and Asia	King and Brown (2010)
Ecological Limits of Hydrologic Alteration (ELOHA)	Top-down	International	Poff et al. (2010)

Holistic methods may produce different types of outcomes that communicate the environmental flow recommendations in alternative formats. Figure 4 provides one such example from the Savannah River (Richter et al. 2006). Figure 4a shows the panel's recommendations for one specific location in the watershed incorporating both low-flow and high-flow guidelines. The shaded band captures a range of potential river discharges that explicitly acknowledges the differences in dry and wet years. Figure 4b presents flow recommendations for a second watershed location as they relate to key ecological objectives. This example demonstrates the type of recommendation that may be made using holistic approaches as well as examples of formats that may be used to present that recommendation.

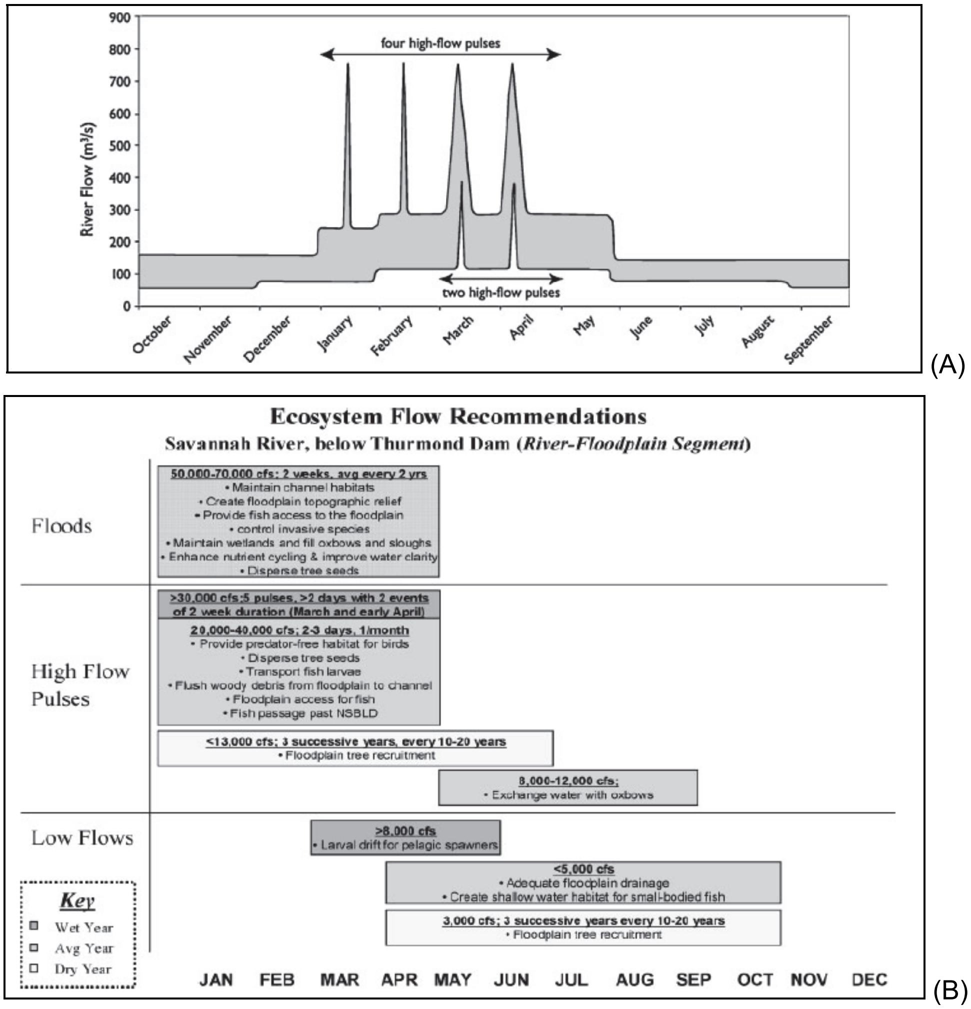

Figure 4. Two alternative presentations of flow recommendations (from Richter et al. 2006).

Optimization. Reservoir operation for non-environmental objectives has historically relied on rule curves that specify release targets throughout a given year. These curves may be written as a set of objective functions and constraints, which may then be subjected to optimization analyses. Recently a number of authors have extended these analyses to include environment flows as objectives, penalty functions, and constraints for optimization (Suen and Eheart 2006; Shiau and Wu 2007; Suen et al. 2009; Chen 2010; Yin et al. 2010, 2012). Although these methods are new, they show great promise when environmental flows may be written as a set of quantifiable objectives and/or constraints. In conjunction with increased computational capacity, development of more sophisticated optimization algorithms will only lead to greater utility of these analyses for environmental flow management. These more sophisticated algorithms are capable of addressing multiple reservoirs in series, multiple competing objectives, and stochastic processes (Labadie 2004).

Regionalization: The most recent suite of environmental flow methods build on prior techniques to define flow recommendations at a regional scale. The Ecological Limits of Hydrologic Alteration (ELOHA) framework approaches environmental flow management from a holistic perspective, which couples interacting scientific and social processes (Figure 5; Poff et al. 2010). The framework represents an internationally collaborative effort to present a consensus framework for environmental flow management, which can be applied to multiple rivers within a region simultaneously. The flexible approach emphasizes hypothesis testing and adaptive management and consists of four primary steps for scientific evaluation: (1) building a hydrological foundation of baseline and altered hydrographs, (2) classifying rivers into regionally distinct types for broad scale application, (3) analyzing flow alterations for each unique river class, and (4) developing flow-ecology relationships for each river type. Although quite new, this framework's broad consensus view and regional approach have already been applied in many states across the United States (Apse et al. 2008, DePhilip and Moberg 2010, Kendy et al. 2012, USACE 2012); Spain (Belmar et al. 2011); China (Zhang et al. 2012); New Zealand (Snelder et al. 2011); and more are in development. Owing to its importance to the ELOHA process, objective techniques are being developed for hydrologic and geomorphic classification (Kennard et al. 2010, Liermann et al. 2011, Olden et al. 2012), although in practice such rigorous classification often is not required (Kendy et al. 2012). In addition to the ELOHA framework, regional statistical methods have been applied to predict both streamflow (e.g., Archfield et al. 2009) and accompanying ecological responses (e.g., Knight et al. 2008).

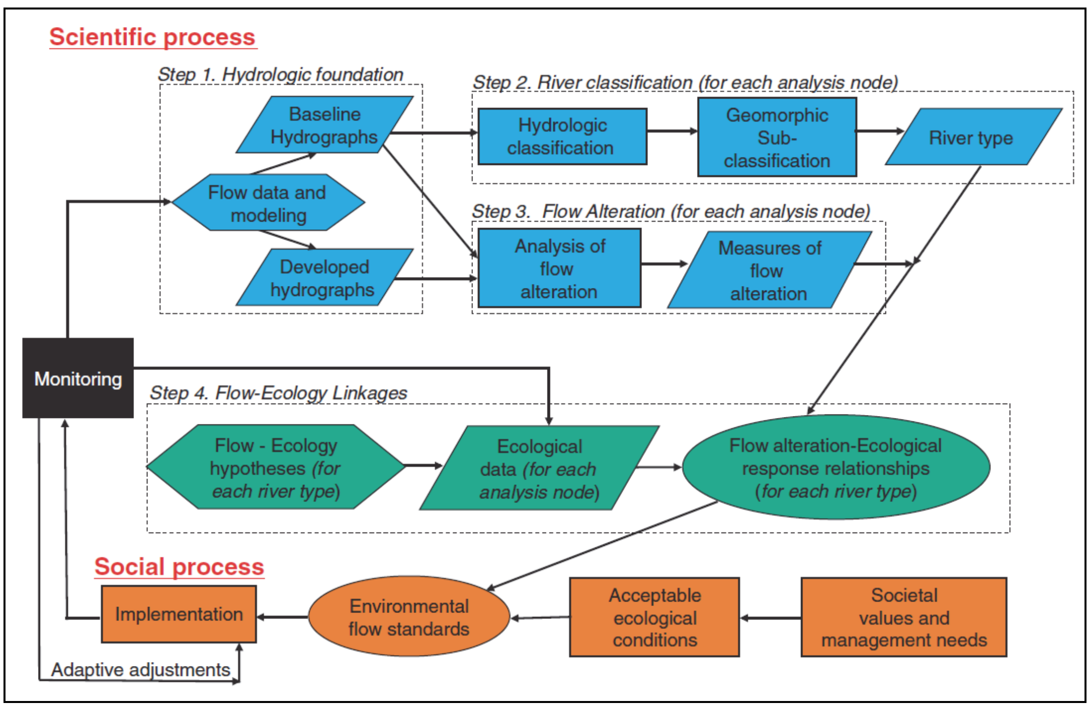

Figure 5. The ELOHA framework (from Poff et al. 2010).

SELECTING ENVIRONMENTAL FLOW REGIMES: No environmental flow management scheme is appropriate to all applications, and in many cases multiple techniques may be applied to a single environmental flow problem (e.g., informing initial decisions with a more basic approach as data is collected for more complex analyses). Table 2 presents a basic comparison of these methods based on prior reviews of the topic (Jowett 1997, Arthington et al. 2003a, Tharme 2003, Acreman and Dunbar 2004, Freeman 2005, Kilgour et al. 2005, de Freitas 2008, Navarro and Schmidt 2012).

Table 2. Comparing alternative environmental flow methods. Developed following tables and text of prior reviews.

Scheme	Strengths	Weaknesses
Hydrologic	• Low resource requirements • Rapid application • Desktop approach • Broad spatial application is simple	• Often results in simplistic, inflexible, or low-resolution outputs • Low ecological relevance • Not site-specific • Flow dynamism is seldom considered • Likely inappropriate for highly controversial decisions
Hydraulic	• Readily available tools and support • Rapid application	• Low ecological relevance • Proxy for habitat • Few recent developments
Habitat	• Repeatable • Predictive • Demonstrated legal precedent • Capacity to examine multiple focal taxa	• Habitat is not necessarily the endpoint of interest (populations are) • Focus on specific taxa rather than ecosystem health • (Often) Limited consideration of flow regime beyond flow magnitude • Significant uncertainty can be associated with suitability indices
Holistic	• Flexible and robust • Broad ecological basis and focus on the whole ecosystem • Multi-disciplinary input • Incorporates socio-economic endpoints • Scalable to data-rich and data-poor environments • Addresses multiple flow regime components	• (Often) Resource- and time-intensive • Reliant on expert judgment • Challenges in reconciling a vision for the river and conflicting judgments • High ecological data or knowledge requirements
Optimization	• Objective development of flow recommendations based on specification of objectives and constraints • Familiar to classical dam operation • Can be used in conjunction with holistic methods	• Numerical expertise required • Developing holistic, quantitative objectives (and a multi-objective combination algorithm) is challenging • “Optimality” may not exist due to incomplete specification of objectives
Regionalization	• Generates flow prescriptions for many rivers and streams in a region, which accelerates implementation • Holistic view of multiple components of the socio-ecological system • Broad spatial application to sites beyond those studied • Multi-disciplinary input • Emphasizes hypothesis-driven, adaptive management	• Regional development may be time- and resource-intensive • Requires significant expertise to facilitate the process (hydrologic foundation, classification, flow alteration, flow-ecology relationships) • Better suited to tributaries than to river mainstems • For any individual site, it’s not as robust as site-specific assessment

Table 2 provides a basis for side-by-side comparison among alternative environmental flow management schemes. However, many of these approaches are often applied simultaneously. For instance, a holistic method may be used to identify objectives and an optimization approach could be applied to numerically identify the flow targets. Alternatively, a habitat methodology could be used as the quantitative criteria for a holistic analysis. Distinguishing between techniques for establishing environmental flow targets, measuring the effects of environmental flows, and implementing flows can be challenging given the intertwining nature of methods.

BEST PRACTICES: Additional considerations are needed to help a project team identify which environmental flows are needed. The following questions often need to be addressed to adequately inform environmental flow decision making, regardless of the method being applied.

- What are the project objectives? As described above, holistic methods often consider many portions of an ecosystem including multiple taxa, hydrologic and geomorphic criteria, and socio-economic considerations. A clear understanding of project objectives can clarify the need for a particular environmental flow component as well as provide a mechanism for measuring the success of a given flow recommendation (Dyson et al. 2003, O'Keeffe and Le Quesne 2009, Sheer 2010). In particular, identification of focal taxa (e.g., threatened and endangered species, keystone species) or processes (e.g., sediment movement) not only focuses the discussion on the importance of a flow component; it also streamlines the analyses undertaken. To date, many analysts have focused on habitat-related outcomes of environmental flows (Petts 2009). However, demographic processes (e.g., survival or recruitment; Bunn and Arthington 2002, Craven et al. 2010, Peterson et al. 2011, Freeman et al. 2012), energetic processes (e.g., food web stability; Cross et al. 2011), and ecosystem processes (e.g., leaf breakdown, nutrient uptake, or primary production; Doyle et al. 2005) are also appropriate metrics to measure the success of an environmental flow regime.
- What is the project scope? The spatial extent of a project influences the selection of environmental flow methods. For instance, collecting fine-resolution habitat data is likely to be prohibitively difficult for large-scale regional analyses (e.g., ELOHA), whereas regional methods may not inform site-specific decision making, while habitat models could.
- What constraints exist? The time and resources devoted to an environmental flow analysis can vary enormously, and the methods applied should be tailored to fit the constraints of a given problem. A few critical items that may drastically influence an analysis include the level of controversy associated with a decision, the availability of expertise, and the accessibility of existing data. Furthermore, there are often physical (e.g., capacity to adjust the shape of a bedrock channel, maximum discharge through a structure) and operational (e.g., non-negotiable water supply uses, public safety) constraints. An up-front documentation of all constraints associated with a project serves as a useful tool for technique selection, project implementation, and negotiation.
- Who should be on the team? Only holistic methods explicitly call for a team or panel approach, but most environmental flow decisions should include a multi-disciplinary team familiar with the local conditions. Depending upon the scale of analysis, the degree of interdisciplinary interaction may vary from simple review to workshop discussion to side-by-side development of an analytical method. Stakeholders, water users, and other constituencies may also be included in decision making, when appropriate (Poff et al. 2003).

- How do we get started quickly? In some cases (particularly controversial or high-profile ones), environmental flow analyses may take significant amounts of time, on the order of years. Because of this lag, many authors (Acreman and Dunbar 2004, Navarro and Schmidt 2012) propose a tiered approach to setting environmental flows with simpler analyses such as hydrologic methods preceding more complex forms, such as holistic methods. Richter et al. (2011) suggest that a sustainability boundary approach provides a strong starting point due to the preservation of flow variability. Under any circumstance, part of the quick-start process should include a literature search to understand general flow-ecology relationships.
- What are key sources of variability within the ecosystem? Many river ecosystems undergo variation such as periodic seasonal effects and catastrophic floods. These elements are often characterized in the description of an environmental flow regime. However, variation can occur over longer time scales as well (e.g., wet versus dry years, multi-decadal oscillations, climate non-stationarity). Some of the more robust environmental flow recommendations plan on this variability and contain drought contingencies (e.g., Savannah River planning in Figure 4, Richter et al. 2006).
- Is discharge (or flow) the "master" variable? River discharge is often assumed to be the key driving force or "master variable" in river ecosystems, but this is not the case for many conditions. Discharge may be mediating other processes and conditions such as velocity or shear stress, or another driving force may be governing system dynamics such as temperature (Olden and Naiman 2010, Poff et al. 2010). Care should be taken not to over-emphasize the importance of discharge if other aspects of system dynamics also need to be addressed.
- What time scale is appropriate to a given ecological process? Daily and/or monthly discharge data are often used in environmental flow recommendations. Many ecological processes respond to different time scales, and appropriate consideration of time scale is critical to useful flow recommendations (Richter and Thomas 2007, Shen and Diplas 2010). For instance, a single fish species could show movement response on the scale of minutes, habitat utilization on the scale of hours, and survival on the scale of weeks or months. Hourly changes in stage associated with hydropower or withdrawal peaking could easily affect all three of these time scales. Minimally, the time scale of recommendations (e.g., Is the minimum flow an instantaneous or daily averaged threshold?) should be considered for each process of interest.
- How are experts used in the process? Many environmental flow methods rely on an expert panel for various parts of the process (e.g., threshold identification, habitat suitability indices, or holistic flow recommendations). Cottingham et al. (2002) and Arthington et al. (2003a) offer the following best practices for working within a panel approach (many of which apply beyond environmental flow decisions).
    - Prior to flow recommendations, clearly identify the processes for selecting panel members (e.g., discipline-specific scientific experts versus stakeholders), protocols for panel conduct (e.g., consensus versus majority decision), and the interaction between panelists (e.g., workshop, correspondence, data transfer, etc.).

  - Develop a clear vision statement and accompanying management objectives, which may then be applied to measure success or adaptively manage outcomes.
  - Develop guidelines for the selection of field sites, collection of new data, and data quality management.
  - Acknowledge uncertainty associated with environmental flow recommendations and identify a mechanism for documenting limitations of some lines of evidence.
  - Consider both the social and environmental implications of flow recommendations.
  - Develop a standard process for presentation and documentation of findings.
  - Make recommendations on additional information needed to improve future decision making and strengthen the scientific basis for environmental flow decisions.
- <u>How can hypotheses be tested</u>? Environmental flow recommendations always contain uncertainty and should be considered hypotheses regarding the response of a stream ecosystem to a given driver (usually discharge). Environmental flows and their ecological outcomes should be monitored to validate hypotheses and adaptively manage accordingly (Poff et al. 2003, Richter et al. 2003, Postel and Richter 2003). In some cases, environmental flow releases may be experiments used to test a hypothesis (Konrad et al. 2011), in some cases leading to unexpected conclusions (Cross et al. 2011). “Top-down” methods should be carefully monitored to avoid crossing tipping points or irreversible thresholds.
- <u>What is the reference condition</u>? As with many restoration projects, the choice of an appropriate reference condition can influence many aspects of the project (Miller et al. 2012). Many rivers have relatively short discharge records, which often reflect significant amounts of human impact. Reference conditions should be chosen in light of this fact to avoid creating a “shifting baseline” where expectations are consistently lowered through time.
- <u>Where is the project positioned in the watershed</u>? Rivers are embedded within their watershed networks. A project’s position within this network may influence environmental flow decision making (Dyson et al. 2003), and watershed-scale planning can highlight opportunities that may otherwise go unnoticed (King and Brown 2010). For instance, a channel reconfiguration project may not be as successful if there is significant change in the upstream watershed due to land use development. Conversely, a reservoir management project may influence not only the reach directly downstream of the dam, but many dozens or hundreds of miles of habitat and an accompanying estuary or near-shore zone.
- <u>What tools exist</u>? Fortunately, many numerical tools have been developed to support environmental flow decision making. Models ranging from spreadsheets to location-specific computational scripts may be useful, but a few tools have recently been developed with this application specifically in mind; these new tools (listed below) are particularly germane to this discussion.
  - Indicators of Hydrologic Alteration (IHA; Richter et al. 1996)
    - Calculates characteristics of natural and altered flow regimes.

        - http://conserveonline.org/workspaces/iha
    - Physical Habitat Simulation (PHABSIM)
        - Simulates relations between streamflow and physical habitat.
        - http://www.fort.usgs.gov/Products/
    - Mesohabitat Simulation Model (MESOHABSIM)
        - Simulates relations between streamflow and physical habitat at larger scales.
        - http://www.mesohabsim.org/
    - Ecosystem Functions Model (HEC-EFM)
        - Quantifies ecosystem responses to streamflow.
        - http://www.hec.usace.army.mil/software/hec-efm/
    - Regime Prescription Tool (HEC-RPT)
        - Facilitates entry, viewing, and documentation of flow recommendations.
        - http://www.hec.usace.army.mil/software/hec-rpt/
    - System of Environmental Flow Analysis (SEFA).
        - Simulates relationships between streamflow and physical habitat.
        - http://sefa.co.nz/
- What is the institutional, legal, and cultural framework? As environmental flow methods have developed, increasing recognition has been given to the importance of the administrative, legal, and cultural context of a watershed (King and Brown 2010). An adequate, upfront understanding of the setting and constraints could help avoid conflicts both within the team and with existing regulations (Dyson et al. 2003, Hirji and Davis 2009, O'Keeffe and Le Quesne 2009).

SUMMARY: Although significant progress has been made, environmental flow science remains young, and many lingering questions persist, particularly with respect to assessing ecological response to changes in flow regime (Petts 2009). This Technical Note has presented six alternative schemes for developing environmental flow recommendations as well as a number of considerations for selecting a technique. Via the Sustainable Rivers Project (http://www.iwr.usace.army.mil/Missions/Environment/SustainableRiversProject.aspx), The Nature Conservancy and the U.S. Army Corps of Engineers have developed case studies demonstrating application of many environmental flow techniques. Regardless of the methods applied, environmental flow recommendations, minimally, must consider: (1) the five characteristics of each flow regime component, (2) social and ecological trade-offs associated with alternative actions, (3) key assumptions and uncertainties of the approach taken, and (4) how these uncertainties can be reduced over time through monitoring and adaptive management.

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