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A Social-Ecological Framework to Integrate Multiple Objectives for Environmental Flows Management

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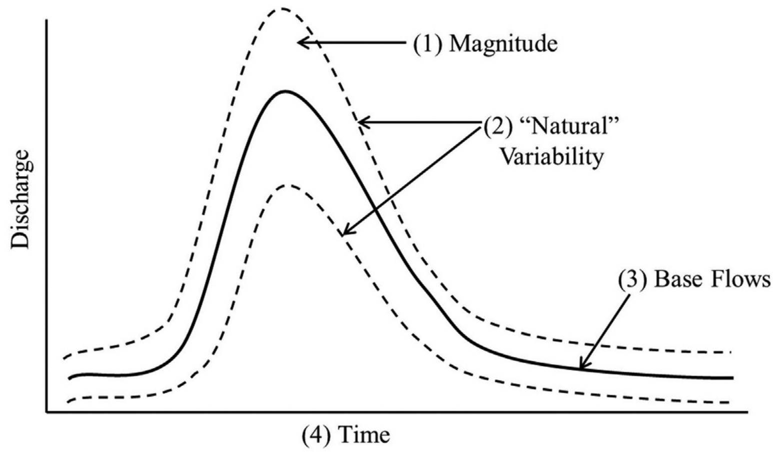
Abstract: "Environmental flows" is a research discipline that emphasizes freshwater allocation in rivers to sustain desired ecological conditions and human well-being. The basis for environmental flow requirements has traditionally relied on hydrological and ecological data. Contemporary methods focus on detailed hydro-ecological relationships within river ecosystems; however, there is currently no structured approach to systematically incorporate socially relevant data into the environmental flows discipline. To address this limitation we developed a flexible framework that applies a social-ecological systems approach to account for multiple flow-related objectives that reflect both biophysical sustainability and societal preferences. First, we conceptualize the freshwater social-ecological system as a hierarchy of human and environmental domains. Then, we recommend stepwise procedures to assess flow-related vulnerabilities of important system attributes, address their feedbacks, and translate these assessments to a common classification for comparative analyses that guide holistic flow management decisions.

Keywords: *Environmental flows, social-ecological systems, river management*

Unique management challenges over freshwater have been developing throughout the world over the last century (Postel 2000; Postel and Richter 2003). Appropriation of freshwater from rivers to meet human needs and socio-economic development is made difficult by withdrawals for competing demands (Gleick 1998; Poff et al. 2003; Vörösmarty et al. 2010) and from external climate drivers (Bates et al. 2008; Beniston 2003). Additional pressures are put on the availability of freshwater resources for non-consumptive uses like recreation and environmental conservation. Recent legal recognition of the "beneficial use" of non-consumptive needs for instream flows in U.S. state statutes (Mathews 2006) is an important step towards legitimizing the preservation and restoration of healthy, functioning river ecosystems (Baron et al. 2002).

"Environmental flows" is a science-based discipline that emphasizes the beneficial use of instream flows in rivers. The discipline has developed out of growing knowledge that the ecology of the river is coupled with natural patterns of streamflow variability; this is formalized in Poff et al. (1997) as the natural flow regime paradigm. Research on environmental flows typically begins by using daily stream gauge data to derive and compare flow regimes in river hydrographs, which are graphical depictions of fluctuating river discharges per unit of time (Figure 1). Hydrographs are fundamental for establishing flow-ecology relationships (Poff et al. 2010), which define how ecological variables change in response to deviations in flow from natural, baseline conditions. These relationships require two basic steps. First, the statistical derivation of flow metrics (Richter et al. 1996; Olden and Poff 2003) explain important disturbance characteristics of the flow regime such as magnitude, frequency, seasonal timing, duration, and rate of change. Second, flow metrics are used to model hypothesized effects on the biophysical components of a river system (Arthington et al. 2006; Poff et al. 2010).

The natural flow regime provides a range of flow characteristics that facilitate conditions responsible for maintaining ecological structure and function of rivers and streams (Poff et al. 1997). Natural disturbances and human impoundments like dams and diversions cause alterations to the flow regime,



(1) Large and peak floods allow access to floodplains at the right time for spawning fish, vegetation recruitment, flushing sediment
(2) Overall flow variation maintains habitat (channel and floodplain)
(3) Base flows provide adequate wetted habitat
(4) Timing used as cues for organismal life history characteristics

Figure 1. Example of a river hydrograph, typical flow regime characteristics, and examples of their hypothesized effects.

which impair the distribution and abundance of aquatic organisms, water quality, and the ecological integrity (i.e. unimpaired condition) of the river ecosystem. Several mechanisms that underlie these impairments include (Bunn and Arthington 2002):

1. Undesirable modifications to river biophysical habitat and processes;
2. Loss of life history cues for aquatic organism survival and recruitment;
3. Loss of longitudinal and lateral connectivity upstream, downstream, and across the river and its floodplain;
4. Encouraging exotic species proliferation.

An Environmental Flow Requirement (EFR) (Tharme 2003) is a flow regime that targets desired ecological conditions through statistical deviations between a river's un-altered and altered flow regime. Flow-ecology relationships are typically used to prescribe EFRs and can be visualized as statistically derived trade-offs between percent flow alteration and ecological condition.

The methods for establishing EFRs were traditionally driven by hydrologic and biophysical data requirements for small-scale river flow management. The earliest holistic methods embodied an ecosystem-based management approach but lacked a social component (Poff and Matthews 2013). Contemporary holistic methods extend management considerations to societal and ecological objectives. Although the holistic methods advocate multiple freshwater needs, they lack structured approaches to assimilate and screen different types of data.

This paper extends the current practice from holistic environmental flows management to include an understanding of societal objectives expressed through socio-economic data. We frame this discussion by beginning with a historical assessment of hydrological and biophysical considerations for flow management. Next, we review several contemporary and holistic methods that integrate socio-economic data to assess how flow alterations affect societal objectives. We end by presenting a conceptual framework that systematically assimilates relevant data from societal and ecological objectives to support holistic environmental flows management.

Traditional Criteria for Environmental Flows: Hydrologic and Biophysical Data

Hundreds of methods for assessing environmental flows have been developed to address river ecosystem condition (Tharme 2003).

Table 1. Selected reference list of environmental flow methods and relevant data by class. Information in this table is a sub-set of methods and is provided to illustrate the breadth of the existing knowledge base and data requirements.

Class	Example Methods	Relevant Data	Metrics	Source
Hydrologic	Tennant Method	Percentage of mean annual flow (MAF) for two six month seasonal periods	Recommended % of MAF	Tennant 1976
	Range of Variability	Multiple years of daily flow records (e.g. stream gauge, groundwater wells)	32 statistically-derived hydrologic metrics	Richter et al. 1996, 1997
	"Percent of Flow" approaches	Observed or modeled "unaltered" daily flows	% deviation above and below "natural" flow regime	Richter et al. 2012
Hydraulic Rating	Wetted Perimeter Method	Cross-section width of the stream bed and banks in contact with water for various discharges;	Relationship between discharge and wetted perimeter	Gippel and Stewardson 1998
	R-2 Cross Method	Hydraulic parameters for mean depth, percent of bankfull wetted perimeter, and average water velocity	Plots of wetted perimeter vs. discharge	Nehring 1979
Biophysical Habitat	Instream Flow Incremental Methodology	Species data: preferred hydraulic habitat attributes by life history stage; channel geometry; modeled flow-hydraulic attribute relationships (PHABSIM)	Weighted Usable Area (WUA) versus discharge function	Stalnaker et al. 1995; Milhous 1998
	Physical Habitat Simulation Model (PHABSIM)	Cross-section data: depth, velocity, substrate, cover, WUA	Habitat suitability indices	Milhous and Waddle 2012
	Biological Response Modeling	Flow associations for macroinvertebrate taxa; flow parameters associated with community structure	Lotic invertebrate Index for Flow Evaluation	Extence et al. 1999
Holistic	Building Block Methodology	Discharge data; cross-section data; hydraulic characteristics; fish and macroinvertebrate data; riparian vegetation surveys	Monthly flows that describe regime types to meet modeled ecological conditions	King and Louw 1998
	Riparian vegetation-flow response guilds	Hydrologic characteristics for stream classes; functional response traits of riparian plant species; empirical flow response guild relationships	Predictions for riparian trait occurrence; vegetation-flow response guilds	Merritt et al. 2010

Most methods involve a simplified assessment of the river ecosystem and the development of flow-ecology relationships for biotic and abiotic conditions. The methods fall into four general classes: hydrologic, hydraulic rating, habitat simulation, and holistic methods (Acreman and Dunbar 2004; Tharme 2003). Each class of methods has a common conceptual basis for their approach but often differ in their data requirements or in their selection of flow regime metrics to model flow-ecology relationships (Table 1). Hydraulic rating methods, for example, typically assume a strong importance on geomorphology and physical habitat characteristics like river depth, velocity, and sediment substrate. All classes of environmental flows methods require hydrological flow data that are typically provided by stream gauges.

Hydrologic methods represent the simplest of the four classes and typically define acceptable minimum base flow discharge requirements on the basis of a proportional flow volume. More sophisticated hydrologic methods incorporate additional criteria representing biological, hydraulic, or other desired endpoints tied to specific characteristics of the flow regime. Hydraulic rating methods assess relationships between discharge data and hydraulic variables (e.g., instream wetted width, depth) that are used to quantify thresholds for critical instream habitat (Acreman and Dunbar 2004). This may include a specific magnitude and duration of flow required to mobilize instream sediment and scour the channel bed. More complex habitat simulation or physical habitat methods extend this idea to model how changes in discharge affect physical conditions that influence the habitat suitability for target organisms (Booker 2003).

Traditional holistic methods have embodied the perspective of ecosystem-based management, emphasizing large-scale linkages between riverine, riparian, and wetland environments (Acreman and Dunbar 2004). The earliest attempts to incorporate holistic methods established multiple EFRs that specified the timing of acceptable river flows needed to simultaneously achieve multiple environmental objectives like channel maintenance, habitat maintenance and fish spawning and migration (King and Louw 1998). Despite their focus on ecosystem-based management, most of the holistic methods do not include formal frameworks to incorporate socio-economic data that capture societal perspectives on desired ecological endpoints.

Contemporary Social Contexts and Relevant Data

Environmental flows assessments have extended beyond the traditional hydro-ecological research domain into broader river management methods that integrate both ecosystem maintenance and societal objectives like water supply and recreation. At its core, integration of societal objectives requires linking socio-economic conditions with flow variables. In practice, this entails understanding how alterations to a river's hydrograph affect the ecosystem services or benefits supplied to society. For example, recreational visitor days for fishing or whitewater boating are potentially impacted by streamflow alterations (see e.g., Daubert and Young 1981). Socio-economic data like these can be used to derive relationships that describe how social benefits are related to important flow regime characteristics (Sanderson et al. 2012). To date there are limited efforts to actively incorporate societal objectives into EFRs, despite the fact that such incorporation is critical for successful implementation of environmental flow targets (Pahl-Wostl et al. 2013; Poff et al. 2010). We review several common methods for their approaches to integrate socio-economic data requirements into the environmental flows discipline.

The Ecologically Sustainable Water Management framework attempts to design and implement a water management program that establishes EFRs in an open dialogue among stakeholders (Richter et al. 2003). This framework is developed to a large extent using a priori information on the impacts that dams place on river ecology. Ecologically Sustainable Water Management attempts to rehabilitate flow regimes as storage release decisions that use the historical range of variability approach to EFRs (Richter et al. 1997).

The Downstream Response to Imposed Flow Transformation is considered a holistic method that was established for water development projects in South Africa (King et al. 2003). Downstream Response to Imposed Flow Transformation's decision support framework generates multiple scenarios that each describe alternative river ecosystem conditions with varying ecological and socio-economic condition estimates (Brown and Joubert 2003). This information can be used by decision makers for future watershed planning purposes. Downstream Response to Imposed Flow Transformation's sociological module allows for the assimilation of socio-economic data like fish catch, vegetable harvest, and drinking water volume. The resulting relationships are explained as varying degrees of human health risk that correspond to alternative flow scenarios (King et al. 2003). The framework relies on a priori communication with subsistence users of the river ecosystem.

The Ecological Limits of Hydrologic Alteration framework supports large-scale watershed management by classifying hydrologically similar rivers as the basis for developing regional flow-ecology relationships (Poff et al. 2010). The Ecological Limits of Hydrologic Alteration process occurs in two phases: i) a series of science-based steps that specify a regional hydrologic foundation, classification of river types using hydrologic or geomorphic data, and derivation of flow-ecology relationships with biological data; and ii) a social step that integrates societal management needs with EFRs to improve river management policy decisions. Current applications of this framework (Kendy et al. 2012) emphasize the importance of Ecological Limits of Hydrologic Alteration's social process but offer limited guidance for taking steps to accommodate societal objectives.

A Social-Ecological Systems Approach to Flow Management

The contemporary methods for environmental flows management lack a structured approach to integrate ecological and socio-economic data. Such a framework is needed to support multi-objective flow management. To address this limitation, we envision a screening process that accommodates multiple flow-ecology relationships and socially derived flow-related relationships. Our approach is through the research lens of social-ecological systems (SES), a discipline that conceives of managed systems as an aggregation of linked social (e.g., institutions, property rights, behavior) and ecological (e.g., environmental resources) sub-systems (Berkes and Folke 1998). SES research integrates important information from these sub-systems by establishing relationships between ecological and social conditions.

First, we define the freshwater SES as a hierarchy of environmental and human organizational domains. The domains interact through feedbacks to influence overall system behavior, which we define as the ability to achieve a balance between desired societal and ecological objectives. Our characterization of a freshwater SES is based on human institutions for resource management (e.g., ethical and legislative rules, behavior) and adapted from the hierarchical decision systems approaches of Ciriacy-Wantrup (1967) and Ciriacy-Wantrup and Bishop (1975).

Our hierarchical representation of the freshwater SES (Figure 2) includes, at its foundation, the ecosystem, which provides goods and services that facilitate human endeavors at higher levels (Daily 1997). Distinct operational and community domains within the second level of the hierarchy operate through direct interaction (i.e., monitoring and use) with freshwater ecosystems. Operational entities may include irrigation districts, water conservancy districts, academic institutions, dam operators, or water rights holders. The community refers to public elements such as water consumers and other beneficiaries reliant on flow-related sustenance and recreation (i.e., ecosystem services). The institutional domain consists of members who regulate the operation and use of water resources (e.g., Bureau of Reclamation, U.S. Army Corps of Engineers) and conduct appropriate assessments of the freshwater ecosystem (e.g., Environmental Impact Statements). The policy domain of the hierarchy may grant or restrict rights and change the regulating responsibilities of the institutional domain like state soil and water conservation boards, the Environmental Protection Agency, or the use of Threatened and Endangered Species Act designations.

To understand how a freshwater SES functions, identification of system boundaries is followed by an assessment of system performance indicators we term "attributes." System boundaries are defined for each management context. For watershed-based management, the system may be defined at multiple scales depending on the management objectives. For example, Beechie et al. (2010) partition a catchment into watershed and reach scales for defining distinct ecological outcomes. Attributes of a freshwater SES serve as comprehensive, measurable, and manageable proxies for management objectives. We select socially desirable attributes on the basis that they are amenable to flow management decisions.

We developed a framework that extends a SES approach to integrate many types of data into the environmental flows discipline (Figure 2). Our goal with the framework is to provide a systematic account of relevant water data from relevant domains of a freshwater SES and to use the data to assist in integrative environmental flows studies and decision-making.

The framework consists of six steps:

1. Identify the target scenario and define objectives;
2. Determine relevant domains of the freshwater SES;
3. Identify target social-ecological attributes from relevant SES domains;
4. Assess flow-related vulnerabilities of the attributes through expert opinion and/or data analysis;

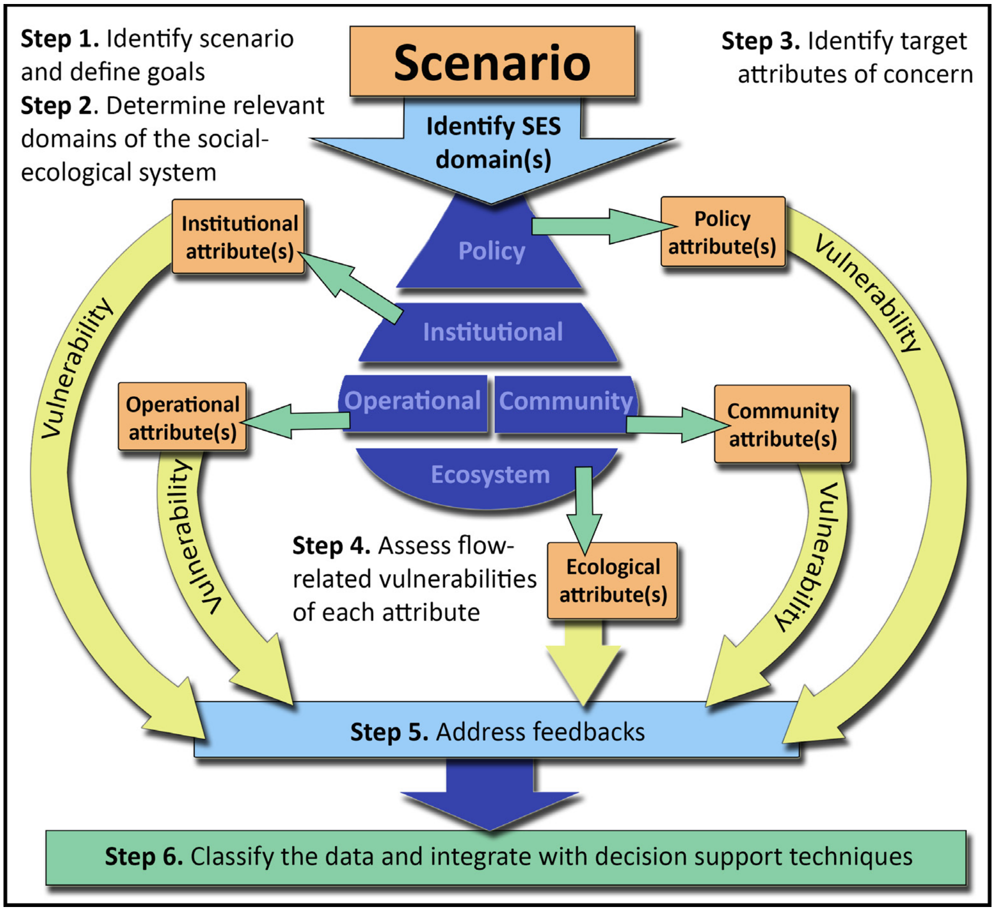


Figure 2. Hierarchical representation of a social-ecological systems approach to flow management.

5. Address feedbacks among system attributes;
6. Classify the data and integrate using decision support techniques.

Steps 1 through 3 in Figure 2 are the data assimilation phase and may be achieved with various stakeholder activities that include but are not limited to: i) focus group meetings to enhance an understanding of the problem and how flow-related data may be effectively used in its analysis; ii) formulate several future climate or management (e.g., water supply) scenarios that may impact the seasonal magnitude and timing of flows; iii) use existing data or perform limited empirical modeling of system components to understand relevant flow-response conditions with respect to the problem scenario(s).

Table 2 provides a growing knowledge base on the different kinds of relevant water data that may be useful for future holistic approaches to environmental flows management. We provide data from the current environmental flows literature that can be used as reference information for identifying SES domains and attributes to develop flow-related relationships. We anticipate this field of research to grow and incorporate flow needs for a multitude of management objectives.

We consider vulnerability in Step 4 as a function of a flow alteration scenario. We measure vulnerability for each attribute by quantifying flow-related condition estimates. In other words, we construct a relationship between the flow regime and the attribute's condition and use that information to assess the effect of a flow alteration scenario. Expert opinion and/or empirical analysis (e.g., results from aforementioned methods Ecologically Sustainable Water Management, Downstream Response to Imposed Flow Transformation, Ecological Limits of Hydrologic Alteration) may be used to derive condition estimates of the attributes for a scenario. Likewise, empirical results of some attributes may be

Table 2. Selected reference data for SES analysis of environmental flows. Each attribute is a manageable performance indicator that corresponds to a domain within the SES from Figure 2.

SES Domain	Social-Ecological Attributes	Relevant Data	Source
Ecosystem	Hydrological Physical Habitat/Hydraulic Biological	Flow regimes estimates and metrics that correspond to biophysical indices (see Table 1)	
Community	Cultural Services		
	-Indigenous harvest species	Catch per unit effort	Finn and Jackson (2011)
	Ecosystem Services		
	-Recreational fishing	Preference survey estimates of willingness to pay for optimal flow ranges	Daubert and Young (1981)
	-Recreational whitewater	Estimated visitor days for optimal flow ranges	Sanderson et al. (2012)
Operational	City Water Quality Standards	Instream nutrient loading exceedence functions	N/A (attribute is a suggestion)
	Agricultural	Percent change of water storage capacity based on instream ecological and policy needs	Grantham et al. (2013)
Institutional	Water Rights	Instream flow availability based on fulfillment of senior water allocations	N/A (attribute is a suggestion)
	Threatened and Endangered Species	Instream flow requirements based on federal regulations	Sanderson et al. (2012)

used alongside alternative data sources that pertain to other relevant attributes. We stress, however, that results of disparate methods must be translated into common values (e.g., "Low," "Medium," "High") in order to enable the simultaneous comparison and evaluation of all attributes. To illustrate, flow-related ecological and socio-economic data modeling may be used with expert opinion to decompose a vulnerability estimate into exposure, sensitivity, and resilience criteria values (Turner et al. 2003) (Table 3).

Step 6 of our framework recommends that attribute condition values are integrated under a management decision context. An example decision context can begin by asking: What attributes are worth managing? In this example, the step is designed to prioritize the attributes based on comparing their vulnerabilities under alternative flow scenarios (Table 3). This step of the framework is similar to the Downstream Response to Imposed Flow Transformation Method's current focus (King and Brown 2006) and we assert that quantitative methods from decision analysis (Howard 1988) are better suited for integration. Decision analysis combines methods from systems theory and decision theory, allows for the assessment of scenarios that have multiple sources and types of attribute data, and addresses feedbacks (Step 5) if strong links can be made among them. We make these recommendations based on challenges from the academic literature to establish a common classification framework to facilitate SES research (Ostrom 2009) and to blend evolved methods from decision theory with contemporary integrative research methods like scenario planning and resilience theory (Polasky et al. 2011).

The Quest for Holistic Flow Management

The challenge to sustain freshwater ecosystem conditions while satisfying consumptive and non-consumptive uses lies at the complex interface of ecological science and social science. Lasting

Table 3. Example evaluation matrix for scenario planning on a single, hypothetical scenario ("A"). The definitions for vulnerability criteria are uniquely tied to each attribute and intentionally not defined here. Attributes are stakeholder defined and defined in specific metrics and units. Estimates of attribute condition (based on unit data) are translated into a common ordinal scale of criteria values, which are uniquely defined for each attribute. Management priority depends on the decision context. In this example scenario, stakeholders want to know which attributes will be most vulnerable ("1") or least vulnerable ("4").

Flow Scenario "A"

Attribute	Expert/Empirical Data		Vulnerability Criteria			Management Priority
	Metrics	Units	Exposure Value	Sensitivity Value	Resilience Value	
Native Fish	Discharge (% alteration); wetted perimeter	Seasonal fish abundance	Low	Moderate	Good	4
Recreational Whitewater	Discharge (% alteration)	Seasonal usable days	High	Very Low	Fair	3
City Water Quality	Discharge (% alteration); nutrient loading	Parts per million	High	High	Fair	2
Agriculture	Discharge (% alteration); storage capacity	Square kilometers	Medium	Very High	Poor	1

solutions will require blending ecological theory with social science methods in an open dialogue with collaborations among ecologists, biologists, geomorphologists, economists, watershed planners, and other, non-technical stakeholders. This paper reviews traditional approaches for making EFRs and highlights the need for a systematic approach to account for and integrate societal objectives for holistic environmental flows management. Our framework operationalizes the multi-objective integration needed for sustainable river management.

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