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Organizing Environmental Flow Frameworks to Meet Hydropower Mitigation Needs

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Abstract The global recognition of the importance of natural flow regimes to sustain the ecological integrity of river systems has led to increased societal pressure on the hydropower industry to change plant operations to improve downstream aquatic ecosystems. However, a complete reinstatement of natural flow regimes is often unrealistic when balancing water needs for ecosystems, energy production, and other human uses. Thus, stakeholders must identify a prioritized subset of flow prescriptions that meet ecological objectives in light of realistic constraints. Yet, isolating aspects of flow regimes to restore downstream of hydropower facilities is among the greatest challenges of environmental flow science due, in part, to the sheer volume of available environmental flow tools in conjunction with complex negotiation-based regulatory procedures. Herein, we propose an organizational framework that structures information and existing flow paradigms into a staged process that assists stakeholders in implementing environmental flows for hydropower facilities. The framework identifies areas where regulations fall short of the needed scientific process, and provide suggestions for stakeholders to ameliorate those situations through advanced preparation. We highlight the strengths of existing flow paradigms in their application to hydropower settings and suggest when and where tools are most applicable. Our suggested framework increases the effectiveness and efficiency of the e-flow implementation process by rapidly establishing a knowledge base and decreasing uncertainty so more time can be devoted to filling knowledge gaps. Lastly, the framework provides the structure for a coordinated research agenda to further the science of environmental flows related to hydropower environments.

Keywords Dams · Rivers · Regulation · Policy · Environmental flow · Hydrology

Introduction

The global recognition of the natural flow regime (i.e., the dynamic quantity, timing, and variation of natural stream flows, Poff et al. 1997) has led to increased pressure from environmental stakeholders on hydropower dam owners to

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modify operations with the intention of improving conditions for aquatic ecosystems. Alteration of natural flows leads to changes in river structure and function (Carlisle et al. 2011; Taylor et al. 2014). Not surprisingly, pressures have increased on dam operators to move away from highly altered hydrologic conditions (e.g., peaking operations) to more natural conditions (e.g., run-of-river operations) at the expense of energy losses and based on the justification that downstream biological communities will improve under more natural flows.

Although many examples exist where project operations have moved from highly altered flows to more natural conditions (Jager and Bevelhimer 2007; Haas et al. 2014), a complete reinstatement of the natural flow regime is unfeasible for many project operations due to energy losses, controlled reservoir levels, and reductions in other services provided by the projects (e.g., recreational boating releases and tailwater fisheries). In a hydropower context, there are usually multiple competing users of water beyond just energy production and river ecosystem needs. Stakeholders may desire flow regimes that compromise reservoir habitat, recreational boating or fishing, or sensitive habitats downstream (e.g., loss of spawning substrates). Other constraints may include factors outside the control of project operations, such as substantial losses in total flow due to irrigation requirements, limitations by existing dam design and infrastructure (Lessard et al. 2013), or lack of operational flexibility in providing optimal conditions (Uría-Martínez 2015). Complexities arising from the multidimensional nature of balanced water demands are compounded by uncertainties in the ecological responses to prescribed flow regimes.

A reasonable compromise is found by identifying key flow characteristics that support healthy aquatic communities (Richter 2010) and using that information to identify possible mitigation opportunities in light of operational constraints (Lessard et al. 2013). Certainly, restoring key aspects of flow regimes (e.g., minimum flows) has proven ecologically effective in many regulated river systems (Travnicheck et al. 1995; Propst and Gido 2004; Lamouroux et al. 2006). Other studies, however, have shown that flow enhancement alone did not meet predefined ecological goals due to limitations by other constraints (Bednarek and Hart 2005; Krause et al. 2005; McManamay et al. 2013a). Identifying and prescribing flow regimes for improving downstream conditions may require consideration of ecological and social constraints that do not necessarily fall in line with traditional environmental flow (e-flow) science. Defining these key flow elements that improve downstream river communities is among the most pivotal concerns of e-flow science (Richhter et al. 1996; Poff et al. 2010).

In addition to the challenge of balancing competing water demands, understanding the regulatory procedures and how the plethora of instream flow tools might apply in a hydropower context can be daunting. While regulatory procedures are meant to be fair and objective, the process may fail to identify the most balanced and ecologically effective e-flow implementation. In this paper, we propose an integrated framework that identifies commonalities and mismatches between scientific and regulatory processes to facilitate the implementation of e-flows using a scientific and objective process while acknowledging the inherent ecological and regulatory complexity. First, we identify the major challenges of implementing e-flows in streams affected by upstream hydropower dams. Next, we review the existing tools available for determining e-flows that support ecological needs and specifically focus on two holistic frameworks used for determining e-flows in hydropower contexts: a scientific framework outlined by Richter et al. (2006) and the predominant U.S. regulatory-based process, Federal Energy Regulatory Commission licensing. We identify areas where regulations fall short of the needed scientific process, and provide suggestions for stakeholders to ameliorate those situations through advanced preparation. We highlight the strengths of existing flow paradigms in their application to hydropower settings and suggest when and where tools are most applicable in that process. Our suggested framework is beneficial to increasing the effectiveness, efficiency, and clarity of the e-flow process in hydropower settings by rapidly establishing a knowledge base and decreasing uncertainty so more time can be devoted to filling knowledge gaps.

The Challenge of Implementing Environmental Flows in Hydropower Settings

Among the most pivotal challenges for determining e-flows for hydropower dams is quantitatively predicting ecological responses to newly prescribed flow regimes. Conceptually, this would seem straightforward; however, the majority of our knowledge of ecological responses to flow is based on deviation from natural conditions rather than improvements in degraded conditions. The ecological limits of hydrologic alteration (ELOHA) are among the most widely used and accepted processes for identifying e-flows at the regional scale (Poff et al. 2010, Richter et al. 2012). The ELOHA framework establishes flow-ecology relationships, which form the basis of defining thresholds (i.e., ‘limits’), beyond which hydrologic alteration is unacceptable (Poff et al. 2010; Richter et al. 2012). In the absence of flow-ecology information or resources to execute frameworks like ELOHA, Richter et al. (2012) proposed a presumptive standard of $\leq$20 % hydrologic alteration beyond which ecological degradation occurs. However, hydrologic conditions in rivers below hydropower facilities may already exceed these ‘acceptable’ limits. The highly modified nature of regulated rivers predisposes these environments as challenging systems to manage because these systems require *restorative* as opposed to *preventative* actions. Thresholds or limits, while very suitable for setting withdrawal standards and basin planning, may not provide much guidance for restorative actions (McManamay et al. 2013a). This is especially the case in situations where hydrologic conditions are an artifact of cumulative upstream disturbances (e.g., urbanization and irrigation) and not just a result of hydropower operations.

Another fundamental challenge of developing e-flows for hydropower is that the dam, rather than flow, is likely the ‘master variable’ of the regulated river downstream (McManamay et al. 2015). In regulated systems, many dynamic flow-ecosystem relationships differ from predictable patterns found in natural systems (Ward and Stanford 1983). For example, discharge-temperature relations in regulated rivers reflect reservoir stratification and the depth of water-withdrawn during power generation (Olden and Naiman 2010). Resulting e-flow implementation may dramatically improve hydrologic conditions but have little influence on downstream water temperature (Krause et al. 2005). Similarly, impoundments trap bedload leading to increased erosive potential downstream and often stream bed armoring (Kondolf 1997). To better inform e-flow decisions, we need to better understand flow-ecology relationships in streams below hydropower facilities. Developing flow-ecology relationships for each hydropower context will require knowledge of individual systems. Obtaining information about each individual system is unlikely given the cost and time; therefore, another challenge is translating information from regional knowledge to these unique regulated-river settings. While no framework will remove the need for individual attention in regulated-river contexts, we envision that regional analyses can inform the early stages of e-flow determination.

Existing Environmental Flow Frameworks and the Regulatory Process

Globally, substantial effort has been devoted to improving flows conditions in regulated river systems (Tharme 2003; Roni et al. 2008). In order to help inform our framework, we reviewed existing e-flow tools and conceptual frameworks. The Instream Flow Council (IFC) recognizes over 30 documented e-flow methods with a substantial range of effort related to each approach; however, this excludes some of the more holistic strategies (e.g., ELOHA). We provide examples of common and novel e-flow approaches along with their application to hydropower in Appendix 1.

Of particular importance are two holistic frameworks used for implementing e-flows in hydropower contexts; one framework focuses on the scientific process while the other is primarily a regulatory process, with many scientific components. Richter et al. (2006) proposed a science-based process for implementing e-flows below dams, modeled after stakeholder negotiations of flow enhancements downstream of Thurmond Dam, a US Army Corps of Engineers facility on the Savannah River (Fig. 1). Public involvement in the development of this science-based process is omnipresent throughout the process via a series of workshops. The preliminary assessment was informed by a literature review and existing knowledge base, and knowledge gaps were identified as part of that initial assessment. E-flows are implemented as experiments and followed by monitoring to fill these information gaps, which provide the basis for adaptive management via indefinite iterative adjustments in the flow regime as new information is obtained (Fig. 1).

In contrast to a purely science-based approach such as Richter et al. (2006) process, the U.S. hydropower regulatory determination of e-flows is within the complex, negotiation-based Federal Energy Regulatory Commission (FERC) relicensing process (Fig. 1). Almost 81 % of the 2100 hydropower dams in the U.S. are owned or operated by nonfederal entities and subject to FERC regulations. There are three different processes available for hydropower licensing managed by FERC: the integrated licensing process (ILP), traditional licensing process (TLP), and the alternative licensing process (ALP). We primarily focus on the ILP as this is the default process; however see Layman et al. (2006) for a review. Each licensing procedure takes 5–10 years, is typically commensurate with project size, and re-occurs every 30 years (FERC 2015). Although there are similarities between Richter et al.’s approach and the FERC relicensing process, there are several important differences. As with any regulatory process, achieving a knowledge-discovery approach to reduce environmental uncertainty is difficult. Although public involvement is *encouraged*, it is not consistent through the entire process. Stakeholder involvement starts with scoping meetings that are used to identify environmental and socioeconomic issues in need of mitigation (FERC 2015) (Fig. 1). However, scoping meetings may not foster the development of an existing knowledge base or assist in developing stakeholder goals; they are meant to address stakeholder input and identify studies to fill information gaps, some of which may be unrelated to flow entirely (e.g., reservoir shoreline management). Thus, scoping meetings require adequate representation and preparation by stakeholders well in advance. Practitioners may be unfamiliar and unprepared

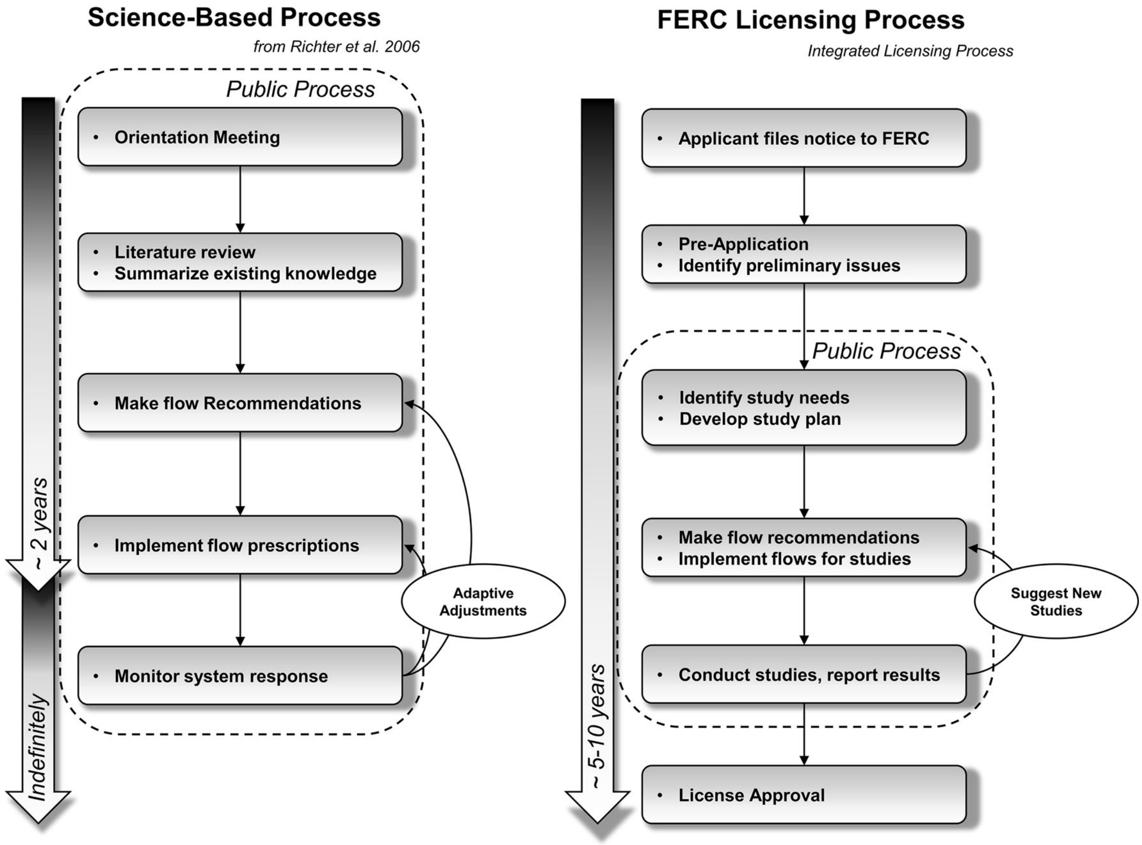

Fig. 1 Comparison of stepwise processes for determining e-flows for hydropower dams. The science-based process outlined by Richter et al. (2006) is reliant on a series of public workshops to summarize the existing knowledge base and then recommend environmental flows. Following flow implementation, monitoring ecological responses is used to make indefinite adaptive adjustments. Within the FERC Integrated Licensing Process public involvement begins with scoping meetings, which are used to address stakeholder input and identify studies to fill information gaps. Flows may be implemented for evaluation through field studies, and public discussion of results may elicit requests for modification to any study plans, i.e., new studies. Once environmental flows are implemented under the final FERC order, provisions for adaptive management are limited

to deal with these structured procedures and negotiations. Stakeholders can request that applicants fund field studies to address information gaps useful for making an informed decision but these requests require well-defined justification. The most divergent aspect of FERC licensing procedures from the Richter et al. approach is that e-flows, if implemented under the final order, typically remain unchanged for 30 years thereby limiting use of a meaningful adaptive management framework post-license approval (Fig. 1). There are, however, less commonly adopted provisions within FERC licensing analogous to adaptive management, such as ALP where applicants and environmental stakeholders can address uncertainty through monitoring in the prefiling process or via settlement agreements that extend beyond the approved license (Mount et al. 2007). Ultimately, however, FERC is reluctant include any adaptive terms in license approval, as currently defined by the Federal Power Act (Mount et al. 2007).

A Proposed Organizational Template

Uncertainty is inherent in the process of determining e-flows for hydropower dams. The process is typically driven by questions to fill knowledge gaps: (1) How do current hydrologic conditions compare to predisturbance conditions or conditions in reference streams? (2) Are flow targets based on the natural flow regime an obtainable or desirable end goal? (3) What are the key hydrologic and ecological targets of the system? (4) What aspects of the flow regime are important to ecological communities in this system? (5) Are other factors potentially more important than hydrology in organizing the current state of the ecosystem? (6) What alternatives to the natural flow regime should we consider? and (7) What is the predicted ecological response to e-flows after they are implemented? Addressing multiple difficult questions is an overwhelming challenge to any stakeholder, especially if time is limited. Paradigms that embrace uncertainty in managing dynamic systems focus on filling knowledge gaps in the most efficient manner possible. Specifically, some of the questions posed above can be addressed prior to any field study.

Our proposed organizational framework aligns well with the Richter et al. (2006) science-based approach, but with differences that embrace aspects of the regulatory licensing process (Fig. 2). We identify common challenges within the FERC process so stakeholders can prioritize their efforts in determining e-flows. By considering these challenges a priori, stakeholders can anticipate and prepare for licensing (e.g., building a knowledge base) (Fig. 2); thus, our framework helps to maintain scientific rigor regardless of the regulatory environment. A better understanding of the regulatory process would allow stakeholders to identify information gaps in advance of public negotiations. Because the FERC e-flow decisions generally remain in place for 30 years, reducing uncertainty in our knowledge increases the likelihood that an ecologically meaningful outcome can be found as part of the process. In order to reduce uncertainty, the framework promotes efficiency in gathering existing information so that more time can be devoted to meaningfully addressing knowledge gaps.

The organizational framework starts by building a knowledge base, transfers to identifying information gaps, and finally shifts to the flow implementation stage (Fig. 2). The framework orients stakeholders to identifying approaches, data, and useful tools in a time-saving manner, such as suggesting where existing e-flow tools and frameworks are best adapted (Fig. 3). Existing e-flow tools are utilized at different stages of the process that can be linked as sequential steps that first draw from existing knowledge at coarse spatial scales (e.g., classifying flow patterns of hydropower stream segments) and then shift to a focus on the immediate system by conducting studies at finer spatial scales (Fig. 3). The five sequential steps are (1) context, (2) assessment, (3) scoping, (4) prescription, and (5) feasibility (Figs. 2, 3). Context is provided at basin or regional scales to characterize the biophysical and operational settings around each hydropower project and provides a point of reference to other regulated rivers and reference streams. Assessment can be conducted at national or regional scales and includes fully describing the current hydrologic and ecologic conditions relative to stakeholder-determined ecological and hydrologic objectives. Scoping is used to identify key hydrologic and ecological targets, isolate information gaps, and develop flow-ecology relationships to predict the ecological outcomes of alternative flows. Based upon best available knowledge, prescription presents a series of alternative flow scenarios based on objectives and the knowledge gained within the assessment and scoping stages. Lastly, analyses are conducted to determine the feasibility (i.e., ecological versus economic benefit) of alternative flows at the site-specific scale. Following the feasibility analysis, flows are implemented and

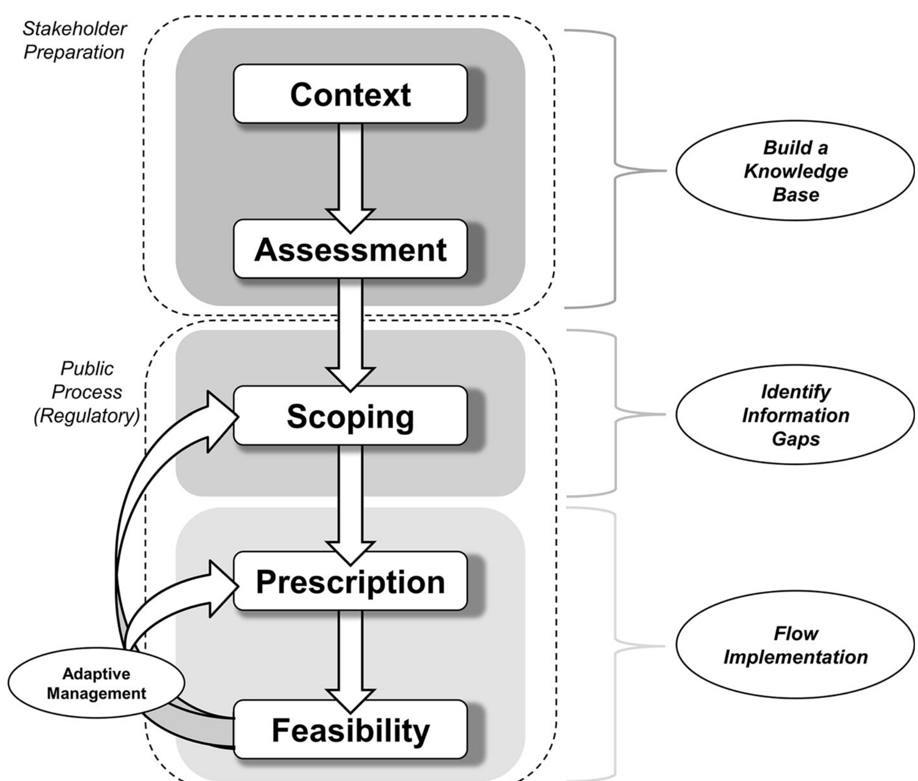

Fig. 2 Organizational framework providing a stepwise process for implementing e-flows. The framework integrates the scientific approach presented by Richter et al. (2006) with regulatory procedures from the Federal Energy Regulatory Commission licensing process. Because of regulatory constraints, stakeholders are encouraged build a knowledge base in advance of engagement in the regulatory process

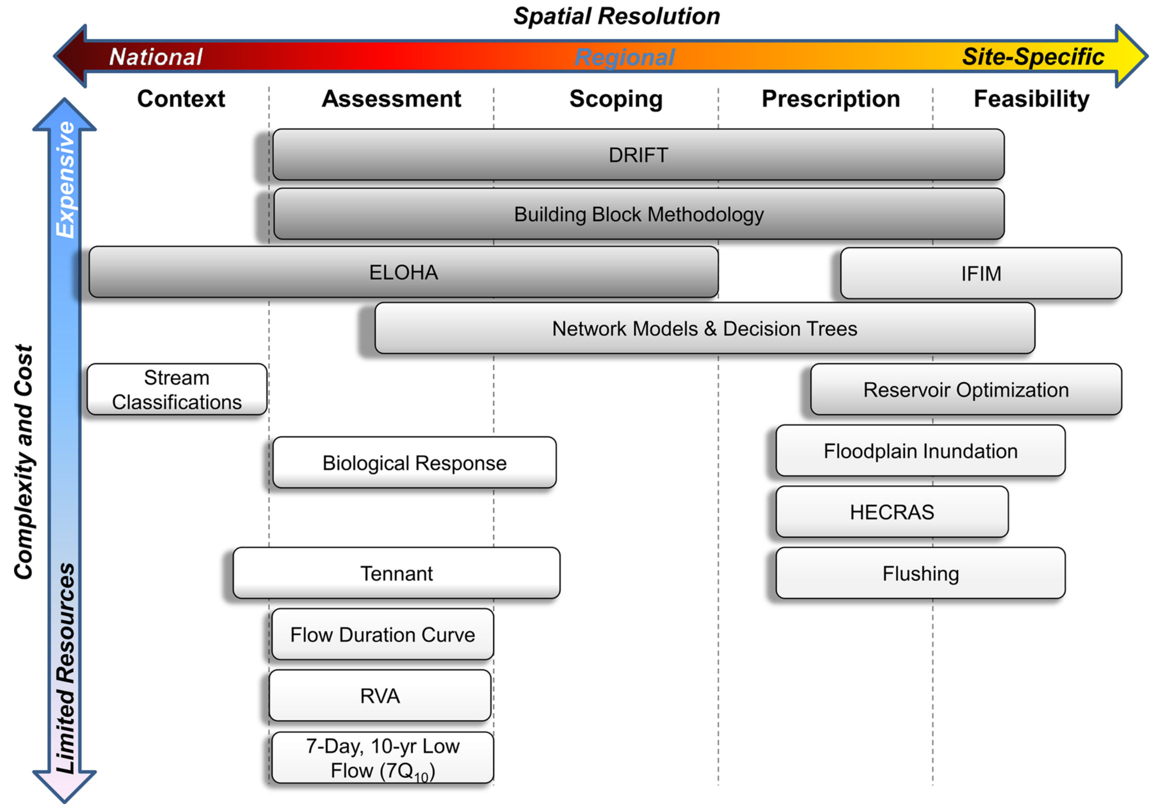

Fig. 3 Applicability of existing e-flow tools depending on sequential steps within the organizational framework. Sequential steps, and associated e-flow tools, range from national to site-specific spatial scales of application. E-flow tools also range in cost and complexity (*left axis*) and in the degree of stakeholder participation (increasing *gray shading*)

followed by adaptive management to monitor ecosystem responses and make adjustments when needed.

Context

Although generalities exist regarding the behavior of regulated river systems, hydropower dams, even in close spatial proximity, are unlikely to have the same natural settings, operations, and biophysical effects on river systems (McCartney 2009). These different settings may provide a preliminary estimate of what restoration or mitigation measures are necessary, given the type of dam operation. Because of the complex variation in river systems and their responses to disturbance, a common trend in broad-scale management is creating classification systems as they consolidate variability of ecosystems into interpretable units (e.g., Rosgen 1994; Wehrly et al. 2003; Wollock et al. 2004). Classification systems provide a context to organize management actions at the national scale (Wollock et al. 2004), generalize ecosystem behavior (Bailey 1983), and stratify analyses (Wolock et al. 2004).

Stream classifications based on multiple variables (e.g., hydrology and temperature) can provide information early in the relicensing process (Fig. 4). Each stream class layer provides a baseline to make assessments of the condition of multiple habitat components. In addition, these assessments can be used to compare the relative importance of flow relative to other habitat elements (e.g., temperature), which can inform prioritizations of mitigation actions. In addition, for hydropower projects undergoing relicensing, classification systems can help identify suitable case studies where licensing or e-flow negotiation has already occurred or aid in identifying references to develop conservation objectives (see Case Study 1, Fig. 4). Extending classification systems to include multiple components of in-channel alteration (e.g., temperature, geomorphology) may increase the predictive accuracy of assessing ecological responses to flow variation (Liermann et al. 2012, McCargo and Peterson 2010).

The way in which dams harness water for energy has implications for energy production, project economics, and downstream hydrology. For example, dams that operate in a run-of-river mode (i.e., harnessing energy solely based on incoming flows) will likely have far less influence on hydrology than those that operate in a peaking mode (i.e., storing and releasing water to generate energy during peak

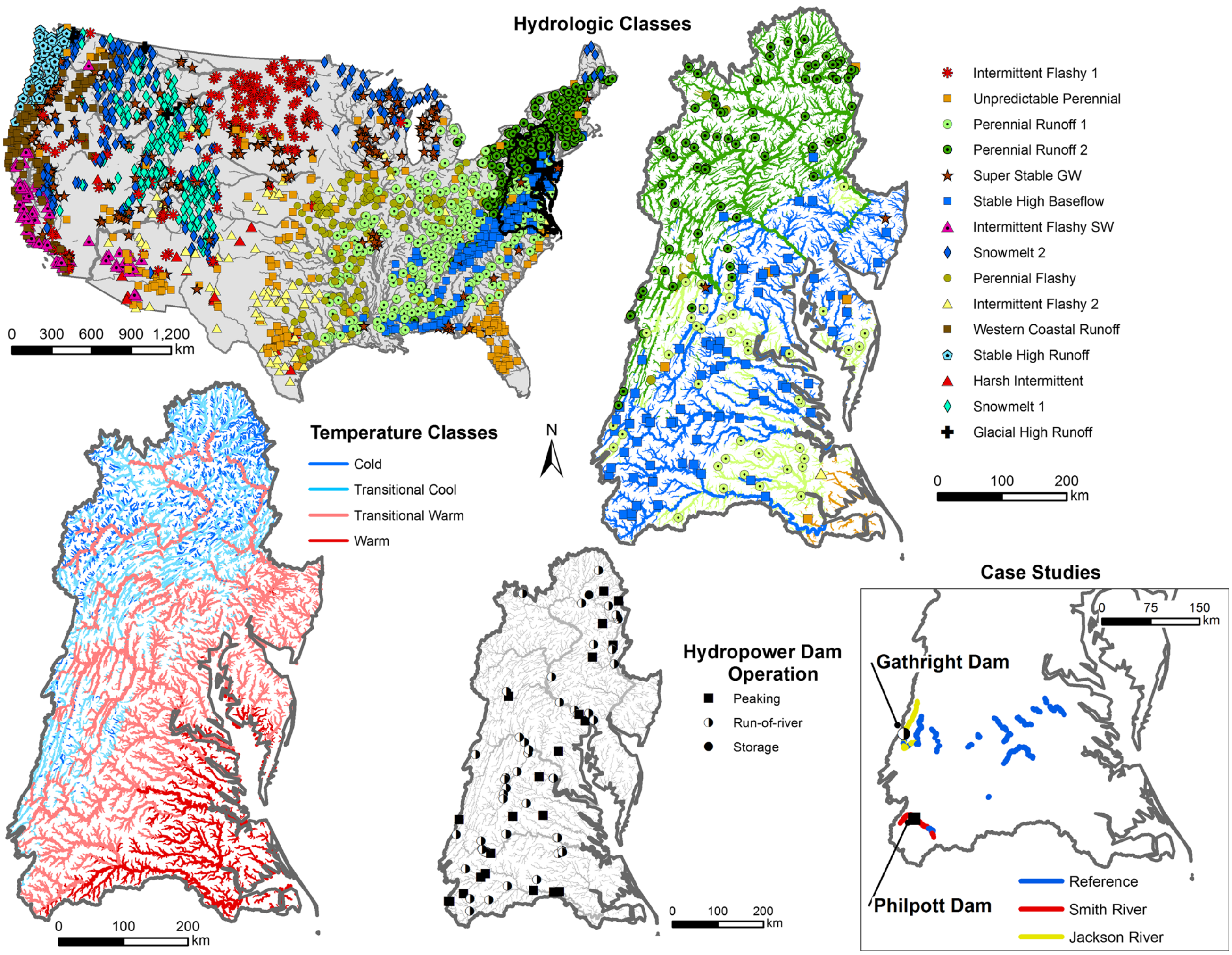

Fig. 4 Stream classes providing physical and regulatory context for e-flow assessments at hydropower facilities within the mid-Atlantic region of the US. *Top figures* show hydrologic classification developed for US (McManamay 2014), which were applied to stream reaches within the mid-Atlantic region. *Bottom left* figure shows temperature classes applied to stream reaches (from Olivero and Anderson 2008), whereas bottom middle shows hydropower dams according to operation type (McManamay et al. 2016). *Bottom right panel* shows streams selected as case studies or reference streams for the Smith River below Philpott Dam, VA

demand) (McManamay et al. 2016). To date, most dam classifications have been coarse, by arbitrarily defining dams according to size or purpose (USACE 2015) or by simplified operation (storage versus run-of-river) (Poff and Hart 2002). However, hydrologic patterns may not follow these coarse classifications predictably (McManamay 2014). Recently, a classification of hydropower dam operations across the entire US was produced, resulting in 18 unique classes explaining considerable variation in hydrologic patterns (McManamay et al. 2016). These classes assist in understanding the dimensionality of water demands and identifying potential flexibility of accommodating e-flow recommendations.

Understanding the regulatory context prior to engaging in the relicensing process can also benefit environmental stakeholders in the negotiation process by focusing attention on areas that can benefit most from flow improvement. For example, many dams are managed as groups often called projects (FERC 2015), which are owned by the same entity and may cover large portions of a basin. Each project may consist of complex infrastructure: multiple dams, penstocks, canals, diversion-bypass reaches, and auxiliary dams and reservoirs to increase total storage. Thus, evaluating a project at a coarse level may reveal the most ecologically beneficial opportunities for flow enhancement, such as longest reaches of diverted water or longest free-flowing reach to estuary. In other situations, the regulatory context is so complex that pressure from environmental stakeholders to implement flows at some facilities is either impractical or directed at the wrong entity (Pearsall et al. 2005).

Assessment

Assessing the ecological and hydrologic conditions of a hydropower project is critical to understanding where a project sits in the spectrum of natural to artificial environments. In addition, this information is needed to inform the scoping phase (next section) and eventually developing predictable relationships between flow and ecology. The hydrologic condition of a project can be conceptualized as a tri-point continuum, which provides a baseline for moving towards ideal conditions depending on ecological objectives (Fig. 5). A project may modify the timing and distribution of flows without large losses to the annual water budget (endpoint B, Fig. 5). However, diversions reduce the water budget thereby limiting the quantity and quality of habitat (endpoint C, Fig. 5). Similarly, the ecological condition can also be conceptualized within a tri-point continuum (Fig. 5) and provides an indication of hydrologic and general environmental conditions (e.g., Does the system support high biodiversity or a recreationally valuable sportfishery?). A comparison of fish assemblages below a hydropower project to that of local sites within the same hydrologic class can provide a rapid assessment of shifts in community structure including missing species.

Most strategies for assessing hydrologic conditions include calculating hydrologic indices that summarize daily discharge data and then comparing those values between unaltered and altered conditions (e.g., Indicators of Hydrologic Alteration, Richhter et al. 1996). However, hydropower operations influence hydrology at temporal scales on the order of minutes to hours (Cushman 1985), which are not captured by daily-averaged flow metrics. Bevelhimer et al. (2014) suggested that subdaily hydrologic statistics explained more variation among dam operations than analogous statistics compiled from daily discharge data. Subdaily flow metrics and associated tools have received far less attention (Zimmerman et al. 2010; Meile et al. 2011), but are necessary to advance assessments of hydropower operations including correlations with changing downstream geomorphic and biological responses, which are also likely to occur at a wide range of temporal and spatial scales.

Contextual information provides the groundwork to efficiently conduct ecological and hydrologic *assessments* of hydropower dams (see Case Study 2). For example, predam discharge information is often unavailable for hydropower dams; however, hydrologic classes represent a range of natural flow variation and provide a quantitative approach to measure hydrologic condition (Case Study 2; Fig. 6). Similar assessments could be conducted for other habitat features, such as temperature and substrate. Contextual information may yield opportunities for more sophisticated, larger-scale analyses, such as comparisons of ecological and hydrologic conditions among multiple hydropower dams within similar natural settings and operations and among unregulated streams (Case Study 2; Fig. 6). These larger analyses may provide evidence of causal relationships between hydrologic and ecological conditions and hence, support negotiations within the scoping phase.

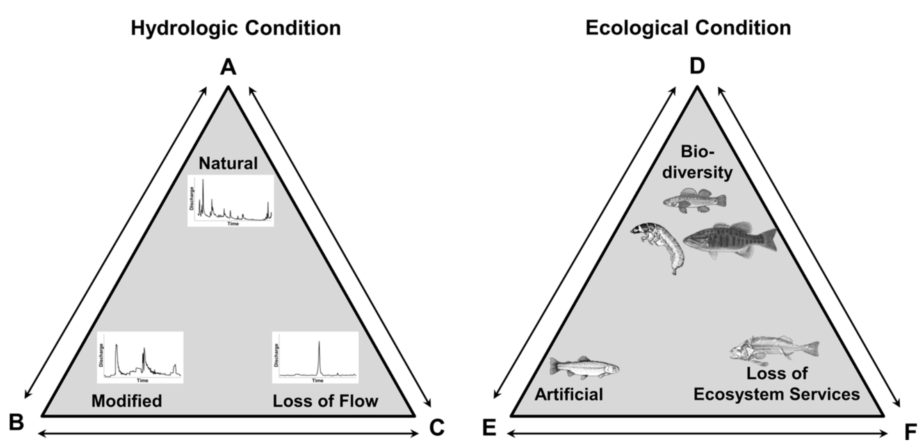

Fig. 5 Tri-point continuum of hydrologic and ecological condition for a given hydropower project. A project may (*A*) have little modification to flow magnitude or timing (*B*) modify the timing and distribution of flows without large losses to annual water budget, or (*C*) divert large quantities of water thereby reducing the water budget thereby limiting the quantity and quality of habitat. Likewise a project may (*D*) have little modification to natural biodiversity (*E*) have highly modified river communities that support ecosystem services, such as sportfisheries, or **f** have extensive losses to ecosystem services. Associations among hydrologic and endpoints are likely to exist; however, ecological endpoints should not be viewed as directly related to hydrologic endpoints (e.g., *B* does not necessarily result in *E*)

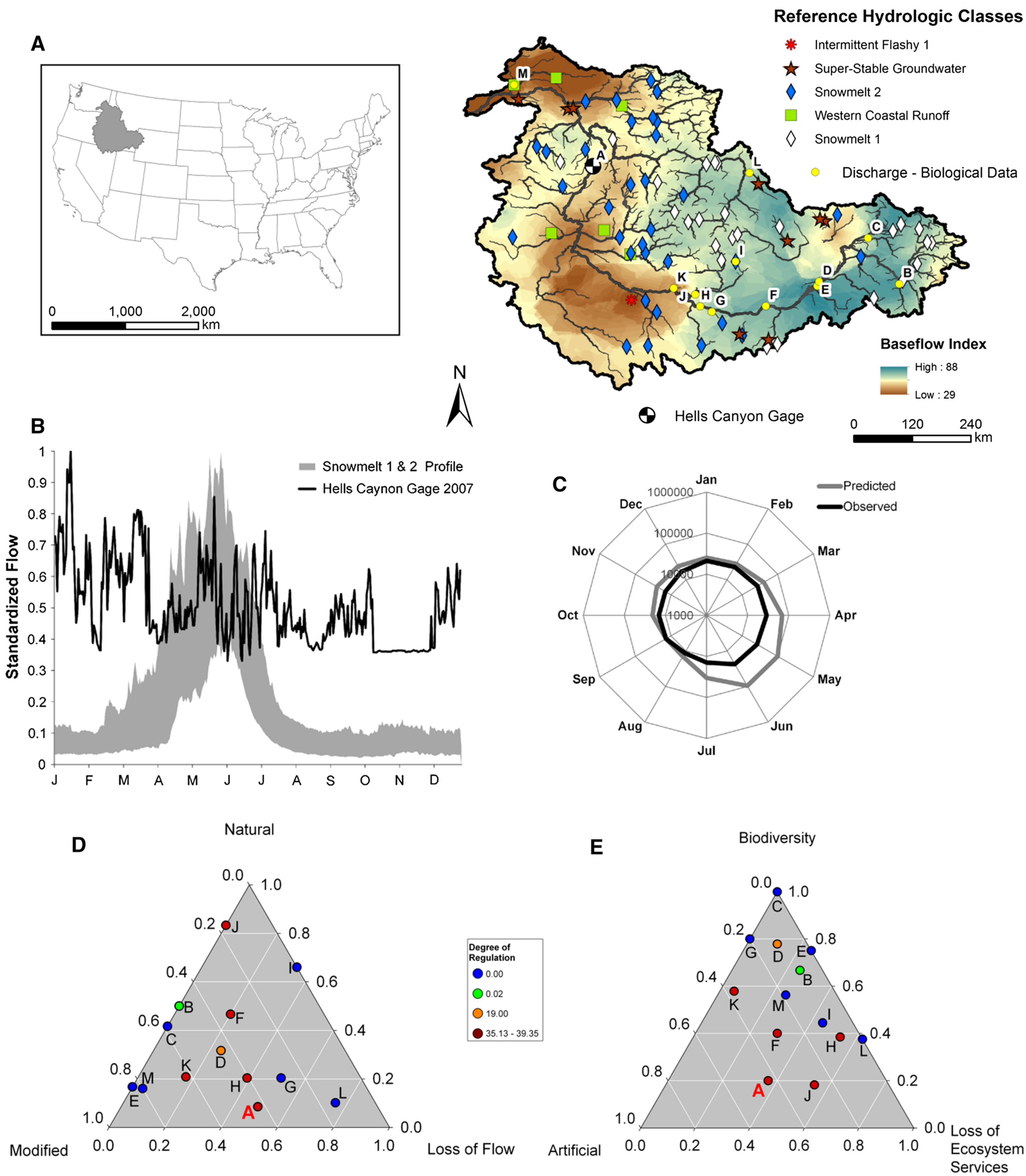

Fig. 6 Hydrologic and ecological assessment of the Snake River below Hells Canyon Dam, Idaho. **a** Using predictive models, the Hells Canyon stream gage (USGS 13290450) was classified as a Snowmelt 1 or 2 type stream. Locations of biological sampling (fish communities) are provided. **b** Comparisons of the current flow below Hells Canyon Dam to the Snowmelt 1 and 2 reference hydrologic profile (10th–95th percentile of standardized flows) reveal departures from the relative magnitude of annual maxima and seasonal baseflows. Standardized flow calculated by dividing each year by maximum flow. **c** Using drainage area-discharge relationships of reference streams, historic magnitudes of flow were predicted for Hells Canyon and compared to current observations. **d** Assessing hydrologic conditions and **e** ecological conditions below Hells Canyon relative to other streams within the hydrologic and ecological tri-continuums, respectively

Scoping

While the context and assessment steps can be conducted at coarse scales, the scoping, prescription, and feasibility elements require stakeholder participation, intensive knowledge-base development, and individual attention to each hydropower project (Figs. 2, 3). The scoping phase includes objective-setting and designing field studies to fill information gaps, both of which set the stage for the remainder of the e-flow process. Successful restoration depends on developing appropriate goals considering the context of each management situation (Roni et al. 2002); however, appropriate goals must be substantiated by establishing measurable objectives (Tear et al. 2005).

Based on the current and desired ecological and hydrologic conditions, stakeholders identify measurable ecosystem targets for improvement (e.g., increases in biodiversity, sportfish biomass, or the frequency and duration of floodplain inundation) (Richter et al. 2003). These ecosystem targets could be identified through a subset of key hydrologic and ecological indicators (Richter et al. 2003), which are predictably linked through quantitative relationships to inform management actions. Within hydropower contexts, these relationships provide hypothetical predictions of ecological responses to flow enhancement; however, preexisting relationships such as these are rarely available (Poff et al. 2010; Poff and Zimmerman 2010).

In the absence of quantitative and robust flow-ecology relationships, several novel approaches are available to assist in e-flow decisions. For example, Norris et al. (2012) developed a form of causal criteria analysis, called *Eco Evidence*, which uses published literature to support a priori developed cause-effect hypotheses. For example, if increasing salmonid spawning success was selected as an ecological target, a possible hypothesis might be: *decreasing sub-daily flow fluctuations (range in flows) during the spawning season will increase salmonid redd success*. Extensive reviews of the stream flow and ecology literature and associated database compilation can provide support for hypotheses (Webb et al. 2015), but also quantitative predictions at global (Poff and Zimmerman 2010) to regional scales (McManamay et al. 2013b). While developing a knowledge-base of flow-ecology relationships can aid in making flow prescriptions (next section), a practical outcome of this development is objectively identifying relevant hydrologic and ecological indicators.

Prescription

Based on the knowledge base developed during the previous steps, alternative flow prescriptions are developed with the intent of filling information gaps through field-based studies (Fig. 2). Prescription should not be confused with the final outcome, but rather, a stakeholder-driven process that uses the best available science to identify a spectrum of scenarios of varying risk for hydropower and environmental stakeholders. Alternative flow scenarios should address key hydrologic and ecological indicators identified in the scoping process (Table 1) and then evaluated and tested in feasibility analyses (next section).

It is quite possible that roundtable discussion could generate a large number of potential flow prescriptions and these will need to be filtered to the most relevant components to evaluate via field studies. Because hydrologic metrics are highly correlated (Olden and Poff 2003), redundant flow indices need to be removed by prioritizing the most ecologically relevant or interpretable metrics (Knight et al. 2008), or by assessing variance explained by metrics (Olden and Poff 2003; Kennen et al. 2008). The scoping process should yield hypothetical and, ideally, quantitative relationships between flow prescriptions and ecosystem components (or individual species) (Fig. 7). However, the resultant flow prescriptions could be filtered or prioritized under varying degrees of relevance or uncertainty (Fig. 7). First, if flow components are identified to sustain ecosystem targets, then the most relevant question becomes, “Are the ecosystem targets currently present in the system?” If these targets are not present, then an important consideration is whether restoring flow components will restore the missing ecosystem targets or if other additional mitigation actions will be necessary. Likewise, if target species are missing, then stakeholders might consider: (1) Is natural recolonization possible? (2) Would short-term reintroductions be required or is the species conservation reliant? (3) Can the species be propagated and reintroduced? If ecosystem targets are present, then the potential for other factors to limit ecological recovery post-flow enhancement could be considered. For example, restoring some components of flow may be insufficient to improve ecological conditions if thermal regimes are outside an organism’s physiological tolerance or other key habitat features are missing (McManamay et al. 2013a). Even if answers to all the questions posed above are unknown, stakeholder discussions help identify these as information gaps to be addressed through field studies and feasibility analysis.

Feasibility Analysis

Feasibility analyses range from field studies to mathematical modeling. Typically, the objective of using a feasibility approach includes at least one of the following: (1) reducing uncertainty in ecological responses to flow prescriptions, (2) finding optimal solutions among competing users of flow, and/or in uncertainty, or (3) understanding

Table 1 Examples of alternative flow scenario components to be tested during feasibility studies for stream reaches below hydropower facilities. Alternative scenarios can represent one to many different flows within each component and/or one to many different combinations of components

Flow scenario component	Description	Potential ecological/societal benefit
Baseflow		
Minimum flow	Constant baseflow supplied year-round between generation	Entire channel perimeter remains inundated and reduces fish stranding following generation. Creates more stable environment
Seasonally variable baseflow	Baseflow magnitude varies according to season	Seasonally fluctuating flow provides enhanced flows during different spawning times for fish and habitat refugia to support varying life stages of macroinvertebrates and riparian vegetation
Flood pulses		
Frequent small flood (rafting release)	Scheduled releases of small flood events periodically during year (5–10 times) during appropriate seasons	Provides channel maintenance such as scouring or flushing sediment, inundating roots, removing encroaching vegetation, and redistributing spawning substrates. Also could provide recreational boating opportunities
Annual large flood (floodplain pulse)	Scheduled large flood event (per 1.5 years)	Creates new habitats by shifting large amounts of substrates, provides organic matter inputs from floodplain, inundates backwater habitats, and provides nursery habitats for fish
Special-events		
Attractant flow	Pulsed flows attract upstream migrating fish to ladders	Enhances fish passage, reproduction, and population viability
Passage flow	Pulsed flows to enhance/protect outmigration	Enhances fish survival, recruitment, and population viability
Subdaily		
Ramping restriction	Restrictions in the rate of change of the rising limb of generation pulse	Creates less disturbance by reducing square-shaped hydrograph. Allows time for behavioral responses to initiation of peak generation
Down-ramping restriction	Restrictions in the rate of change of the falling limb of generation pulse	Prevents fish stranding by providing time for behavioral responses to flow recession
Daily range restriction	Restrictions in range of min/max flows during day	Reduces disturbance and creates more stable environment to enhance feeding and spawning habitats
Diurnal variation in generation	Shifting the timing of generation within a day	Generating during different times of the day may provide more temporal overlapp of hydrologic stability and peak feeding times

complex relationships between flows, other physical properties, and ecological dynamics.

Field studies may be required to elucidate complex relationships within the system. Biota may not respond predictably to flow improvements for several reasons including that other physicochemical factors besides stream flow are key ecological drivers (e.g., Krause et al. 2005; McManamay et al. 2013a). For example, existing water-quality constraints imposed on these systems may not benefit from alternative flow scenarios (Krause et al. 2005; Olden and Naiman 2010). Additionally, e-flow recommendations must take into account hydrologic interactions with the stream channel (Trush et al. 2000). For example, new flow regimes should match the dimensions of current channels, which may be incised versions of the historical stream (Fig. 8). In some cases, historical flow magnitudes are not only irrelevant, but potentially harmful to endemic populations in this context (McManamay et al. 2013a). Additionally, increasing flow magnitudes also increases transport capacity of river systems, which may coarsen the streambed and lead to the loss of valuable substrates (Jackson and Pringle 2010). As a final consideration, dams lacking passage facilities block the migration and dispersal of organisms among populations and habitats required for various life stages (Vaughn and Taylor 1999; Han et al. 2008; Reid et al. 2008). Depending on the context, feasibility analyses could consider local colonization, extinction, and meta-population dynamics (Shea et al. 2015). Identifying the distribution of various species may help determine whether migratory potential is inhibited by physical barriers or poor habitat quality inducing barrier-type effects (e.g., Worthington et al. 2014).

Beyond increasing our comprehension of the system complexities, feasibility analyses try to find the most effective solutions to e-flows given regulatory, socio-economic, ecological constraints, and uncertainty in river

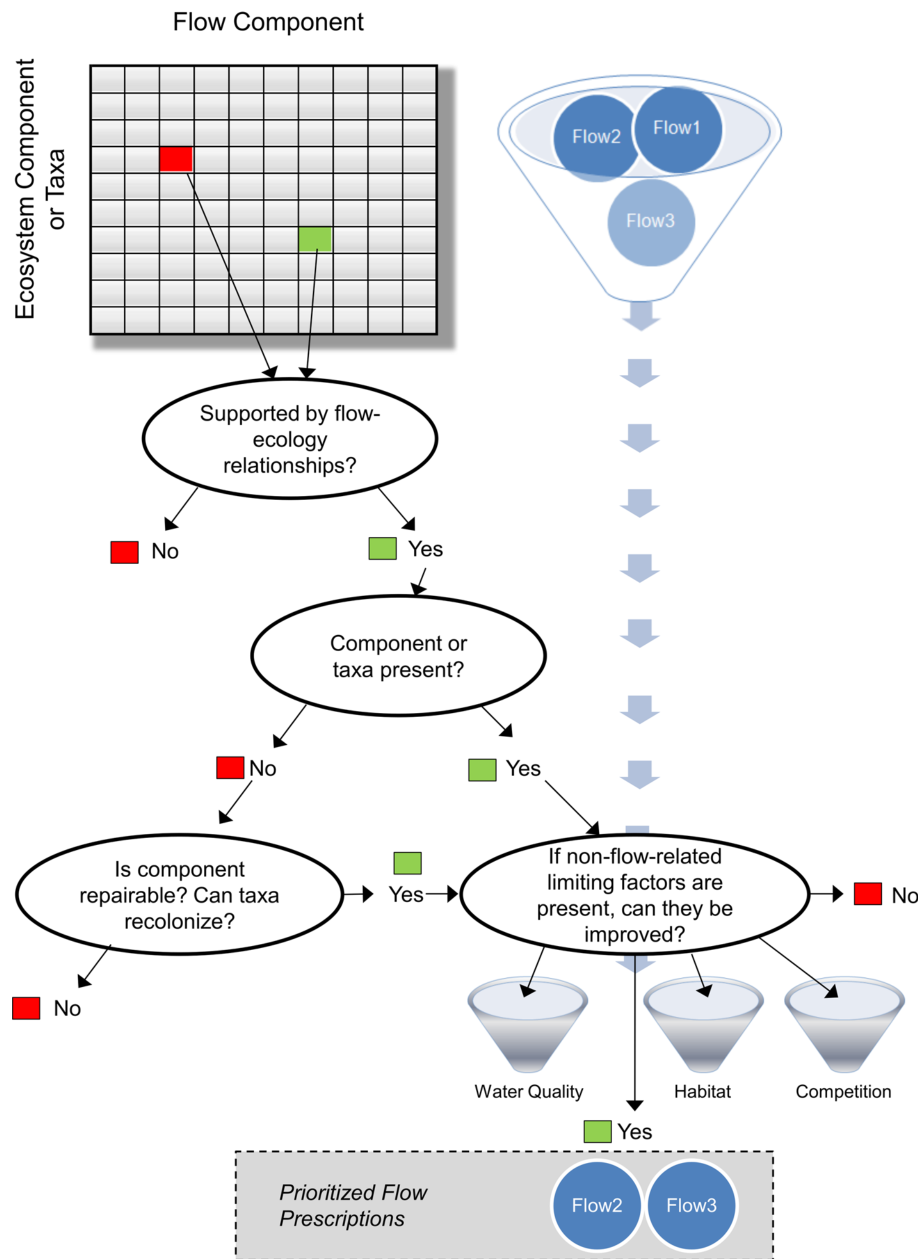

Fig. 7 An example process for screening and prioritizing flow prescriptions based on evidence of causal flow-ecology relationships between a specific flow components and ecosystem components (*matrix*) and the presence or status of ecosystem components in relation to flow and other limiting factors

system responses (see Case Study 3). Feasibility analyses require detail on individual systems to provide the most accurate ecological predictions within alternative flow scenarios. Instream-Flow-Incremental-Methodologies (IFIM) are the most common feasibility framework applied to regulated river systems (Tharme 2003). IFIM tools are typically used to assess specific ecological targets under varying flow conditions within a particular stream reach. Reservoir optimization algorithms are also very common and are well adapted to determining flows optimal to meet ecological and economic (energy) objectives (Case Study 3; Fig. 9). Other feasibility approaches include complex mathematical approaches (e.g., BBN networks) to model the ecological responses to varying flow regimes while accounting for ecosystem complexity, unknown variables, and uncertainty.

Adaptive Management

Unfortunately, predicting ecological responses to newly implemented e-flows does not come without uncertainty. Reducing the uncertainty about which aspects of flow regimes are most important to ecosystem targets increases the efficiency and objectivity of negotiations between environmental stakeholders, hydropower stakeholders, and regulators. In addition, reducing uncertainty increases the

Fig. 8 Example of a miniaturized channel due to >80 years of dewatering for downstream hydropower production (Cheoah River, North Carolina). The top photograph of the Cheoah River was taken in the early 1930s, soon after Santeetlah Dam was completed (http://tailofthedragon.com/tail-of-the-dragon-info/history/). In comparison, the bottom photograph shows decreases in channel width due to widened road embankments and encroachment by riparian vegetation (photograph taken by Ryan McManamay)

likelihood of all stakeholder participants embracing risk. Managing complex and highly uncertain ecosystems requires an adaptive approach and thus, we suggest that iterative monitoring and adaptive adjustments follow implementation. While adaptive management is included in the framework, our underlying assumption is that authentic adaptive management (i.e., post- rather than prelicense approval) may not be an option, especially within the regulatory process. The framework attempts to guide stakeholders to preemptively mitigate this situation as best as possible by reducing uncertainty early in the e-flow implementation process. In cases where adaptive management is possible, the hope is that the framework increases the efficiency in finding ecologically effective solutions.

Case Studies

Case Study 1: Stream Classes Aid in Identifying Case Studies

Philpott Dam is a U.S. Army Corps of Engineers (USACE) hydropower facility located on the Smith River in Virginia. Although the river below Philpott Dam boasts a $500,000 revenue blue-ribbon trout fishery downstream (Hartwig 1998), studies have shown that extremely low temperatures (8 °C) are suboptimal for brown trout growth, in addition to limiting Roanoke logperch (*Percina rex*) populations, a federally endangered fish (Krause et al. 2005). With increasing demands from the recreational industry and requests for improved conditions for both trout and

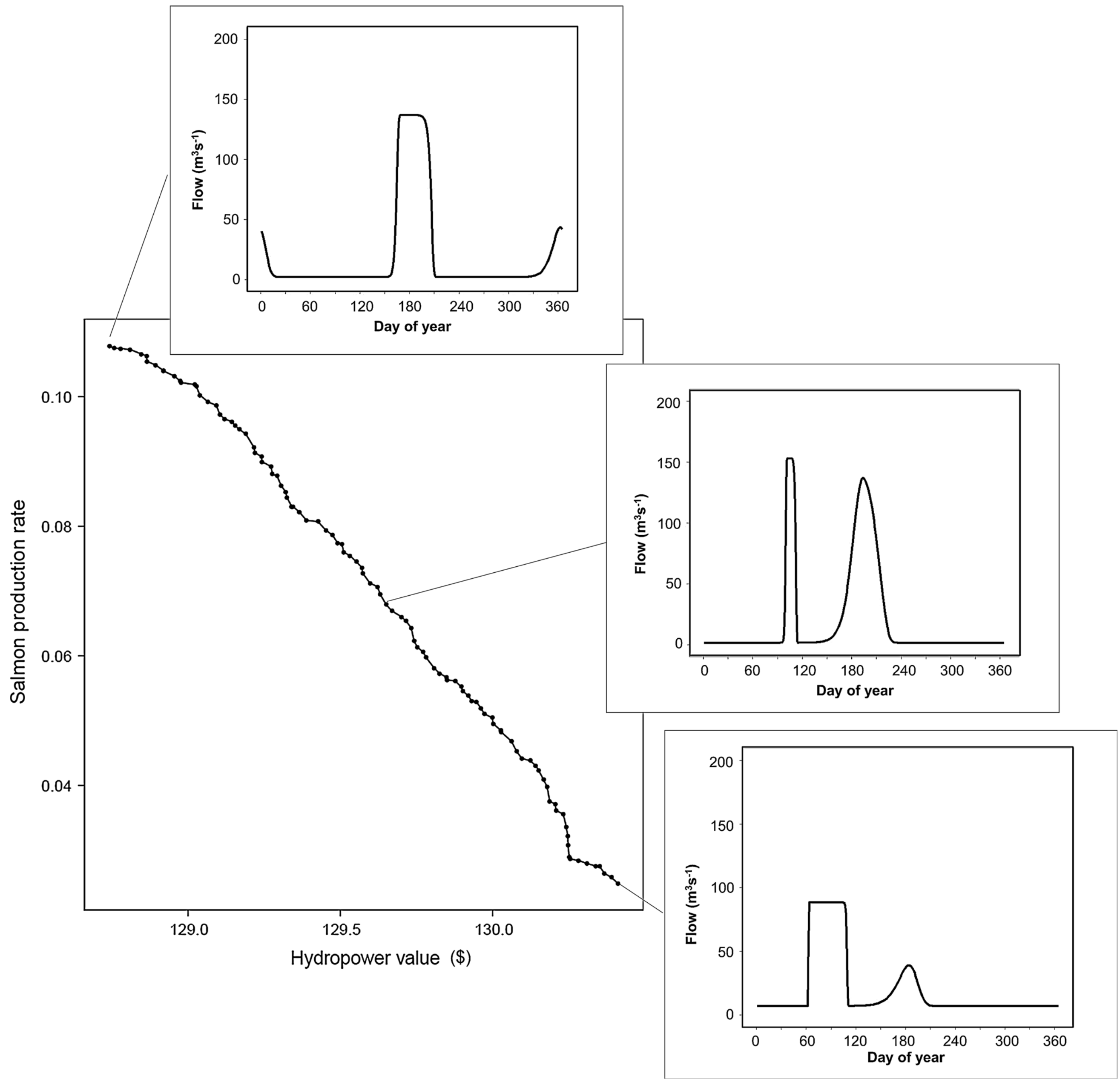

Fig. 9 Pareto-optimal frontier representing tradeoffs between salmonid production rate and hydropower value among a range of alternative seasonal flow regimes (*insets*). Salmon production rate represents survival from egg to outmigration where hydropower value is a relative measure of daily energy value (i.e., a product of energy generation (MWh) and relative seasonal deviation in marginal price, $ MWh^{-1}). Alternative flow regimes range from seasonal flows maximizing the survival of salmon (*top inset*) to a flow regime producing the maximum hydropower electricity value (*bottom inset*). The center flow regime represents a compromise between these two endpoints. A pulse flow in winter permitted juveniles to occupy floodplain habitat and grow faster, whereas summer high flows provided benefits to both objectives. This optimization was conducted for the Tolumne River, California below Don Pedro Dam (from Jager 2014; Jager and Uria-Martinez 2012)

logperch, the USACE has considered alternative operations or mitigations to improve conditions (Krause et al. 2005). Additionally, an invasive species of diatom algae (*Didymosphenia geminate*) has caused great concern as it produces substantive nuisance growth in consistently cold, low nutrient environments, such as stream reaches below dams. Given these concerns, evaluating approaches to mitigation at other dams would be informative. Likewise, identifying unregulated streams to serve as reference conditions may provide baselines for improving habitat conditions.

Philpott dam is located within the Mid-Atlantic Region of the US (Fig. 4). A stream classification including hydrology, temperature, and size typologies (Olivero and Anderson 2008; McManamay 2014) were overlain with hydropower dam operation types, altogether comprising 34 unique stream class-dam operation combinations (Fig. 4). The reach of the Smith River regulated by Philpott Dam occurs within a Stable-High Baseflow-Medium Tributary-Transitional Warm type (SHBF-MT-TW). Gathright Dam (USACE), located on the Jackson River, was selected as a case study, as it also occurs on a SHBF-MT-TW system (Fig. 4). Similar to Philpott, Gathright Dam operates as a hypolimnetic release with a high-quality trout fishery, but also with federally endangered species (James Spinymussel, *Pleurobema collina*) (USACE 2012). Due to *Didymosphenia* colonization in the reaches below Gathright Dam, the USACE conducted experimental flushing releases to dislodge the algae with some success, while protecting habitat for a federally endangered species (Flinders and Hart 2009). Gathright Dam provides a useful case study for Philpott Dam in a system that is of the same natural setting, regulatory constraints, and thermal operations. Using the stream classification in combination with indicators of habitat alteration (Esselman et al. 2011), several unregulated streams in the region were identified as appropriate reference streams that fell within the same stream class (Fig. 4). These may provide relevant comparisons or baseline information for habitat conditions (e.g., hydrology, temperature, substrate) or functional components of fish communities to guide restoration efforts.

Case Study 2: Using Context to Make Hydrologic and Ecological Assessments and Identify Targets

The Hells Canyon Project consists of three dams (Brownlee, Oxbow, and Hell Canyon) operated in tandem as peaking operations on the Snake River, Idaho. Since the project's FERC license expired in July 2005, negotiations over e-flows have included operational constraints, such as increasing releases to augment flows to enhance juvenile fall Chinook salmon (*Oncorhynchus tshawytscha*) migrations, additional ramping restrictions during Chinook rearing periods, and more stringent constraints on reservoir fluctuations (FERC 2007). E-flow alternatives are also complicated by reservoir operations supporting warm-water sportfish interests in Brownlee reservoir (FERC 2007). Understanding the current ecological and hydrologic conditions of the Hells Canyon Project relative to other streams in the area could help guide the scoping process by identifying appropriate targets.

Because of a long history of regulation and irrigation in the basin, very little predisturbance information is available for the lower Snake River. In the absence of pre-dam information, hydrologic classes provide a natural range of variation expected within a given region—in other words, they provide hydrologic context (McManamay 2014). Using predictive models, Snowmelt 1 and 2 (SNM 1-2) hydrologic classes were determined as the appropriate hydrologic types for the Hells Canyon Project (Fig. 6a). Discharge records from the Hells Canyon gage (USGS 13290450) were compared to the SNM1-2 hydrologic class profile and revealed departures from the relative magnitude of annual maxima and seasonal baseflows (Fig. 6b) (Supplementary Material 1). These comparisons suggest that seasonal pulsed flows matching critical time periods, not necessarily magnitudes, for salmonids downstream would be optimal. The magnitude of pre-dam flow conditions were estimated using drainage area-discharge relationships for gages within the SNM1-2 classes (Fig. 6c) (Supplementary Material 1). Based on these relationships, only slightly more than 50 % of the historic flow magnitude, on average, is still available due to extensive upstream diversions; thus, the full magnitude of expected flows, especially peak flows, would not be realistic or recommended. This would suggest that proposed flow regimes should adequately match channel dimensions.

Placing multiple hydropower projects and unregulated systems within the surrounding context yields correlative relationships between altered hydrology and ecological conditions, thereby identifying aspects of e-flows for future evaluation (i.e., scoping). Overlapping hydrologic and biological information were compiled at multiple locations ($n = 14$) in the Snake River Basin, including the Hells Canyon Project (Supplementary Material 1). Hydrologic conditions at each location were calculated according to proximity to the each tri-continuum endpoint, based on reference gages from SNM1-2 classes (Fig. 6d) (Supplementary Material 1). Likewise, proximity of sites to each ecological endpoint was also calculated (Supplementary Material 1). The Hells Canyon gage was an extremity compared to other sites and fell midway along the "loss-of-flow" and "modified" hydrologic axis, and midway along the "loss-of-ecosystem-service" and "artificial" ecological axis. Hydrologic condition did not necessarily translate into ecological condition. Ecological condition, but not hydrologic condition, was related to the degree of dam regulation (Fig. 6d and e). Comparisons of Hells Canyon Project to other sites with less-modified hydrology and ecology may provide realistic targets. Specifically, the Snake River near Minidoka, ID (F site) and near King Hill, ID (K site) are both regulated but have lesser impacts to late-winter/early spring flows and June/July flows; thus, these may represent desirable flow component targets for scoping studies.

Case Study 3: Tradeoffs Between Flows to Benefit Fish and Other Goals of Reservoir Operation

Reservoirs are operated to satisfy many objectives, two of which include hydropower production and ecosystem demands. In a practical sense, it is very important to understand the complementarities and trade-offs among different objectives and to identify compromise solutions that can meet multiple needs, including those of fish communities. Mechanistic population models can be used to represent relationships between fish reproduction, survival, and flow. Similarly, the value of hydropower generation has been modeled as a function of energy demand. Electricity prices vary seasonally as heating and cooling needs increase, and some models incorporate seasonal components to price forecasts (Zhou and Chan 2009). Jager and Uria-Martinez (2012) conducted a case study in the Tuolumne River, California, below Don Pedro Dam where they modeled the seasonal effects of flow on salmon and electricity value. An optimization was conducted to identify flow regimes along a frontier from maximizing salmon to maximizing electricity value.

To represent seasonal effects of flow on salmon, Jager (2014) developed a quantile-based (*Quantus*) salmon recruitment model. Salmon eggs were tracked by space–time quantiles that define the reach (space) and date (time) that spawning parents fertilized eggs. Cohorts were then tracked from deposition of eggs until out-migration. The *Quantus* model assumed that temperature-driven processes exerted the most-important effects of flow on age-0 salmon, such as incubation, development, survival, and predation. The model also represented the positive effect of floodplain inundation on juvenile salmon growth due to increased prey availability. Optimal seasonal flows for maximizing juvenile survival were medium-magnitude early summer pulses that moderated temperatures and a larger late-winter pulse providing floodplain access to increase juvenile recruitment. Because of complex mechanism induced by river regulation, optimal flows to maximize juvenile salmon survival did not mirror natural flow regimes in the region.

Predictable seasonal patterns in the marginal cost of electricity in the California energy market was developed via an empirical model (Jager and Uria-Martinez 2012). Historical price data (2003–2008) were used to model the influence of air temperatures and season on the mean and variance of marginal cost of electricity (MCE). Optimal flow releases were based on relative seasonal fluctuations in MCE. A range of solutions (seasonal flow regimes) ranging from those favoring salmon to those favoring hydropower value were developed along a pareto-optimal front (Fig. 8). Optimal flow regimes demonstrated concordance between the two objectives in the need for pulse flows in summer during hot temperature. Summer pulses benefited salmon including mitigating high water temperatures (increasing juvenile survival) whereas increased summer generation offset increased energy demands from elevated household cooling. However, higher minimum flows and a late-winter/early spring pulse favoring salmon were not included in regimes that maximized hydropower value (Fig. 8).

Conclusions

The organizational framework is a standardized means of engaging in a complex regulatory process while achieving a scientific approach. Much of the scientific community and environmental stakeholders may be unfamiliar with regulatory procedures discussed herein; thus, we suggest that the framework helps orient stakeholders prior to engaging in that process. Because the reoccurrence interval for licensing hydropower projects is long (30 years), environmental stakeholders may participate in only one licensing during their entire career and this experience may never be shared.

Organizing when and where existing tools are most meaningful in identifying e-flows has the potential to increase efficiency in aspects of the regulatory process, thereby increasing time devoted toward developing field studies and, in turn, increasing the likelihood prescribed e-flows are ecologically beneficial. Considerable time and money are devoted to conducting field studies that address information gaps. If poorly informed, expensive studies may be misguided and, in turn, may result in e-flows that are inadequate to improve ecological targets. The framework aids this process by suggesting key hydrologic and ecological indicators be identified earlier in the process as a product of efficient knowledge-generating steps (context and assessment). In doing so, the framework emphasizes the importance of a comprehensive and coordinated research agenda to further the science of e-flows related to hydropower environments.

Although the framework attempts to achieve the most ecologically meaningful outcome, predictive analyses cannot replace monitoring in addressing uncertainty (Konrad et al. 2011). Regardless of whether adaptive management is an option, monitoring the ecological outcomes of newly implemented flow regimes provides much needed information to improve future efforts. However, most of the information and data generated from scoping studies, field analysis, feasibility studies, and post-licensing monitoring are not readily available beyond reports (e.g., FERC e-library- http://www.ferc.gov/docs-filing/elibrary.asp). Therefore, we encourage environmental stakeholders, hydropower industry, and FERC to collectively publish datasets generated from pre- and post-licensing studies to inform future licensing efforts.

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Appendix 1

E-flow tools and conceptual frameworks were categorized into four types following Annear et al. (2004): (1) Assessment, (2) Incremental, (3) Model Building, and (4) Information-Base strategies. Assessment methods make e-flow determinations on the basis of simple evaluations of ecohydrologic conditions. These include policy-driven evaluations to set limits or thresholds to determine appropriate flow regimes (Stalnaker 1995). Incremental methods are among the most time-intensive and analyze modeled river-stage ecological (biotic and abiotic) relations within a stream channel to compare alternative flow scenarios (Stalnaker et al. Stalnaker 1995; Annear et al. 2004). Model building includes complex mathematical routines that aid decision making, such as optimization modeling (Jager 2014) or Bayesian belief networks (Webb et al. 2015). Lastly, information-base strategies are among the most holistic frameworks that typically build knowledge bases and fill information gaps in a series of steps. These frameworks use the current state of knowledge, information compiled at regional scales, and quantitative relations between river flow and ecology to assess river conditions to reduce uncertainty in order to make e-flow recommendations. We describe commonly applied methodological approaches under each framework below.

Assessment

Two of the most common assessment techniques are the Range of Variability Approach (RVA) (Richhter et al. 1997) and the Tennant method. The RVA identifies the extent of hydrologic alteration from predisturbance conditions using 66 flow metrics (e.g., Indicators of Hydrologic Alteration). The RVA approach is dependent upon obtaining pre and post-disturbance discharge data to determine deviation from the system's *natural* range of variation (Richhter et al. 1997). The convenience of RVA is that complex hydrologic behavior is dwindled into a summary of descriptive and informative statistics. When used in isolation, however, the RVA approach has no quantitative stage-channel relationships or support for in-stream ecological unless accompanied by stage-specific information (e.g., Nislow et al. 2002) or biological information (e.g., Taylor et al. 2014). Another assessment technique, the Tennant or Montana method, estimates habitat quality at various flows using limited field measurements, hydrologic records, and photographs of the stream channel (Tennant 1976). This method can be used as a reconnaissance-level tool for determining acceptable seasonally variable flow magnitudes in situations where there are little or no major competing uses (Annear et al. 2004).

Incremental Methods

Instream-Flow-Incremental-Methodologies (IFIM) are the most commonly applied techniques used to estimate e-flows (Tharme 2003) despite several shortcomings. IFIM approaches use field measurements of ecohydrologic conditions of the river channel at incremental discharges to model flow-ecology relationships. IFIM approaches can consider hydrology, biology, habitat, sediment transport, and water quality over a range of given discharges or under various flow regime alternatives (Bovee et al. 1998). The IFIM approach can range in complexity from describing simple relations between hydrologic indices and aquatic habitats to more complex hydrodynamic models linked to multiple river components (Tharme 2003). Although even the most complex IFIM application can be scientifically sound and provide assessments of management alternatives, the IFIM approach is: (1) only applicable to the specific study reach (Moir et al. 2005), (2) typically assumes that higher habitat suitability translates into a biological response (Anderson et al. 2006), and (3) often focuses only on individual species (Anderson et al. 2006).

Model Building

Mathematical models are often applied to balance water allocation among competing users, and also predict the ecological effects of modified flow regimes, particularly when there is substantial uncertainty in our estimates. Two examples of mathematical models are reservoir optimization algorithms and Bayesian belief networks (BBN). Reservoir optimization algorithms find optimal balances among multiple water demands (e.g., ecological and societal needs, Yeh 1985; Wurbs 1993). Algorithms can be relatively simple, or address more complex variables by incorporating stochasticity in forecasted inflows (Stedinger et al. 1985) or uncertainty in reservoir operations (Shresha et al. 1996). Reservoir optimization algorithms are highly useful for assessing the feasibility of flow alternatives, but still require a priori knowledge of the water needs for the ecosystem. BBN have increasingly been used to support water-management decisions (e.g., Hart and Pollino 2009; Stewart-Koster et al. 2010; Chan et al. 2012). BBN provide a simple graphical depiction of complex probabilistic reasoning about the relationship among important key variables. The key feature of BBN is that they allow us to model uncertainty in the relationships among variables. Other advantages of BBN include: (1) accommodating missing data and small sample size, (2) incorporating unorthodox data (e.g., expert opinion), and (3) being updated as new data are available (Korb and Nicholson 2004). More recent software packages (e.g., Netica, Hugin) have provided some solution to the limitations of these models such as the inability to include feedback loops between input and output variables, and the lack of time-dependent variables (Hart and Pollino 2009; Landuyt et al. 2013). These models have been used to aid the evaluation of many environmental flow issues (e.g., the effects of water withdrawals on fishes, Chan et al. 2012; the effectiveness of restoration strategies, Shenton et al. 2013).

Information-Base Approaches

Information-Base approaches including the Building Block Methodology (BBM, King and Louw 1998) and the Downstream Response to Imposed Flow Transformations (DRIFT) have been developed as conceptual alternatives to traditional e-flow techniques. These methods build on expert knowledge to support complex, stakeholder-driven management decisions and they emphasize monitoring post implementation. The BBM addresses all riverine ecosystem component needs (including societal) using existing knowledge and expert opinion in a structured workshop process. The DRIFT method builds upon the BBM and quantifies biophysical and sociological linkages to flow regimes and then evaluates biophysical, social, and economic responses under various flow scenarios (King et al. 2003). The strength of the DRIFT procedure is that stage-specific ecohydrologic assessments are conducted as opposed to relying only on predicted responses to flow.

The need for quantitative predictions to support e-flows led to the development of a process known as the Ecological Limits of Hydrologic Alteration (ELOHA) (Poff et al. 2010). ELOHA has been considered the most holistic e-flow framework to date (Richter et al. 2012) and has formally been applied in nine states of the US (Kendy et al. 2012). Within the ELOHA framework, streams are classified based on similar hydrology as a foundation for later assessing hydrologic alterations and flow-ecology relationships (see Arthington et al. 2006; Poff et al. 2010) within those stream groups (i.e., with similar hydrology). The flow-ecology relationships are then used in social processes to identify acceptable "ecological limits" to inform flow alteration thresholds and water-policy standards. However, ELOHA was not constructed to address applications requiring river-specific socio-economic and ecological issues (Kendy et al. 2012), a possible reason for its limited application in hydropower contexts (but see McManamay et al. 2013a, Rolls and Arthington 2014). Even so, ELOHA is flexible in that it provides context for the ecologic and hydrologic conditions of rivers, and reduces information gaps by isolating the most relevant hydrologic and ecological indicators, which may be relevant to the initial stages of e-flow implementation in hydropower.

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