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CHAPTER

11 EVOLUTION OF ENVIRONMENTAL FLOWS ASSESSMENT SCIENCE, PRINCIPLES, AND METHODOLOGIES

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11.1 INTRODUCTION

The science underlying environmental water allocations (environmental flows assessment science or environmental water science) is based in the quantification of the linkages between hydrological processes and components and various ecological variables. This understanding supports the recommendations and establishment of a water regime needed to manage rivers (and other wetland systems) in a more ecologically and socially sustainable fashion (Chapter 1). Principles based in hydroecological (or ecohydrological) theory and concepts (Acreman, 2016; Bunn and Arthington, 2002; Dunbar and Acreman, 2001; Hannah et al., 2007), combined with empirical literature and stakeholder or indigenous knowledge guide and inform environmental water science and its practical application. Achieving a more quantitative understanding of ecological and social responses to both natural flow variability and its alteration by humans is one of the fundamentally challenging goals of environmental water science and assessment in order to achieve more precise and effective environmental water regimes. The application of environmental water has largely been in the context of managing existing water resources infrastructure (e.g., dams, diversion weirs, direct abstraction points), which are globally ubiquitous causes of hydrologic alteration (Richter and Thomas, 2007). However, environmental water science is also increasingly needed to contribute to achieving conservation objectives through protection of flow regimes in rivers and basins under pressure from proposed developments (Acreman et al., 2014a; Poff, 2014). Typically, the focus is on the ecological response to purely hydrologic change, and less so on the other important environmental factors that can be strongly modified by large infrastructure (Chapter 21), primarily thermal and sediment regimes (Chapter 12). Further, environmental water science has disproportionately emphasized the biophysical aspects of ecosystems (Tharme, 1996). There is growing attention, however, on the social dimensions of environmental water, from inclusion of ecosystem services and their

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flow-linked dynamics (Chapter 8) through to the broader areas of culture, indigenous water, and social justice (Finn and Jackson, 2011; Wantzen et al., 2016; Chapter 9).

Environmental flows science and assessment have been driven primarily by concerns over the extent and rapid pace of deterioration in the biodiversity, ecological condition, and ecosystem function of rivers where natural flow regimes have been partially or completely regulated by humans (Chapter 4). The scientific understanding of flow–ecological relationships is continually evolving, as is the technical ability to characterize and analyze the biophysical features of rivers. We now have the ability to ask sophisticated, complex questions that guide the setting of meaningful flow targets to restore regulated rivers or to sustain the conservation values of rivers where new water developments are planned. However, achieving successful environmental water implementation requires application of appropriate tools and methods (including modeling) that can lead to successful outcomes. This process of linking predictive science to successful ecological and societal outcomes creates an important tension in environmental water, one that drives the further evolution of science and methods.

Fundamentally, the framing of a particular environmental water management question determines which methods and tools are required to adequately describe flow–ecology relationships (Chapter 14) that help address that question. A wide range of frames exist: from single species to entire ecosystem management, from short-term experimental flows to long-term flow regime modification, from rapid desktop estimation to guidance for planning of new water infrastructure, and from detailed field-based assessment of flows to achieve river restoration at individual sites, to assessments spanning systems across a large landscape or region. Over the more than 50-year history of environmental water science and assessment, the questions, approaches, and tools have advanced and diversified, in response to changing societal objectives, world views, and values (Chapters 2, 7, and 9), an increasing knowledge base (including indigenous knowledge), and significant advances in modeling capabilities (Chapters 13 and 14).

As the global human population continues to increase and place more demand on freshwater resources, and as climate change simultaneously imposes unprecedented challenges for sustainable resource management, new questions and frameworks for managing environmental water are emerging. These will be increasingly transdisciplinary and drive the development of novel approaches that will move forward as hydroecological and social understanding increase through research and monitored implementation of environmental water management actions.

11.1.1 FOUNDATIONS AND TYPES OF ENVIRONMENTAL FLOWS ASSESSMENT METHODOLOGIES

Environmental flows assessments began in earnest in the late 1940s in snowmelt streams and rivers of the western United States, where their main objective was to protect valuable cold-water fisheries (Poff and Matthews, 2013; Tharme, 2003). Here, and in Europe, early minimum flow recommendations were also being made to mitigate the problems of poor water quality at low flows and for pollution control. Rapid progress in the 1970s was primarily a result of new environmental and freshwater legislation coupled with demands for quantitative assessment of flows to protect aquatic species impacted by dam construction, then at a peak in the United States. The US *Clean Water Act 1972* set the objective of restoring and maintaining the chemical, physical, and biological integrity of that nation's waters. These foundations gave rise to more formalized hydrological, hydraulic rating, and habitat simulation methods, which collectively stimulated global awareness and developments of the science and implementation of environmental water. England, Australia, South Africa, and New Zealand began to engage strongly in the topic in the 1980s, followed by Brazil, Japan, and several countries of continental Europe (Arthington and Zalucki, 1998; Dyson et al., 2003; Tharme, 2003). Each application brought fresh perspectives on the challenges and solutions to streamflow management in different hydroclimatic, biophysical, and socio-political realms (Acreman and Dunbar, 2004).

From the 1990s onward, within a putative *modern* era (Poff and Matthews, 2013; Fig. 11.1), the evolution and expansion of the science and practice of environmental water were explosive. By 2002, a global review of environmental flows assessment literature and practice (Tharme, 2003) identified over 207 methods and several broader frameworks used to assess the water requirements of aquatic species, habitats, or ecosystem features, and support flow management practices to meet ecological and, increasingly, also social targets. These methods were recognized to differ widely in the extent to which they were capable of adequately representing the water needs of ecosystems (Tharme, 2003). Several of the earlier methods, particularly, were largely carryover methods that addressed water pollution and were, subsequently, seriously limited in their ability to satisfactorily reflect the diverse water quantity needs of ecosystems and deliver truly sustainable ecological and social flow outcomes.

Despite various strengths and limitations (Table 11.1), by the year 2000 these diverse environmental flows assessment approaches were in use in at least 44 countries within six broad regions: Australasia (Australia and New Zealand), the rest of Asia, Africa, North America, Central and South America (including Mexico and the Caribbean), Europe, and the Middle East. Places that had previously shown little or no activity in this area began to take environmental flows assessment principles on board and to tailor existing approaches for local application, including additional countries in Latin America, eastern Europe, southern and eastern Asia, and various African countries and river basins (Tharme, 2003). Recent developments in China, Kenya, Tanzania, Colombia, and Brazil, among others, are now extending the influence of environmental water as a major plank of water management, although implementation is not without challenges (Le Quesne et al., 2010; Chapter 27). The concept of environmental water has a firm place in many intergovernmental agreements (e.g., the Convention on Biological Diversity signed by 168 countries, https://www.cbd.int/information/parties.shtml). Environmental water concerns are now integrated into water policy and legislation in countries and regions as diverse as Australia, South Africa, Lesotho, New Zealand, Costa Rica, Tanzania, Pakistan, Mozambique, China, the Philippines, the United States, and the European Union (Acreman and Ferguson, 2010; Arthington, 2012; Hirji and Davis, 2009; Le Quesne et al., 2010; Chapter 27). Speed et al. (2011) provide an interesting analysis of the ways in which some environmental water concepts and frameworks have been linked with those of water management in various countries.

The four main categories of methods that were evident early on (Tharme, 1996, 2003) remain relevant today—hydrological, hydraulic rating, habitat simulation, and holistic methods (Table 11.1), but with expansion of holistic (ecosystem) approaches to include the kinds of regional frameworks discussed in Section 11.5. The more recent methods continue to improve with regular applications on the ground and through ongoing advances in the science. Although these types of approaches continue to focus largely on rivers, many are applicable, with some modification, to other water bodies such as standing waters (e.g., marshes, lakes) that also experience natural spatial and seasonal patterns in water-level fluctuations, wetting and drying, and connections with groundwater (Arthington, 2012). Methods tend to be applied hierarchically (Tharme, 1996), from hydrology-based approaches common and more appropriate in a precautionary, low-resolution framing of environmental water requirements at a water resources planning level, to increasingly comprehensive assessments using holistic methods. The broad types of methods described by Tharme (2003) were also typically used for single or multiple river reaches within a river system. Recent method developments to support more advanced river basin and broader landscape water management are the subject of Section 11.5.

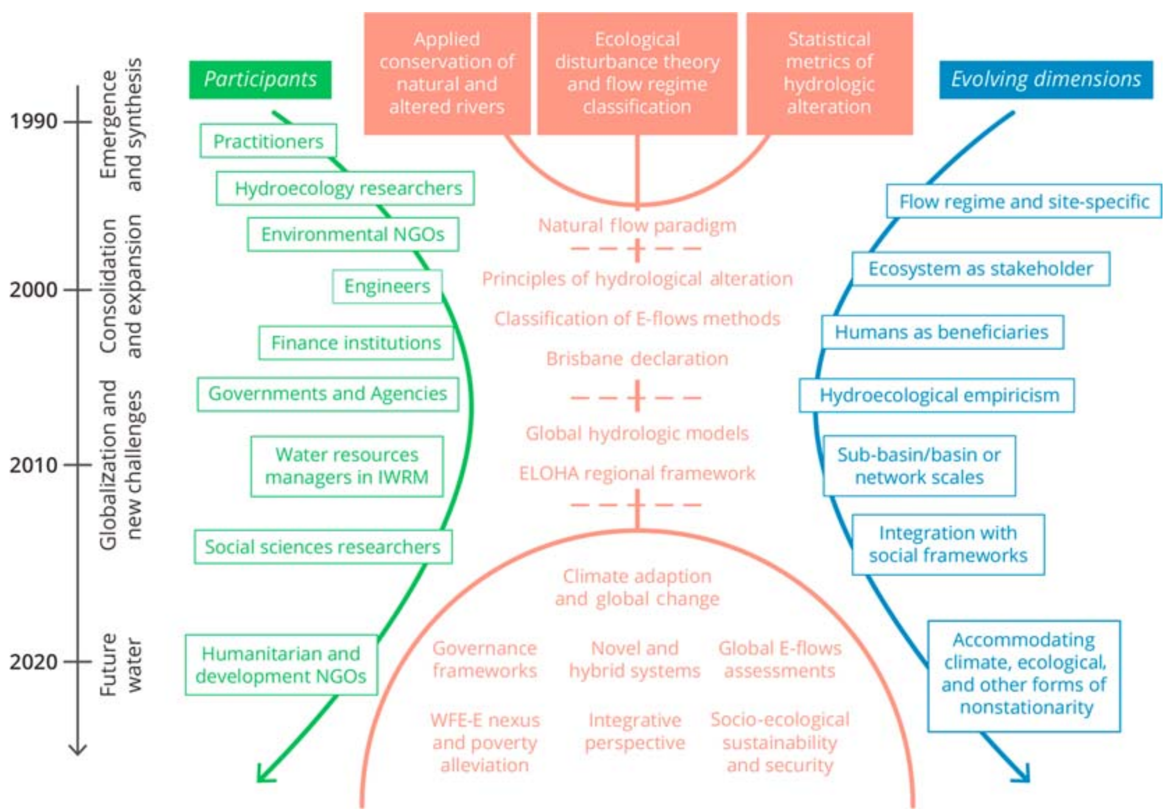

FIGURE 11.1

Historical timeline for "modern" environmental water, showing emerging directions in the principles and concepts that underpin the science and growth in the number and diversity of engaged institutions and practitioners. Timelines are shown that fall into relatively discrete periods of types of activities. Timelines for participants engaged in environmental water over time are shown to the left, for benchmark achievements in the center, and for evolving dimensions of environmental water on the right. ELOHA, ecological limits of hydrologic alteration; IWRM, Integrated Water Resources Management; NGO, nongovernmental organization; WFE-E, water, food, and energy-environment nexus.

Source: Adapted from Poff and Matthews (2013)

Table 11.1 Generalized Comparison of the Four Main Types of Methods and Frameworks Used Worldwide to Estimate Environmental Water Regimes for Rivers from Site to Regional Levels

Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
Hydrological	Whole ecosystem condition/ health, or nonspecific. Some include specific components (e.g., physical habitat, fish).	Primarily desktop, with low data needs. Use virgin/naturalized (or other reference state) historical flow records (daily, monthly, or annual). Single flow indices (often low-flow metrics), or more commonly multiple ecologically relevant flow metrics characterizing flow regime/whole hydrograph. Some use historical ecological data, hydraulic habitat data, or meta-analysis of results of multiple environmental water assessments to derive rules. Require expertise of a hydrologist. Few require ecological or geomorphological expertise, but such expertise is highly advantageous.	Low time and cost, and low or moderate technical capacity.	Mostly simple, flow targets for maintaining river health, based on estimates of the percentage of annual, seasonal, or monthly volume (often termed the minimum flow) that should be left in a river to maintain acceptable habitat or varying levels of river condition. Often expressed as % of monthly or annual flow (median or mean); or as limits to change in vital flow parameters, commonly low-flow indices. Low resolution, complexity, flexibility and confidence, or moderate and dynamic in a few more recent regime-focused methods.	Reconnaissance/planning level of water resource developments. Unsuitable for high-profile, negotiated cases, or where whole flow regime dynamics are critical. As a tool within habitat simulation or holistic methods. For highly data-deficient systems with limited ecological information. Regionalization potential for different river ecotypes.

Used widely in many developed and developing countries/basins. Simple single index, rule-of-thumb, and look-up table approaches (e.g., Montana method, Tennant, 1976; flow percentiles derived from Flow Duration Curve Analysis; Tharme, 2003, provides examples) becoming less common. Shift toward ecologically relevant flow metrics addressing multiple aspects of hydrological regime (e.g., Range of Variability approach, Richter et al., 1996; Environmental Flow Duration Curve, Smakhtin and Anputhas, 2006) and use of desktop models derived from meta-analyses of multiple environmental flows assessments (e.g., Desktop Reserve Model, Hughes and Hannart, 2003; Hughes et al., 2014).

(*Continued*)

Table 11.1 Generalized Comparison of the Four Main Types of Methods and Frameworks Used Worldwide to Estimate Environmental Water Regimes for Rivers from Site to Regional Levels *Continued*

Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
Hydraulic rating	Aquatic (instream) physical habitat for target species or assemblages.	Low to moderate data needs. Desktop analysis and limited field surveys. Historical flow records. Discharge linked to hydraulic variables, typically single river cross-section/transect. Single or multiple hydraulic variables. Require moderate expertise (hydrologist, field hydraulic habitat assessment, and modeling). Few require ecological or geomorphological expertise.	Mostly low, sometimes moderate time, cost, and technical capacity.	Hydraulic variables (e.g., wetted perimeter, depth) used as surrogate for habitat flow needs of target species or assemblages. Low, sometimes moderate, resolution, complexity, flexibility, and confidence.	Water resource developments where little negotiation is involved. As a tool within habitat simulation or holistic methods.
Used widely historically, mostly in developed countries (see Annear et al., 2004; Arthington, 2012; Tharme, 2003), but nowadays largely superseded or used as one of several integrated habitat modeling tools in habitat simulation or holistic methods (e.g., used within DRIFT, Arthington et al., 2003; King et al., 2003).					
Habitat simulation	Primarily instream physical habitat for target species, guilds, or assemblages. Some also consider channel form, sediment transport, water quality, riparian vegetation, wildlife, recreation, and esthetics.	Moderate to high data needs. Desktop, and field surveys. Historical flow records, typically average daily discharge. Few to many hydraulic variables are modeled at a range of discharges at multiple river cross-sections. Physical habitat availability, utilization, and preference data, or similar models, for target biota. A few use statistical summary methods based on results of multiple physical habitat studies.	High to sometimes moderate time, cost, and technical capacity.	Output in the form of weighted usable area (WUA) or similar habitat metrics for target biota (fish, invertebrates, plants). Often includes comparative analyses of time series of habitat availability, and duration and use. Moderate to high resolution, complexity, and confidence, moderate flexibility.	Water resource developments, often large scale, involving rivers of moderate to high strategic importance, often with complex, negotiated trade-offs among users. Commonly used as a method within holistic approaches and frameworks. Useful to examine a variety of alternative environmental water regime scenarios for several species/life stages/ assemblages.

		High level of expertise, with hydrologist, hydraulic habitat modeler. May use hydrodynamic modeling, GIS/remote sensing, ecological or geomorphological expertise			
Move away from single-species focus to increasing use for needs of species, guilds, and assemblages (IFIM, Bovee, 1982; see examples in Annear et al., 2004; Arthington, 2012; Tharme, 2003). Primarily applied in developed countries, using increasingly sophisticated and multidimensional (eco)hydraulic habitat modeling (e.g., Lamouroux and Jowett, 2005). Less commonly used in developing countries/basins, and then tending to be one of a suite of tools used to set environmental water within holistic approach (e.g., USAID, 2016).					
Holistic (ecosystem) methods and frameworks	Entire ecosystem, all or several ecological components. Most consider instream and riparian components, some also consider groundwater, wetlands, floodplains, deltas, estuaries, lagoons, coastal waters. Few consider geomorphic processes (e.g., sediment dynamics, channel adjustments), or ecological functions/processes (e.g., nutrient dynamics, food web structure). Several explicitly address social and economic (e.g., livelihoods of rural subsistence users, human health) dependencies on species, ecosystem resources, and processes (i.e., ecosystem services, e.g., fisheries).	Typically, moderate to high knowledge and expertise, but several used in data-poor contexts. Desktop and often field studies (seasonal or more intensive). Many reliant on mix of data and expert judgment, using expert panels. Some use both scientific and traditional knowledge to develop or infer flow–ecology–social relationships. Use virgin/naturalized historical flow records, or rainfall records/other data for ungauged sites. Several use hydraulic habitat variables from multiple cross-sections. Typically use biological data on flow–ecology relationships for lifecycle stages of aquatic and riparian species, assemblages and components (e.g., fish migration and spawning cues, riparian water quality tolerances, exotic species requirements).	Moderate to high time, cost, and technical capacity.	Recommended hydrological regime linked to explicit quantitative or qualitative ecological, geomorphological, and sometimes, social and economic responses and consequences. Some address environmental water regimes for dry or wet years. Moderate to high complexity and confidence. Typically, high resolution and flexibility. Several with potential to generate outputs for multiple scenarios (past, future). Some explicitly address probabilities, interaction effects, risk, and/or uncertainty. A few incorporate climate change.	Water resource developments, typically large scale, involving rivers of high conservation and/or strategic importance, and/or with complex, negotiated trade-offs among stakeholders. Simpler approaches (e.g., expert panels) often used in basin contexts where flow–ecology knowledge is limited, and limited trade-offs exist among users, and/or time, resources, and capacity constraints exist. Used in planning stage of new developments to protect high conservation values. Also used in highly modified or novel ecosystems, with focus on flow regime to deliver specific restoration objectives, or to address socio-ecological values and services in novel ecosystems.

(*Continued*)

Table 11.1 Generalized Comparison of the Four Main Types of Methods and Frameworks Used Worldwide to Estimate Environmental Water Regimes for Rivers from Site to Regional Levels ***Continued***

Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
		Range of experts from different disciplines, including ecologists, hydrologists, and often a geomorphologist. Several include social scientists, other specialists (e.g., water chemistry, health), water managers.			
Regional and landscape-level holistic approaches.	As for other holistic methods, but for large-scale system(s).	Designed to use existing data sets and knowledge. In some cases, includes collection of new data, or modeling for system locations of interest for which hydrological and/or ecological data are absent.	As for other holistic methods.	Quantified environmental water release rules or standards for rivers of contrasting hydrological type or ecotype and points of management interest, at user-defined regional scale(s). Flow alteration-ecological/ social response relationships by river type. As for other holistic methods.	As for other holistic methods. Large systems/basins or aggregations of smaller ones, regions, entire states, or multiple projects. May be integrated with water management systems.

Increasingly common in developing and developed countries (e.g., BBM, *King and Louw, 1998*; Benchmarking, *Brizga et al., 2002). Recent attention in developed regions focused on in-depth analysis of ecosystem components and, less commonly, functions/processes. Used regularly in developing countries, including for capacity development, and in complex basins with development pressures and, in many cases, communities with clear dependencies on aquatic systems (e.g.,* DRIFT, *Arthington et al., 2003, 2007*; *Blake et al., 2011*; *King and Brown, 2010*; *King et al., 2000, 2014*; *Lokgariwar et al., 2014*; *McClain et al., 2014*; *Speed et al., 2011*; *Thompson et al., 2014*; *USAID, 2016). At regional scale, most applications are adaptations of a single framework, the* Ecological Limits of Hydrologic Alteration (ELOHA, *Poff et al., 2010*; *e.g., Arthington et al., 2012*; *James et al., 2016*; *McManamay et al., 2013*; *Rolls and Arthington, 2014*; *Solans and de Jalón, 2016) or similar approaches (e.g., Kendy et al., 2012). Expansion underway from applications in a few developed countries, to pilots in several developing countries, and increasing numbers of applications in large developed basins, with explicit links to water management tools and decision support systems (e.g.,* PROBFLO, *Dickens et al., 2015).*

Current practice is summarized below each method type, with select application examples from various world regions (for additional details of methods and case studies, see Acreman et al., 2014b; Arthington, 2012).
Source: Adapted from Tharme (2003)

The first *hydrological methods* were simple, low-resolution estimates of the percentage of annual, seasonal, or monthly flow volume (often termed the *minimum flow*) that should be left in a river to maintain minimal fish habitat and/or acceptable stream condition (e.g., single figure flow recommendations based on low-flow indices, derived from flow duration curves such as Q95; Tharme, 2003). Hydrological methods are often called fixed-percentage or look-up table methods, as they rely on formulae linked to historical flow records to estimate desirable discharges. Unusual for its time, the Montana method (Tennant, 1976) stands apart from such desktop approaches inasmuch as the look-up table of percentages of average annual flow, which correspond to different degrees of desired river condition, was derived from an empirical base of field-level flow habitat and ecological (fish) studies of many small US streams of specific bio-physical character. Without appropriate validation for streams in new geographic regions or of different types, the use of the tabulated flow levels carries the risk of setting environmental water recommendations that are unsuitable (e.g., too high or too low) for local conditions; untested extrapolations of this kind remain a challenge common to many environmental flows assessment methods (Arthington, 2012). Hydrology-based methods have been variously elaborated over the years, and in the last decade or so have substantively advanced by taking a more regime-based approach that estimates a range of ecologically relevant streamflow characteristics such as magnitude, frequency, timing, and the duration of specific flood and low-flow events (e.g., Hughes and Hannart, 2003; Hughes et al., 2014; National Water Commission of Mexico, 2012; Richter et al., 2012).

Hydraulic rating methods emerged in parallel, with the intent to quantify how flowing water interacted with channel boundaries to create aquatic habitats of varying depth, velocity, substrate, and cover characteristics that varied over time with discharge pattern. The best known of these wetted perimeter methods define a minimum acceptable discharge that maintains wetted aquatic habitat for selected (*representative* and/or *critical*) channel cross-sections or stream reaches. These foundational hydraulic habitat methods paved the way for *habitat simulation* methods and associated tools (e.g., the *Physical Habitat Simulation [PHABSIM]* component of the *Instream Flow Incremental Methodology [IFIM]*; Bovee, 1982) and later, sophisticated innovations focused around two- and three-dimensional habitat modeling supported by spatially referenced habitat mapping techniques (Chapter 13). Habitat simulation methods, by virtue of their quantitative data and analytical demands, have been applied primarily to the description of habitat flow conditions for a few species (usually valued fish). Although efforts to expand these methods to the broader contexts of entire fish and macroinvertebrate communities have occurred, including through modeling of a range of habitat types occupied by different functional guilds (e.g., King and Tharme, 1994; Leonard and Orth, 1988; Parasiewicz, 2007), the many other facets of the flow regime and complex ecosystem requirements of rivers (Bunn and Arthington, 2002; Poff et al., 1997) require different kinds of methods (Section 11.3). Habitat simulation methods remain a vital and well-utilized tool, however, in desktop level (e.g., Hughes et al., 2014), habitat (with a focus on individual species threatened by loss of critical habitats), and holistic methods (Tharme, 2003). For examples of use in holistic frames, see Arthington et al. (2003), Blake et al. (2011), Illaszewicz et al. (2005), King et al. (2000), O'Keeffe et al. (2002), and USAID (2016).

11.2 HOLISTIC ENVIRONMENTAL FLOWS ASSESSMENT METHODS

11.2.1 EVOLUTION OF PRINCIPLES AND APPROACHES

The *holistic* or whole ecosystem perspective emerged conceptually from the growth in scientific understanding of flow−ecology relationships (see Section 6.3 and Chapter 14), as well as from a pressing need to reflect the flow conditions necessary to maintain the structure and function of entire ecosystems and the local communities and livelihoods they support (as was the case in South Africa; Tharme and King, 1998). By the late 1980s, the focus of river restoration and conservation or protection had begun to broaden well beyond individual species. Informed by advances in ecological theory, community and ecosystem perspectives explicitly incorporated the principle that hydrologic variability and disturbance are key to maintaining a dynamic aquatic environment that provides varying conditions under which many species can coexist over time (e.g., Resh et al., 1988). It similarly drew on new directions in geomorphological understanding of channel-forming processes over the same period (e.g., Hill et al., 1991; Newson and Newson, 2000; Petts and Calow, 1996; Rowntree and Wadeson, 1998).

This rapid transition to a new category of methods can be attributed to three separate strands of research and application that emerged in this period and eventually coalesced into the foundation of contemporary environmental water science (Fig. 11.1). One strand emerged simultaneously and collaboratively in Australia (Arthington, 1998; Arthington et al., 1992) and South Africa (King and Tharme, 1994; Tharme and King, 1998), where resource scientists were pursuing environmental water assessment and allocations based on multiple ecological targets, using modern hydroecological principles applied through expert judgment in specific, site-based river applications. These researchers and practitioners made fundamental contributions to the conceptual framing and elaboration of holistic environmental flows assessment frameworks to guide management of environmental water allocations (e.g., benchmarking and flow restoration methods, Arthington and Pusey, 2003; hierarchical application of methods and inclusion of social flow dependencies, King et al., 2003; Tharme, 1996) that are still widely used today.

A second source of activity was more academic, developing from investigation of how hydrologic disturbance in free flowing rivers could be analyzed statistically and classified across large hydroclimatic gradients. Following on Resh et al.'s (1988) articulation of the critical role of disturbance (extreme hydrologic events) in shaping the structure and function of lotic ecosystems, Poff and Ward (1989, 1990) developed a streamflow classification scheme based on flow metrics defined specifically to be ecologically relevant in covering the full range of hydrologic variation (from zero flow to peak flows). Similar regime-based ideas emerged in the United Kingdom (Gustard, 1979), Australia (Hughes and James, 1989), New Zealand (Biggs et al., 1990), and South Africa (Joubert and Hurly, 1994), as well as at the global scale (Haines et al., 1988). Flow metrics were extracted from long-term hydrographic data for unimpaired rivers to reveal geographically variable patterns of streamflow variability characterized by magnitude, frequency, duration, timing, and predictability of flow levels judged to be functionally important to riverine community and ecosystem processes. The focus on the theoretical role of natural disturbance regimes in regulating species performance and shaping whole communities and ecosystem states laid a strong foundation for future environmental water science and its application to rivers where hydrologic regimes, particularly their temporal variability and disturbance characteristics, were modified by dams or extensive water abstraction.

A third strand arose from the general perspective of river conservation and a desire to provide a method to enable managers to easily understand and more effectively manage the interrelationships between the types of flow alteration by dams and the ecological impairment downstream of them. The *Indicators of Hydrologic Alteration (IHA)* software program was developed by The Nature Conservancy and partners (Mathews and Richter, 2007; Richter et al., 1996) as a tool that calculated a diverse range of simple, but meaningful statistical metrics to characterize the alteration (in magnitude, frequency, duration, timing, rate-of-change, and variability) of the ecologically relevant components of an impaired flow regime. This readily available tool could be employed simply and universally in methods such as the *range of variability approach (RVA;* Richter et al., 1997), wherever there are discharge time series of pre- and/or postimpact hydrographs. The desktop IHA program has been highly successful, providing a common technical platform for assessment and comparison of flow alteration (as well as trend and seasonal comparative analyses) in rivers across the globe.

These three strands coalesced under the *natural flow regime* paradigm (Poff et al., 1997; Richter et al., 1997; Stanford et al., 1996), which later formed one of the foundational principles of the Brisbane Declaration (2007), an influential call for universal implementation of environmental water (see Arthington et al., 2010). *The natural flow regime (NFR)* paradigm provided a theory-based approach to understand the ecological roles of dynamic flow regimes, and a basis for evaluating the ecological consequences of flow alteration in any particular hydroclimatic setting (Bunn and Arthington, 2002; Lytle and Poff, 2004). It also supported frameworks for guiding environmental water efforts of two main types—environmental water to support the conservation of minimally impaired rivers and environmental water to guide restoration of highly flow-altered rivers (Arthington et al., 2010). The former circumstance requires maintaining components of an NFR to conserve biodiversity and ecosystem functions and services, whereas the latter is concerned with the restoration of key ecologically and socially relevant flow characteristics that have been lost through regulation or water abstraction.

A fundamental aspect of holistic approaches has been to use a long-term hydrologic time series of daily or monthly flows to derive a set of static flow metrics that quantify various aspects of the magnitude, frequency, timing, duration, and rate-of-change in discharge. The question as to which of many hundreds of flow metrics to use to characterize flow alteration in rivers has been approached in many ways, with the option to identify a final smaller, nonredundant suite through statistical filtering of metrics that are highly intercorrelated or convey redundant information (Olden and Poff, 2003). However, final selection of metrics is often largely arbitrary or highly context-dependent. Another approach to constrain metric selection has been to focus on key *functional* aspects of the flow regime that have clear ecological significance (e.g., Arthington and Pusey, 2003; Mathews and Richter, 2007; Yarnell et al., 2015). Regardless of the number of metrics used, the basic approach to quantifying hydrologic alteration has been to compare a current, modified hydrograph against a preimpact *baseline* hydrograph, which has generally been considered to reflect the *natural range of variation* (Auerbach et al., 2012; Richter et al., 1996) in ecologically relevant flow dimensions for a particular stream or river.

This general approach has allowed great ability to statistically compare river flow regimes in different hydroclimatic and geologic settings across large geographic extents. This facilitated classification of flow regime *types*, which in turn provided a template for how to stratify streams and rivers into hydrological classes that could be treated as similar management units (Arthington, et al., 2006; Poff et al., 2010). Flow typologies for unregulated (*natural*) rivers have proliferated over the years, and are available nationally for, among others, the United States (McManamay et al., 2014; Poff, 1996; Poff and Ward, 1989), Australia (Hughes and James, 1989; Kennard et al., 2010), New Zealand (Biggs et al., 1990), and individual large river basins such as the Huai River, China (Zhang et al., 2012), the Ebro River, Spain (Solans and Poff, 2013), and the Magdalena River Basin, Colombia (Walschburger et al., 2015). Some international comparisons of flow differences have also been pursued (e.g., Poff et al., 2006a,b). Extensive stream gauge networks have also allowed for the quantification of hydrologic alteration of regulated rivers (Carlisle et al., 2010; Mackay et al., 2014) and calls for a regulated river classification (Poff and Hart, 2002). However, streamflow classification systems for regulated rivers have not been developed as successfully, in part because of the somewhat idiosyncratic nature of flow alteration below dams (Mackay et al., 2014; McManamay et al., 2012; Poff et al., 2007).

11.2.2 A SURVEY OF HOLISTIC METHODS

The ease with which hydrologic data can be manipulated and placed into an *ecologically relevant* context led to new tools that could potentially guide environmental water assessment. For example, the RVA (Richter et al., 1996) was proposed as a simple rule to sustain a *normative* pattern of hydrologic variability (Stanford et al., 1996) in regulated rivers in the absence of strong empirical flow−ecology relationships. A similar hydrological approach of using *sustainability boundaries* around the natural (historical or other baseline) flow regime to establish presumptive guidelines for environmental water assessment has also been proposed, though rarely applied to date. There has, however, been a politically mobilized operational rule curve for Owen Falls Dam on the White Nile in Uganda, based on similar principles and in place since 1954 (M. McClain, pers. comm.). The approach uses risk-based envelopes reflecting decreasing levels of ecosystem protection with greater departure from the reference flow regime (Brizga et al., 2002; Richter et al., 2012). One disadvantage to this approach is that it is based on a statistical comparison of long hydrological time series and therefore not designed to guide short-term operations of dams to deliver environmental water. A similar precautionary, regime-based approach to setting environmental water regime standards is under development in the Magdalena Basin, Colombia (R. Tharme, pers. comm.).

The *building block methodology (BBM;* King and Louw, 1998; King et al., 2000) has been applied numerous times and at various levels of resolution in South Africa, as one of the standard methods for ecological reserve determination (King and Pienaar, 2011). It has also been adapted for local application in eastern African river basins (e.g., Rufiji Basin, Tanzania; USAID, 2016). In South Africa, environmental water regime prescriptions from available BBM applications have been grouped according to river hydrology, to extract more general hydroecological principles to guide assessment in rivers of contrasting hydrology such as the desktop reserve model (Hughes and Hannart, 2003). Its successor, the habitat flow-stressor response method, which is well aligned with the local holistic methods, is now widely applied for desktop-level reserve determination (Hughes et al., 2014). Some holistic methods, such as the BBM (e.g., Alfredsen et al., 2012) and Savannah method (Warner et al., 2014), have been developed for more proximate operational use for dynamic flow allocation.

The *Downstream Response to Imposed Flow Transformation (DRIFT)* methodology (King et al., 2003) evolved out of the BBM as a top-down, scenario-based alternative founded on a similar basis of flow−ecology relationships. King et al. (2003) developed DRIFT to meet the demand for a rigorous and transparent approach with the capacity to evaluate alternative scenarios of water management in data-rich and data-limited situations. The DRIFT methodology involves a robust collection of field and desktop procedures, database systems, and decision support tools for proactive planning of environmental water regimes for rivers (King et al., 2003). The DRIFT framework has been refined through many applications in major river basins in Africa and southeast Asia. It merged into a platform for Integrated Basin Flow Assessment, which can assess future development options in terms of potential changes in a wide range of river characteristics (e.g., channel configuration, riparian forests, estuarine water quality, and invasive species) and flow-related ecosystem services (e.g., food fish; Arthington et al., 2003), societal health, and well-being (Brown and Watson, 2007; King and Brown, 2010; King et al., 2014).

Another widely applied holistic framework is the Benchmarking Methodology (Brizga et al., 2002), used to set provisional limits on levels of hydrological alteration in many relatively undeveloped rivers in the coastal catchments of Queensland, Australia (see Arthington, 2012). Comparisons are made between near-natural *reference* reaches and a set of *benchmark* reaches that have experienced differing levels of impact resulting from existing water resource development (e.g., dams, weirs, pumped abstraction, or interbasin transfers of water). It can generate many scenarios of hydrologic alteration that are used to forecast likely ecological consequences and thus inform recommendations for flow regime implementation (Arthington, 2012). A limitation of this methodology is that it cannot be applied in places with few existing water infrastructure developments, because they are required to provide the negative benchmarks and ecological condition ratings that underpin risk assessment of future flow regime changes.

A generic framework for environmental water assessment that is holistic in scope, scenario-based, and that integrates scientific and social processes, has been developed and piloted in China (Gippel and Speed, 2010; Speed et al., 2011). It utilizes conceptual models of flow interrelationships with ecology, geomorphology, and water quality, to help establish environmental water release rules to maintain riverine and riparian ecological assets in a state of health that matches the agreed management objectives of stakeholders. Addressing river flows using a consistently applied environmental flows assessment methodology (e.g., some form of holistic ecosystem approach, Acreman and Ferguson, 2010) is also a goal of the *Water Framework Directive (WFD)* of the European Union (Council of the European Communities, 2000). The WFD sets the policy framework for restoration of aquatic ecosystems to *good ecological status* (referenced to aquatic biology) in most European rivers, lakes, and wetlands by 2015 (see also recent guidance under the European Commission, 2015).

A common challenge in the application of any environmental flows assessment method is how to characterize and account for uncertainty in relationships between flow alteration and ecological (or social) responses (Arthington et al., 2007; Stewart-Koster et al., 2010). Risk-based and probabilistic methods such as Bayesian methods and networks (Chapter 14) are a clear growth avenue for holistic methods to improve decision making in the face of such uncertainty. For example, the holistic method, Probflo, incorporates probabilistic elements of Bayesian network modeling and ecological risk assessment to evaluate probable socio-ecological consequences of altered flows and establish environmental water requirements for rivers, and it has been applied in Lesotho (Dickens et al., 2015). Efforts are also underway in several regions (e.g., in the Mara River Basin of Kenya and Tanzania) to further tailor Probflo for landscape-level application, borrowing from the architecture of *Ecological Limits of Hydrologic Alteration (ELOHA)* (Section 10.5). Bayesian network models that effectively integrate indigenous and scientific knowledge (Jackson et al., 2014) have supported environmental water decision making in the Daly River, Australia, showing, for example, that if current extraction entitlements were to be fully utilized, significant impacts on the populations of two iconic fish species would occur (Chan et al., 2012).

11.3 FLOW—ECOLOGY AND FLOW ALTERATION—ECOLOGICAL RESPONSE RELATIONSHIPS

At the core of environmental water science and assessment is the relationship between attributes of the flow regime and ecological responses to natural flow variability and to flow alterations, so-called flow—ecology relationships or flow alteration—ecological response relationships, respectively (Arthington et al., 2006; Poff et al., 2010). A tension that has persisted in environmental flows assessment science and application is the question of how much empirical testing of these hydroecological relationships is needed to justify curtailment of water development or flow restoration actions, both of which are often costly and socially challenging to implement. The first principles argument that *ecologically relevant* components of a flow regime should be retained or restored is generally supported by ecological theory (Bunn and Arthington, 2002; Monk et al., 2007; Poff and Ward, 1989; Poff et al., 1997). In the absence of quantitative understanding of how specific levels of magnitude, frequency, duration, and timing can be combined to achieve a desired level of ecological response, the principle of mimicking aspects of the NFR is often invoked from the conservation perspective of the so-called precautionary principle (*sensu* Myers, 1993).

However, a full restoration of natural flow pattern and timing is hardly feasible or necessarily desirable (Chapter 10) below all dams; therefore, the question arises: how much flow conservation (protection) or restoration is needed to effectively preserve or restore the ecosystem to some stated or desired level of condition? This question is long-standing in environmental water science (Richter et al., 1997), but human preferences are now acknowledged as a critical component of setting environmental water objectives (Acreman et al., 2014a; Brisbane Declaration, 2007; Poff et al., 2010). Setting specific restoration targets requires adequate empirical understanding of the relationship between flow alteration and ecological response (Arthington et al., 2006; Davies et al., 2014). Of importance here is whether there are critical thresholds above or below which key functions or elements of the ecosystem are impaired or lost (Arthington et al., 2006). These may include sufficient high flow to connect the river with its floodplain, or move sediment (Yarnell et al., 2015), or low flows that maintain within-channel connectivity between shallow (e.g., riffle) areas. Many flow—ecology relationships are better expressed as continuous curves and, therefore, pose greater challenges in identifying potential thresholds of change to guide management decisions. Irrespective of the nature of the flow—ecology relationship(s), the level of environmental water allocated should be decided using informed judgment or through a negotiated socio-political trade-off among all resource uses and users, including the river ecosystem (Acreman et al., 2014b; Arthington, 2012).

A persisting challenge for environmental water science is to develop robust and, if possible, transferrable flow—ecology relationships (Chapters 13 and 14). Environmental water knowledge generally derives from empirical flow—ecology relationships discovered through both extensive observational studies and manipulating and monitoring dam releases (see Poff et al., 2003), and a large body of environmental water knowledge has accumulated through these avenues

(Arthington, 2012; Olden et al., 2014; Chapter 14). However, environmental water knowledge can also be cogenerated by including local or indigenous perspectives on hydroecological relationships (Jackson et al., 2014). Given the many ways that flow variables and ecological response variables can be (and have been) defined and associated with one another at numerous spatial and temporal scales, generalization and transferability have proven a challenge. To date, generalized flow−ecology relationships that apply across hydroclimatic gradients and complex types of hydrologic alteration caused by dams have proven difficult to extract (Carlisle et al., 2011; Lloyd et al., 2003; Olden et al., 2014; Poff and Zimmerman, 2010; Webb et al., 2015). One incompletely explored avenue for developing a framework for generalization and transferability is the notion that *rules* could be developed for different hydrological types of streams (Arthington et al., 2006; Kennard et al., 2010; Poff and Ward, 1989; Reidy Liermann et al., 2012). Alternatively, different stream types may respond to dams and forms of flow regulation in particular ways (McManamay et al., 2012; Mackay et al., 2014; Poff and Hart, 2002; Poff et al., 2007; Rolls and Arthington, 2014). These avenues toward generalization and transferability merit more research.

A key working premise (assumption) of environmental water assessment has been that flow is a master variable and alteration of the flow regime leads directly to significant ecological responses. Environmental water has primarily and deliberately focused on flow management, because preventing or reversing flow alteration is a necessary condition to sustain or restore the ecological integrity of riverine species and ecosystems. Moreover, reregulation of the flow regime below a dam is relatively easily achieved compared to other types of environmental modification such as altered thermal and sediment regimes. However, from the fuller perspective of riverine ecology, we would expect to only partially explain flow−ecology relationships if we do not include key partially independent variables such as temperature (Olden and Naiman, 2010), sediment (Wohl et al., 2015), and species interactions (Shenton et al., 2012). Thus, the *noisy* flow−ecology relationships that emerge from literature reviews (e.g., Olden et al., 2014; Poff and Zimmerman, 2010) are to be expected.

Expanding the environmental water domain to include other key drivers of ecological process and pattern is not a new idea (e.g., Olden and Naiman, 2010; Poff et al., 2010; Chapter 22). Relationships between flow, thermal, and sediment alteration are likely to be site-specific (or perhaps stream class-specific), raising further challenges in how to adequately characterize environmental change in a generalized, quantitative, and transferrable framework that can guide effective ecological conservation or restoration. Comodeling of thermal and flow conditions is not well developed, but could be improved to help guide reoperation of flow depth releases to improve downstream temperature regimes for ecological recovery (e.g., see Maheu et al., 2016; Olden and Naiman, 2010).

Incorporation of sediment dynamics and channel structure has proven more challenging for environmental water science and implementation, and the need has been long recognized (Hill et al., 1991; Newcombe and Jensen, 1996; Poff et al., 2006 a,b; Rowntree and Wadeson, 1998; Tharme, 1996). Modeling the *natural sediment regime* is difficult (Wohl et al., 2015) because sediment dynamics depend on many catchment characteristics (soils, geology, topography, vegetation) and regional precipitation regime. It is important, however, because in regulated rivers where sediment dynamics are severely out of balance due to upstream storage of sediment by a dam, the *hydraulics* of habitat can change dramatically, such that flow restoration can lead to further habitat modification downstream rather than habitat restoration (see Wohl et al., 2015; Yarnell et al., 2015). Thus, hydrology-based models that fail to account for flow interactions with the channel boundaries and transport of sediment will incompletely capture habitat dynamics and ecological response potential below many dams due to the sediment−water disequilibria.

There is a need to integrate hydraulic and hydrologic models into environmental water applications (Chapter 13); however, a particular challenge is the issue of scale. Hydraulic habitat models are data hungry and best applied at local (reach) scales. The regional nature of many environmental water applications (see below) places logistical and cost constraints on the extent to which hydraulic models and data can be employed in multisite models. Simple geomorphic classification of stream reaches across stream networks (based on slope, geology, etc.) can act as first-order hydraulic surrogates (Poff et al., 2010), but a better approach will be to develop hydraulic regionalization models (e.g., Wilding et al., 2014) that can be combined with hydrologic models to provide insight into habitat structure and dynamics across many sites simultaneously.

11.4 FROM LOCAL TO REGIONAL SCALES OF ENVIRONMENTAL WATER ASSESSMENT

In the past, environmental water methods have generally focused on management of flow regimes in the highly regulated sections of rivers downstream of major water storages. These reaches are often in need of significant flow management to attain some desired ecological condition; however, the consensus among riverine scientists is that ecological impairment from flow alteration is not restricted to river reaches immediately below dams (Acreman et al., 2014b; Bunn and Arthington, 2002; Dudgeon et al., 2006; Nilsson et al., 2005; Poff and Matthews, 2013). Consequently, a broader scope for environmental water management would extend to entire river systems in a regional context, where the network may include a mix of regulated and still undeveloped streams/rivers. Developing a regional (or multisite) environmental water approach is made difficult by the lack of detailed hydrologic and/or ecological information at poorly studied localities, and by the reality that most unstudied sites do not have records of known reference (prealteration) conditions (Flotemersch et al., 2015). Arthington et al. (2006) addressed this challenge by proposing to classify streams in a region into similar streamflow regime types based on unimpaired hydrology; the range of variation in the flow components defining the NFRs across the replicate, unimpaired streams for that class type could be considered as the bounds for *reference* hydrologic conditions. Localities with ecological data could be assigned to a particular flow class and then flow−ecology relationships generalized for unstudied streams in that same class. Through modeling, flow-altered streams could be assigned to the most appropriate unimpaired flow regime type, such that even unstudied, flow-altered streams could be statistically assigned a reference condition. For example, highly seasonal snowmelt-driven streams have different hydrologic conditions of magnitude, frequency, timing, duration, and rate-of-change than do stable groundwater-dominated streams (see Arthington et al., 2006; Poff and Ward, 1989) and the ecological effects of flow alteration by dams on these different types of rivers should manifest differently. This approach has an explicit empirical, hypothesis-driven foundation.

The ELOHA (Poff et al., 2010) extended the Arthington et al. (2006) approach by formalizing a scientific and social framework that can be used to guide the setting of flow prescriptions at the stream reach scale throughout entire stream networks (Fig. 11.2). ELOHA is a framework that represents a coalescence of precursor methods and approaches in environmental water science and assessment. It provides a multistep process of building a hydrologic foundation (modeled hydrographs for ungauged stream segments), streamflow classification, a further geomorphic substratification, assigning flow-altered streams to preimpact reference stream types, developing flow–ecology and flow alteration–ecological response relationships for stream types, and incorporating social preferences in the environmental water ecological targets. A guiding principle of ELOHA is that ecological responses to particular features of the altered flow regime can be interpreted most robustly and usefully when there is some mechanistic or process-based relationship between the ecological (or social) response and the particular flow regime component (Poff et al., 2010). Flow alteration–ecological response relationships can be compiled from existing data, or new data collected along a flow regulation gradient, and tested statistically to determine the form (e.g., threshold, linear) and degree of ecological change (positive or negative) associated with a particular type of flow regime alteration (Arthington et al., 2006).

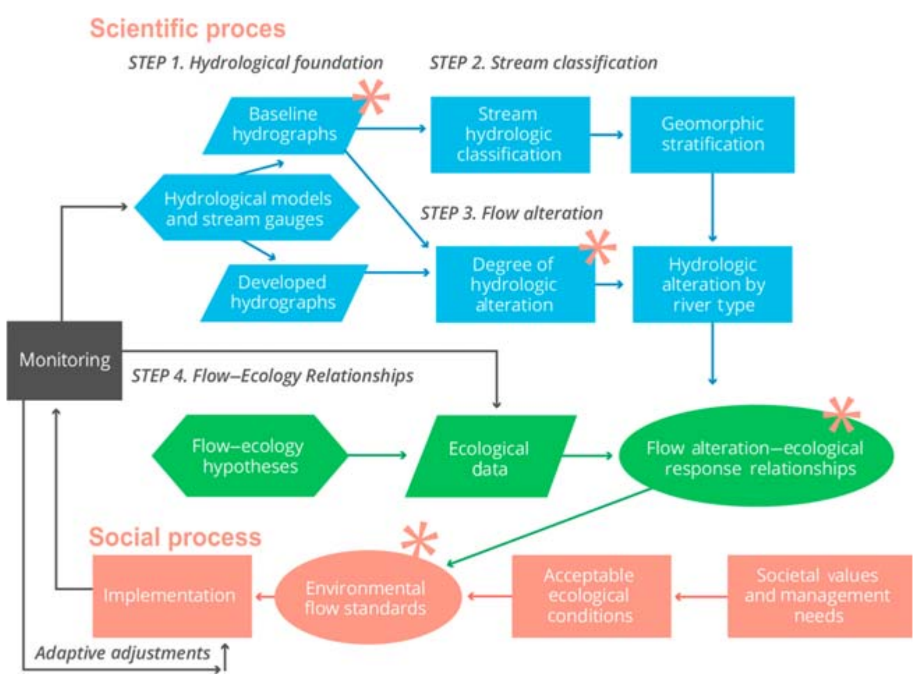

FIGURE 11.2

Framework for determining environmental water requirements for multiple sites throughout a region (river network[s]) as presented by the *Ecological Limits of Hydrologic Alteration (ELOHA)*. Stars indicate steps in the scientific process where the assumption of stationarity is implicit. Implementation, monitoring, and adaptive refinement of the recommended flows form part of the intimately linked social process, which can trigger additional scientific analysis or generation of new knowledge.

Source: Modified from Poff et al. (2010)

The ELOHA framework can be applied at various degrees of resolution in hydrologic data, hydroecological understanding, and ecosystem types. For example, Zhang et al. (2012) demonstrate how flow classification based on monthly flow records, although not ideal, can provide useful insights to support environmental water assessments and restoration in rivers where daily flow records are typically unavailable. Similarly, Sanderson et al. (2012) used monthly hydrologic data to assess potential risk to socially valued ecosystem components due to river damming and stream diversion throughout a small river basin. Studies following the ELOHA framework are developing new hydroecological knowledge for hydrological river classes in several regions (e.g., James et al., 2016; Mackay et al., 2014; McManamay et al., 2013; Rolls and Arthington, 2014).

The ELOHA framework can be used under widely differing governance and management systems (Pahl-Wostl et al., 2013) and more explicitly include indigenous knowledge, cultural services, and other social dimensions (Finn and Jackson, 2011; Jackson et al., 2014; Martin et al., 2015). In southern Mexico, for instance, ELOHA is being piloted for a collection of small coastal basins in Chiapas State, reflecting a diversity of river types, socio-economic contexts, and institutional arrangements for water management (Haney et al., 2015). Finn and Jackson (2011) propose a modified form of ELOHA with the potential capability to address the qualitative elements of indigenous people's ideas, beliefs, and socio-cultural relationships to water and rivers developed over many centuries of close interaction with aquatic ecosystems and dependence upon aquatic resources.

The framework has been adopted by US regulatory agencies (Kendy et al., 2012), and used as a foundation for regional river basin planning (e.g., see de Philip and Moburg, 2010, 2013) and multisite analysis of hydroecological impairment and prioritization of flow restoration (Martin et al., 2015; Sanderson et al., 2012). Applications of ELOHA in flow regime restoration in the Cheoah River (Upper Tennessee River Basin) demonstrated that, whereas fish richness did not increase as expected, recommended increases in flow magnitude reduced riparian encroachment within 4 years after flow restoration, as predicted from relationships between flow alteration and riparian responses (McManamay et al., 2013). In Colombia's Magdalena-Cauca Basin, a decision support system for basin water management has been evolving over the last few years, at both whole basin and lower administrative scales, that integrates ELOHA with elements of the Water Evaluation and Planning System software tool (http://www.weap21.org, see an example in Thompson et al., 2012) and IHA. It allows preliminary analyses to be made of future cumulative socio-ecological impacts by river type and of different scenarios of hydrological regime alteration across the river network (e.g., from urban water abstractions, planned and existing hydropower projects and irrigation). If implemented, it will enable environmental water to be set and adaptively monitored at management points of interest basin-wide (R.E. Tharme, pers. comm.).

The application of environmental water science at both the regional and local scales highlights the importance of appropriate tool selection in environmental water assessment and management (Fig. 11.3). Local, at-a-site application typically employs detailed hydrologic measurement (from streamflow gauges), high-detail hydraulic models, and potentially fine-scale ecological responses (e.g., species population dynamics or changes in abundance) supported by ecological modeling and with monitoring over time. Experimentation has occurred at this scale to test flow−ecology relationships and ecological responses to flow management (see review by Olden et al., 2014).

By contrast, regional methods involve modeling at unstudied locations and therefore generally rely on statistical tools and remote sensing to transfer information from studied reaches to locales

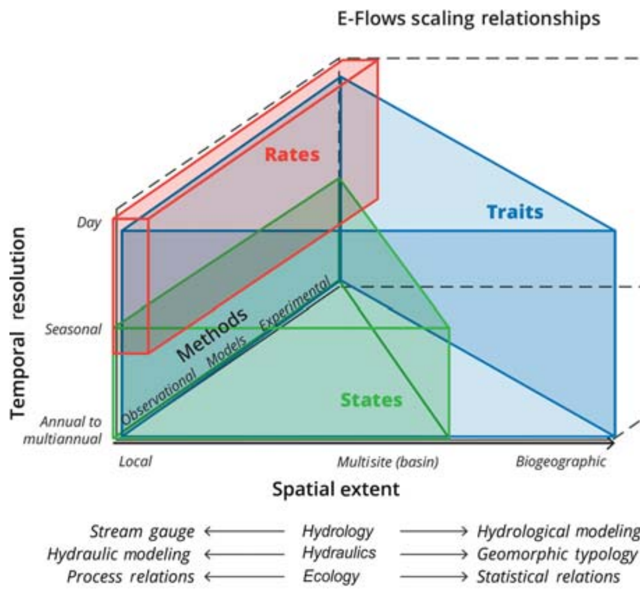

FIGURE 11.3

General scaling relationships in environmental water. Spatial grain of environmental water application (X-axis) ranges from local (single-site reach) to regional (multiple sites or whole stream networks) to biogeographic (where species replacements and shifting species pools naturally occur). Along this axis the tools that are available to characterize hydrologic setting, hydraulic conditions, and ecological relations vary. The Y-axis reflects methods of environmental and ecological data acquisition, from observation of existing conditions relationships, to modeling of relationships, to experimental manipulations of systems to observe responses. Observations can be collected at all spatial extents, and modeling can extend over large extents, but experiments are local in scope due to expense and logistics. The Z-axis shows the timescales over which different types of ecological responses occur. Ecological states (small triangular polygon) are species-based response variables that are limited to seasonal to annual turnover or response times within species' geographic ranges. Ecological rates (small rectangular polygon) are high-frequency response variables that can be measured over short timescales (days) (e.g., population growth or death rates, biogeochemical exchange rates) but that are applied at the local scale given data requirements. Ecological traits (large triangular polygon) are integrative measures of species function or performance (e.g., functional groups, life-history modes, dispersal ability) that can be generalized across species and hence biogeographic boundaries. Traits can be selected to reflect a range of temporal scales, from annual (e.g., inundation regime required) to daily (e.g., tolerance of transient extreme conditions). See text for further discussion.

that lack site-specific data. The broader extent is associated with lower information availability. Coarser hydrologic characterization (based on model calibration to a few gauges in the region) leads to the need for flow classification. Detailed hydraulic modeling is infeasible, so some kind of regionalization based on geomorphic surrogates is needed to generate surrogates of fine-scale hydraulics (e.g., Wilding et al., 2014; Chapter 13). Coarse-grained ecological metrics are also more appropriate, given the prohibitive cost of monitoring multiple sites.

11.5 NEW CHALLENGES FOR ENVIRONMENTAL WATER: MOVING FROM STATIC SYSTEMS TO NONSTATIONARY DYNAMICS

Environmental water science and assessment, like the broader supporting fields of water resources and conservation ecology, have long operated under the assumption of climatic stationarity, for instance precipitation and runoff processes occur within some statistically describable range of variation. The presumption of a stable climate created a scientific and management perspective that conveniently allowed environmental water to treat hydrologic variation and hydroecological dynamics in relatively static terms. Dynamic flow regimes from reference sites could be characterized by time-averaged statistical properties of ecological relevance such as average values (or standard deviations) of the frequency, duration, and timing of particular flow magnitudes. Similarly, ecological response variables could be treated in terms of alteration from some dynamically equilibrial, historical (reference) state (Poff, 2014).

In the last decade it has become clear that the global climate system is *nonstationary* (Milly et al., 2008) and that hydrologic *baselines* are dynamically changing, such that future hydrologic regimes will, in many locations, be significantly different from those of today (e.g., Laize et al., 2014; Reidy Liermann et al., 2012). Reliance on the assumption of historical flow conditions is no longer feasible for long-term planning in most systems due to rapid climate change and other sources of change, including population growth and increasing water demand (Acreman et al., 2014a; Kopf et al., 2015; Poff et al., 2016). In addition, natural ecological communities are rapidly changing with the spread of nonnative species and human-caused degradation (Humphries and Winemiller, 2009), making ecological restoration targets dynamic and variable (Moyle, 2014; Rahel and Olden, 2008).

Climatic and other sources of nonstationarity have thrust the science and management of environmental water into a new era. There is now a need to transition from a largely static to a more dynamic perspective, what has been referred to as a *process-based* understanding and framework for management of rivers (e.g., Beechie et al., 2010). This fundamentally means moving beyond strong reliance on simple correlations between flow variables and ecological responses to a more nuanced understanding of how ecological systems respond to dynamic hydrologic variation. New forms of ecological modeling that emphasize hydroecological process relationships (Chapter 14) can help guide targeted management in a more uncertain future.

Of course, even in highly modified and transient conditions, ecological principles of what might be called *natural flows thinking* will remain important (Acreman et al., 2014a; Auerbach et al., 2012; Kopf et al., 2015) and historical pattern−process relationships will continue to provide a key understanding of the historical and evolutionary context of species adaptations and ecosystem responses to environmental change (see Wiens et al., 2012 for a broad, comprehensive treatment of this issue). Understanding pattern−process relationships of the past helps us to manage the challenges of the present and predict possible futures under changing climates and novel ecological, social, and political environments. Existing frameworks such as ELOHA will continue to guide regional environmental water assessments; however, adjustments will need to be made due to current reliance on stationarity assumptions (see Fig. 11.2 notations), but the required evolution of environmental water in a nonstationary world will pose challenges because environmental water management is likely to become more locally contingent and to entail the loss of the relative comfort of fixed management targets that could be presumed under the long-held assumptions of climatic and ecological stationarity.

A key challenge associated with nonstationarity is to broaden the scope and scale and put environmental water into a larger landscape context of stream connectivity (Poff and Matthews, 2013). This challenge is driven by several factors, including the global biodiversity crisis and degradation of freshwater ecosystems (Dudgeon et al., 2006; Strayer and Dudgeon, 2010) and the competing societal demands for a shrinking freshwater resource. Environmental flows assessments will increasingly be applied beyond a multisite perspective, embodied in ELOHA, to a multibasin-scale perspective where water infrastructure's impact on regional diversity becomes part of a broader conservation or adaptation planning framework that accounts for habitat connectivity and species movements in hydrologically altered and fragmented stream networks (e.g., Jager et al., 2015; Poff, 2009; Winemiller et al., 2016). Conservation (or preservation) and restoration goals will need to be articulated in the context of competing human needs for freshwater, as exemplified in the contemporary basin-scale framing of water resources management as the *nexus* of food, water, and energy.

Environmental water is likely to evolve rapidly over the coming years, due to increasing human demand for water coupled with degrading aquatic ecosystems. Two fundamental challenges face the science of environmental water assessment in its quest to provide sound guidance and support to society on the management of human-impacted rivers to sustain or promote ecological integrity. These challenges focus on a necessary broadening of traditional approaches in environmental water science, with respect both to hydrologic characterization and ecological (and increasingly, also social) responses.

11.5.1 HYDROLOGY: REGIMES AND EVENTS

The hydrologic *regime* represents a template that influences how well species will persist and be capable of accommodating natural (and manmade) hydrologic change (Poff et al., 1997; Puckridge et al., 1998). Species have morphological, behavioral, or physiological traits that allow them to flourish under different types of hydrologic variation. Large differences in magnitude, frequency, duration, and timing of flow events among streams lead to the expectation of patterns of species abundance and persistence in hydrologically distinct streams (Poff et al., 1997). The relative stability of the global climate over the last approximately 10,000 years of the Holocene period has allowed hydrologists to consider the historical (instrumental) record to capture reasonably well the long-term, climatically driven flow regime, although pervasive land-use change has modified rainfall-runoff processes in long-settled regions (Acreman et al., 2014a).

Regime-based thinking has dominated environmental water over the last decades, but nonstationarity is presenting new challenges and alternative modes of framing how hydrologic alteration drives ecological responses. Individual hydrologic events often act as critical disturbances that may individually exert large and lasting effects on local populations or habitat structure. Thus, a focus on patterns of more immediate antecedent flows is arguably just as important as regime-based metrics in understanding and managing flow−ecology relationships. This perspective is increasingly relevant for management of nonstationary regimes where increasing variance in extremes is expected, exposing species to more frequent or intense extreme hydrologic events and perhaps simultaneously exacerbating extinction risk for small populations living in fragmented habitats

(Olden et al., 2007). Natural flow regimes are already shifting (e.g., snowmelt timing in western US streams; Stewart et al., 2005) and are projected to do so at an accelerated pace in the coming decades (e.g., Laize et al., 2014; Reidy Liermann et al., 2012). These trends suggest that environmental water management in the future will need to pay particular attention to novel sequences of hydrologic events that may shape ecosystems in new ways.

In some locations, environmental water applications are being specifically cast in the context of restoring specific elements of the flow regime that support the life-history needs of one or more target species, for example timed flow releases to aid cottonwood tree recruitment (Rood et al., 2003), or to give advantage to native fishes (Kiernan et al., 2012), or to eliminate recruitment bottlenecks for aquatic insects below hydropeaking dams (Kennedy et al., 2016). In situations where water is highly contested, environmental water releases are likely to be judged not only in terms of their measurable ecological benefits but also in terms of economic efficiency and other social considerations (Chapter 27; Poff and Schmidt, 2016). Thus, climate change that brings heightened uncertainty about future water availability will place new constraints on environmental water. However, new opportunities for environmental water management are likely to arise as well, such as the use of dams to provide cool water for downstream fishes (Thompson et al., 2012), or to provide flow refuges for species of interest (Shenton et al., 2012), or to manage against extreme low-flow conditions that may disadvantage native versus nonnative fishes (Ruhi et al., 2015). These kinds of strategic releases may be adjusted to achieve varying management in response to natural interannual variability of flow events, such as *dry* versus *wet* years, as occurs frequently in South African holistic reserve determinations (R.T. Tharme, pers. obs.) and has been proposed for some environmental water projects in the United States (Muth et al., 2000).

11.5.2 ECOLOGY: STATES, RATES, AND TRAITS

Nonstationarity applies to the ecological domain as well, insofar as riverine species distributions and local composition of communities are being reshuffled in response to human-assisted spread of nonnative species (Olden et al., 2004) and to species range changes in response to climate change (Rahel and Olden, 2008).

In the practice of environmental water, the broad question is what are the appropriate ecological *performance indicators* that can be used to gauge success of flow management? *Environmental water* science and practice have been mostly framed in terms of relatively static ecological endpoints such as ecosystem *states*, for example community composition or maintenance of key ecosystem features (riparian structure and condition) or target species populations (Arthington et al., 2006; Poff et al., 2010). This state-based approach has employed the implicit assumption that habitat is limiting and flow restoration improves ecological condition by providing more habitat for species that are often assumed to be *adapted* to the local flow regime (see Lytle and Poff, 2004). The dynamic processes that underlie the assembly of ecosystem states (e.g., connectivity to source populations and variable species' dispersal abilities, differential growth and mortality rates among species, species interactions of competition, predation, and facilitation) are typically ignored in environmental water science and assessment. However, increasing hydrological and ecological variance under nonstationarity will, inevitably, present novel conditions outside of historical, reference-based understanding. Consequently, predicting ecosystem states will require a more process-based (or *mechanistic*) understanding of key hydroecological linkages to guide flow management toward particular ecological endpoints (Beechie et al., 2010; Poff and Matthews, 2013).

Additional ecological endpoints beyond ecosystem states are needed to achieve a greater process basis in environmental water science and practice. One would be underlying biological and ecological *rates*, which can be conceived at the ecosystem level (i.e., rates of nutrient cycling or of production, e.g., Doyle et al., 2005) or at the individual or species population level such as environmentally sensitive and dynamic changes in growth, mortality, and colonization rates (e.g., Auerbach, 2013; Bond et al., 2015; Lancaster and Downes, 2010; Lytle and Merritt, 2004; Yen et al., 2013). These dynamic ecological representations correspondingly demand more attention to dynamic hydrologic processes such as the magnitudes and sequencing of extreme events that may create nonlinearities in ecological response beyond the simple *averaging* approach of traditional hydrologic statistical metrics (e.g., Ruhi et al., 2015; Shenton et al., 2012). Process-based environmental water management has been proposed (Anderson et al., 2006) but not widely employed. One significant challenge with a purely process-based approach is that it is often difficult to collect detailed information necessary to model population dynamics for more than a few species (e.g., Shenton et al., 2012). Thus, this approach may be most suitable for local applications or for particular species of concern where financial resources and scientific capacity are available.

One possible way to suffuse environmental water science with more process-based understanding at the community and ecosystem scales would be to take a more general, functional approach to species characterization, for instance *traits* of species rather than identities of species as ecological response units. Traits are organismal attributes that can be effectively related functionally (*mechanistically*) to environmental conditions (Poff, 1997; Verberk et al., 2013; Webb et al., 2010). Trait assignments have been assembled for various types of species including stream insects (Poff et al., 2006 a,b), fish (Mims et al., 2010, 2012; Olden et al., 2008), and riparian flora (Merritt et al., 2010). There are a growing number of traits-based or *functional* analyses of ecological response to hydrology, hydrologic alteration (or to climate change) that perhaps provide a middle ground of complexity between state-based and process-based analyses.

11.6 CONCLUSION: GUIDING ELEMENTS FOR BEST PRACTICE IN ENVIRONMENTAL FLOWS ASSESSMENT

We can view the development and evolution of environmental flows assessment as one of increasing technical sophistication and expanding focus, from single species to whole ecosystems to socioecological sustainability, as well as to more strongly empirically based flow−ecology relationships (Acreman et al., 2014b; Arthington, 2015; Poff and Matthews, 2013). Advances have helped promote the widespread recognition of the importance of environmental water for sustainable water management policies and water allocation plans, but schemes for active implementation lag behind on a global scale (Le Quesne et al., 2010; Chapter 27; Table 11.1). In this process of advancement and innovation, several critical elements of a full understanding of human alteration of aquatic systems have been underdeveloped. Among them are the inclusion of other key environmental drivers (sediment and temperature regimes) and hydraulic modeling, as well as a greater appreciation of the importance of flow sequences (not just long-term averages). From an ecological perspective, development of a more pluralistic and regionally calibrated approach to a range of ecological responses (states, rates, and traits) is now needed to improve the scientific foundations of environmental water. This is especially as pressures on limited freshwater resources increase with expanding human population growth and water demand and as systems becoming increasingly nonstationary hydrologically and ecologically with rapid climate change. The social sciences dimensions of environmental water, including an appreciation of the major social drivers, the conceptual foundation and empirical knowledge of important relationships between flow regime change and social responses, and methodology integration, also remain weakly developed.

Addressing these various, diverse elements is necessary to achieve more effective environmental water science and practice and to redress the persistent gap in implementation. To this end, we believe that environmental water can build on its past accomplishments, continue to innovate, and be successfully applied in a variety of settings. Here, we offer a set of general guiding principles or elements that are most likely to promote the successful progression and implementation of environmental water, for instance those that will facilitate achieving desirable outcomes for river ecosystems and for people and societies.

Guiding Element 1: *Clearly and quantitatively describe flow−ecology and flow−social relationships.* Flow−ecology relationships will continue to provide the foundation of environmental water applications (Chapter 14). Clear specification of flow−ecology relationships is key to shaping justifiable management expectations and ecological restoration objectives and hence to environmental water success (Davies et al., 2014; Poff and Schmidt, 2016). There are innumerable possible relationships that can form the foundation of an environmental water application. Selection of the most appropriate relationships for each environmental water application reflects a balance of ecological understanding, hydrologic modeling capacity, and management potential (Poff et al., 2010). Further, the selection and modeling of flow−ecology relationships must be understandable to managers, government agencies, and the public, as should the uncertainty contained in these relationships (Chapter 14).

Guiding Element 2: *Engage stakeholders to collaboratively set environmental water vision and objectives.* It is increasingly clear that environmental water restoration (or conservation) objectives are most likely to be achieved when they are collaboratively generated and agreed upon by multiple stakeholders, not just scientists (Chapter 7; Rogers, 2006). Science alone cannot objectively identify what the endpoints of environmental water restoration should be, because endpoints must reflect social values and appropriate socio-ecological goals of concern (Acreman et al., 2014b; Jackson et al., 2014; Roux and Foxcroft, 2011). This will require, in many instances, an explicit integration of social sciences and indigenous or stakeholder knowledge into the descriptions of relationships with flow (see Guiding Element 1).

Guiding Element 3: *Carefully identify what can be attained (and what cannot) from an implementation of environmental water regimes.* Flow manipulations alone are limited in terms of full ecosystem restoration, and other factors (e.g., highly altered thermal or sediment regimes, increasing urbanization or demographic shifts) may limit the extent to which flow management alone can achieve desirable outcomes. Objective assessment of the feasibility of achieving a stated environmental water objective is critical to building credibility of environmental water science as it is applied in ever more complex water resources settings (Acreman et al., 2014b), including climate change (Poff et al., 2016). Appreciating the basin management context and understanding the opportunities for integrated land and water resources management are also important when defining the scope and potential for environmental water to meet ecological targets (King and Brown, 2010).

Guiding Element 4: *Clearly identify at what spatial and temporal scale environmental water applications are appropriate and intended.* A range of possible environmental water frameworks exist that are appropriate across a range of spatial and temporal scales (Table 11.1; Figs. 11.2 and 11.3). Trade-offs in modeling precision and ecological prediction are associated with scale of application; therefore, it is critical to clearly identify scale and to identify which specific methods and tools can best be employed. Similarly, the social spheres of influence and factors for inclusion differ with such changes in scale.

Guiding Element 5: *Make efforts to engage with the proponents and engineers of new water infrastructure developments or proposed relicensing opportunities for existing infrastructure.* Early engagement with water resources developers helps create a bridge between impact assessments (project or strategic planning) and the environmental water process, helps target necessary baseline data collection on potential risks to regime change, and calls attention to the implications for downstream people and ecosystems of water development and management. Early engagement has the potential to more effectively influence project design (e.g., Richter and Thomas, 2007), operational regimes, and of course also decisions on the placement of infrastructure in river networks (e.g., King and Brown, 2010; Opperman et al., 2015; Poff et al., 2016), all of which play pivotal roles in securing environmental water.

Guiding Element 6: *Consider how environmental water goals and applications embed within and interact with other realms of influence that emerge with water governance and management at system scales.* Environmental water frameworks are increasingly of interest to larger spheres of management, social, and economic influence (see Fig. 11.1), such as systematic conservation planning (Nel et al., 2011), *Integrated Water Resources Management (IWRM*; Overton et al., 2014), and associated water allocation systems (Chapter 17). Socio-economic dimensions and governance contexts are increasingly recognized as critical to incorporate into environmental water assessments and effective management (Arthington et al., 2010; King et al., 2014; Pahl-Wostl et al., 2013). Environmental water applications should seek points of connection to these broader spheres of interest, in order to increase the social relevance and visibility of the environmental water activities.

Guiding Element 7: *Incorporate nonstationarity and process-based understanding into environmental water science and implementation to meet a new future.* A key challenge to environmental water science and an emerging and enduring context for environmental water applications is the issue of nonstationarity in hydrologic and ecological (and probably socio-political) conditions. Reference hydrologic and ecological conditions are increasingly impractical to establish, raising the need to shift many environmental water projects from a restoration focus to an adaptation focus (Palmer et al., 2009; Poff and Matthews, 2013; Poff et al., 2016; Thompson et al., 2014). Environmental water implementation can be a major element of more broad-based climate change adaptation in water resources (Matthews et al., 2009). Critical to meeting this challenge is the need for environmental water science to develop a better *process-based* understanding of hydroecological relationships, to allow for more dynamic management of regulated and highly modified river systems in order to meet, often by design, socially desired ecological targets that may be shifting through time as human population growth and climate change continue to accelerate the alteration of hydrologic systems into the future.

REFERENCES

Acreman, M., 2016. Environmental flows – basics for novices. WIREs Water 3, 622–628. Available from: http://dx.doi.org/10.1002/wat2.1160.

Acreman, M.C., Dunbar, M.J., 2004. Methods for defining environmental river flow requirements – a review. Hydrol. Earth Syst. Sci. 8, 121–133.

Acreman, M.C., Ferguson, A.J.D., 2010. Environmental flows and the European Water Framework Directive. Freshw. Biol. 55, 32–48.

Acreman, M., Arthington, A.H., Colloff, M.J., Couch, C., Crossman, N.D., Dyer, F., et al., 2014a. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Front. Ecol. Environ. 12, 466–473.

Acreman, M.C., Overton, I.C., King, J., Wood, P.J., Cowx, I.G., Dunbar, M.J., et al., 2014b. The changing role of ecohydrological science in guiding environmental flows. Hydrol. Sci. J. 59, 433–450.

Alfredsen, K., Harby, A., Linnansaari, T., Ugedal, O., 2012. Development of an inflow-controlled environmental flow regime for a Norwegian river. River Res. Appl. 28, 731–739.

Anderson, K.E., Paul, A.J., McCauley, E., Jackson, L.J., Post, J.R., Nisbet, R.M., 2006. Instream flow needs in streams and rivers: the importance of understanding ecological dynamics. Front. Ecol. Environ. 4, 309–318.

Annear, T., Chisholm, I., Beecher, H., Locke, A., Aarrestad, P., Burkhard, N., et al., 2004. Instream Flows for Riverine Resource Stewardship. Instream Flow Council, Cheyenne, Wyoming.

Arthington, A.H., 1998. Comparative evaluation of environmental flow assessment techniques: review of holistic methodologies. LWRRDC Occasional Paper 26/98. LWRRDC, Canberra, Australia.

Arthington, A.H., 2012. Environmental Flows: Saving Rivers in the Third Millennium. University of California Press, Berkeley, California.

Arthington, A.H., 2015. Environmental flows: a scientific resource and policy tool for river conservation and restoration. Aquat. Conserv. Mar. Freshw. Ecosyst. 25, 155–161.

Arthington, A.H., Pusey, B.J., 2003. Flow restoration and protection in Australian rivers. River Res. Appl. 19, 377–395.

Arthington, A.H., Zalucki, J.M. (Eds.), 1998. Comparative evaluation of environmental flow assessment techniques: review of methods. LWRRDC Occasional Paper 27/98, LWRRDC, Canberra, Australia.

Arthington, A.H., Bunn, S.E., Pusey, B.J., Blühdorn, D.R., King, J.M., Day, J.A., et al., 1992. Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems. In: Pigram, J.J., Hooper, B.P. (Eds.), Proceedings of an International Seminar and Workshop on Water Allocation for the Environment. Centre for Water Policy Research, Armidale, Australia, pp. 69–76.

Arthington, A.H., Bunn, S.E., Poff, N.L., Naiman, R.J., 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecol. Appl. 16, 1311–1318.

Arthington, A.H., Baran, E., Brown, C.A., Dugan, P., Halls, A.S., King, J.M., et al., 2007. Water requirements of floodplain rivers and fisheries: existing decision support tools and pathways for development. Comprehensive Assessment of Water Management in Agriculture Research Report 17. International Water Management Institute, Colombo, Sri Lanka.

Arthington, A.H., Naiman, R.J., McClain, M.E., Nilsson, C., 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Freshw. Biol. 55 (1), 1–16.

Arthington, A.H., Mackay, S.J., James, C.S., Rolls, R.J., Sternberg, D., Barnes, A., et al., 2012. Ecological limits of hydrologic alteration: a test of the ELOHA framework in south-east Queensland. National Water Commission Waterlines Report 75. Canberra, Australia.

Arthington, A.H., Rall, J.L., Kennard, M.J., Pusey, B.J., 2003. Environmental flow requirements of fish in Lesotho Rivers using the DRIFT methodology. River Res. Appl. 19 (5–6), 641–666.

Auerbach, D.A., 2013. Models of *Tamarix* and riparian vegetation response to hydrogeomorphic variation, dam management and climate change. PhD Dissertation. Colorado State University, Colorado.

Auerbach, D.A., Poff, N.L., McShane, R.R., Merritt, D.M., Pyne, M.I., Wilding, T.K., 2012. Streams past and future: fluvial responses to rapid environmental change in the context of historical variation. In: Wiens, J.A., Hayward, G.D., Safford, H.D., Giffen, C. (Eds.), Historical Environmental Variation in Conservation and Natural Resource Management. John Wiley & Sons, Ltd, Chichester, UK, pp. 232−245.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., et al., 2010. Process-based principles for restoring river ecosystems. BioScience 60, 209−222.

Biggs, B.J.F., Duncan, M.J., Jowett, I.G., Quinn, J.M., Hickey, C.W., Daviescolley, R.J., et al., 1990. Ecological characterization, classification, and modeling of New Zealand rivers: an introduction and synthesis. N. Z. J. Mar. Freshw. Res. 24, 277−304.

Blake, D.J.H., Sunthornratana, U., Promphakping, B., Buaphuan, S., Sarkkula, J., Kummu, M., et al., 2011. E-flows in the Nam Songkhram River Basin. Final Report. M-POWER Mekong Program on Water, Environment and Resilience, IUCN, IWMI, CGIAR Challenge Program on Water and Food, and Aalto University, Finland.

Bond, N.R., Balcombe, S.R., Crook, D.A., Marshall, J.C., Menke, N., Lobegeiger, J.S., 2015. Fish population persistence in hydrologically variable landscapes. Ecol. Appl. 25, 901−913.

Bovee, K.D., 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S.D.I. Fish and Wildlife Service, Office of Biological Services FWS/OBS−82/26.

Brisbane Declaration, 2007. Environmental flows are essential for freshwater ecosystem health and human well-being. 10th International River Symposium and International Environmental Flows Conference, 3−6 September 2007, Brisbane, Australia. Available from: http://www.eflownet.org.

Brizga, S.O., Arthington, A.H., Pusey, B.J., Kennard, M.J., Mackay, S.J., Werren, G.L., et al., 2002. Benchmarking, a 'top-down' methodology for assessing environmental flows in Australian rivers. Environmental Flows for River Systems. An International Working Conference on Assessment and Implementation, incorporating the 4th International Ecohydraulics Symposium. Southern Waters, Cape Town, South Africa.

Brown, C.A., Watson, P., 2007. Decision support systems for environmental flows: lessons from Southern Africa. Int. J. River Basin Manage. 5, 169−178.

Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manage. 30, 492−507.

Carlisle, D.M., Falcone, J., Wolock, D.M., Meador, M.R., Norris, R.H., 2010. Predicting the natural flow regime: models for assessing hydrological alteration in streams. River Res. Appl. 26, 118−136.

Carlisle, D.M., Wolock, D.M., Meador, M.R., 2011. Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Front. Ecol. Environ. 9, 264−270.

Chan, T.U., Hart, B.T., Kennard, M.J., Pusey, B., Shenton, W., Douglas, M.M., et al., 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. River Res. Appl. 28, 283−301.

Council of the European Communities, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. OJEC L327 1−73.

Davies, P.M., Naiman, R.J., Warfe, D.M., Pettit, N.E., Arthington, A.H., Bunn, S.E., 2014. Flow-ecology relationships: closing the loop on effective environmental flows. Mar. Freshw. Res. 65, 133−141.

de Philip, M., Moberg, T., 2010. Ecosystem flow recommendations for the Susquehanna River Basin. The Nature Conservancy, Harrisburg, Pennsylvania. Available from: http://www.nature.org/media/pa/tnc-final-susquehanna-river-ecosystem-flows-study-report.pdf.

de Philip, M., Moberg, T., 2013. Ecosystem flow recommendations for the Upper Ohio River Basin in Western Pennsylvania. The Nature Conservancy, Harrisburg, Pennsylvania. Available from: http://www.nature.org/media/pa/ecosystem-flow-recommendations-upper-ohio-river-pa-2013.pdf.

Dickens, C., O'Brien, G.C., Stassen, J., Kleynhans, M., Rossouw, N., Rowntree, K., et al., 2015. Specialist consultants to undertake baseline studies (flow, water quality and geomorphology) and Instream Flow Requirement (IFR) Assessment for phase 2: instream flow requirements for the Senqu River: final report. Prepared by the Institute of Natural Resources NPC on behalf of the Lesotho Highlands Development Authority (LHDA). Maseru, Lesotho.

Doyle, M.W., Stanley, E.H., Strayer, D.L., Jacobson, R.B., Schmidt, J.C., 2005. Effective discharge analysis of ecological processes in streams. Water Resour. Res. 41.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Leveque, C., et al., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163−182.

Dunbar, M.J., Acreman, M.C., 2001. Applied hydro-ecological science for the twenty-first century. In: Acreman, M.C. (Ed.), Hydro-ecology: Linking Hydrology and Aquatic Ecology. International Association of Hydrological Sciences Publication No., 266.. IAHS Press, Centre for Ecology and Hydrology, Wallingford, UK, pp. 1−17.

Dyson, M., Bergkamp, G., Scanlon, J. (Eds.), 2003. Flow. The Essentials of Environmental Flows. IUCN, Gland, Switzerland.

European Commission, 2015. Ecological flows in the implementation of the WFD. CIS Guidance Document no. 31, Technical Report 2015−086, Brussels, Belgium.

Finn, M., Jackson, S., 2011. Protecting Indigenous values in water management: a challenge to conventional environmental flow assessments. Ecosystems 14, 1232−1248.

Flotemersch, J.E., Leibowitz, S.G., Hill, R.A., Stoddard, J.L., Thoms, M.C., Tharme, R.E., 2015. A watershed integrity definition and assessment approach to support strategic management of watersheds. River Res. Appl. Arena paper. Available from: http://dx.doi.org/10.1002/rra.2978.

Gippel, C.J., Speed, R., 2010. Environmental flow assessment framework and methods, including environmental asset identification and water re-allocation. ACEDP Australia-China Environment Development Partnership, River Health and Environmental Flow in China. International Water Centre, Brisbane.

Gustard, A., 1979. The characterisation of flow regimes for assessing the impact of water resource management on river ecology. In: Ward, J.W., Stanford, J.A. (Eds.), The Ecology of Regulated Streams. Plenum Press, New York and London, pp. 53−60.

Haines, A.T., Finlayson, B.L., McMahon, T.A., 1988. A global classification of river regimes. Appl. Geogr. 8, 255−272.

Haney, J., González, A., Tharme, R.E., 2015. Estudio de caudales ecológicos en las cuencas costeras de Chiapas, México. Technical Report. The Nature Conservancy, Mexico and North Central America.

Hannah, D.M., Sadler, J.P., Wood, P.J., 2007. Hydroecology and ecohydrology: a potential route forward? Hydrol. Process. 21, 3385−3390.

Hill, M.T., Platts, W.S., Beschta, R.L., 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. Rivers 2, 198−210.

Hirji, R., Davis, R., 2009. Environmental Flows in Water Resources Policies, Plans, and Projects. World Bank, Washington, DC.

Hughes, D.A., Hannart, P., 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. J. Hydrol. 270, 167−181.

Hughes, D.A., Desai, A.Y., Birkhead, A.L., Louw, D., 2014. A new approach to rapid, desktop-level, environmental flow assessments for rivers in South Africa. Hydrol. Sci. J. 59 (3), 1−15.

Hughes, J.M.R., James, B., 1989. A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. Aust. J. Mar. Freshw. Res. 40, 303−326.

Humphries, P., Winemiller, K.O., 2009. Historical impacts on river fauna, shifting baselines, and challenges for restoration. BioScience 59, 673−684.

Illaszewicz, J., Tharme, R., Smakhtin, V., Dore, J. (Eds.), 2005. Environmental Flows: Rapid Environmental Flow Assessment for the Huong River Basin, Central Vietnam. IUCN Vietnam, Hanoi, Vietnam.

Jackson, S.E., Douglas, M.M., Kennard, M.J., Pusey, B.J., Huddleston, J., Harney, B., et al., 2014. "We like to listen to stories about fish": integrating indigenous ecological and scientific knowledge to inform environmental flow assessments. Ecol. Soc. 19 (1), 43.

Jager, H.I., Efroymson, R.A., Opperman, J.J., Kelly, M.R., 2015. Spatial design principles for sustainable hydropower development in river basins. Renew. Sustain. Energy Rev. 45, 808−816.

James, C., Mackay, S.J., Arthington, A.H., Capon, S., 2016. Does flow structure riparian vegetation in subtropical south-east Queensland? Ecol. Evol. Available from: http://dx.doi.org/10.1002/ece3.2249.

Joubert, A.R., Hurly, P.R., 1994. The use of daily flow data to classify South African rivers. Chapter 11: p. 286−359. In: King, J.M., Tharme, R.E. Assessment of the Instream Flow Incremental Methodology and Initial Development of Alternative Instream Flow Methodologies for South Africa. Water Research Commission Report No., 295/1/94. Water Research Commission, Pretoria, South Africa.

Kendy, E., Apse, C., Blann, K., 2012. A Practical Guide to Environmental Flows for Policy and Planning. The Nature Conservancy, Arlington, Virginia.

Kennard, M.J., Pusey, B.J., Olden, J.D., MacKay, S.J., Stein, J.L., Marsh, N., 2010. Classification of natural flow regimes in Australia to support environmental flow management. Freshw. Biol. 55, 171−193.

Kennedy, T.A., Muehlbauer, J.D., Yackulic, C.B., Lytle, D.A., Miller, S.W., Dibble, K.L., et al., 2016. Flow management for hydropower extirpates aquatic insects, undermining river food webs. BioScience 66, 561−575.

Kiernan, J.D., Moyle, P.B., Crain, P.K., 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecol. Appl. 22, 1472−1482.

King, J., Beuster, H., Brown, C., Joubert, A., 2014. Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system. Hydrol. Sci. J. 59, 786−800.

King, J.M., Brown, C.A., 2010. Integrated basin flow assessments: concepts and method development in Africa and south-east Asia. Freshw. Biol. 55, 127−146.

King, J.M., Louw, M.D., 1998. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. Aquat. Ecosyst. Health Manag. 1, 109−124.

King, J.M., Pienaar, H. (Eds.), 2011. Sustainable use of South Africa's inland waters: a situation assessment of resource directed measures 12 years after the 1998 National Water Act. Water Research Commission Report No. TT 491/11. Water Research Commission, Pretoria, South Africa.

King, J.M., Tharme, R.E., 1994. Assessment of the instream flow incremental methodology and initial development of alternative instream flow methodologies for South Africa. Water Research Commission Report No., 295/1/94. Water Research Commission, Pretoria, South Africa.

King, J.M., Tharme, R.E., de Villiers, M.S. (Eds.), 2000. Environmental flow assessments for rivers: manual for the Building Block Methodology. Water Research Commission Report TT 131/00, Pretoria, South Africa.

King, J.M., Brown, C.A., Sabet, H., 2003. A scenario-based holistic approach for environmental flow assessments. River Res. Appl. 19, 619−639.

Kopf, R.K., Finlayson, C.M., Humphries, P., Sims, N.C., Hladyz, S., 2015. Anthropocene baselines: assessing change and managing biodiversity in human-dominated aquatic ecosystems. BioScience 65, 798−811.

Laize, C.L.R., Acreman, M.C., Schneider, C., Dunbar, M.J., Houghton-Carr, H.A., Floerke, M., et al., 2014. Projected flow alteration and ecological risk for pan-European rivers. River Res. Appl. 30, 299−314.

Lamouroux, N., Jowett, I.G., 2005. Generalized instream habitat models. Can. J. Fish. Aquat. Sci. 62, 7−14.

Lancaster, J., Downes, B.J., 2010. Linking the hydraulic world of individual organisms to ecological processes: putting ecology into ecohydraulics. River Res. Appl. 26, 385−403.

Le Quesne T., Kendy, E., Weston, D., 2010. The Implementation Challenge: Taking Stock of Government Policies to Protect and Restore Environmental Flows. WWF-UK and The Nature Conservancy.

Leonard, P.M., Orth, D.J., 1988. Use of habitat guilds of fishes to determine instream flow requirements. N. Am. J. Fish. Manage. 8, 399−409.

Lloyd, N., Quinn, G., Thoms, M., Arthington, A., Gawne, B., Humphries, P., et al., 2003. Does flow modification cause geomorphological and ecological response in rivers? A literature review from an Australian perspective. Cooperative Research Centre for Freshwater Ecology Technical Report 1/2004. Canberra, Australia.

Lokgariwar, C., Chopra, V., Smakhtin, V., Bharati, L., O'Keeffe, J., 2014. Including cultural water requirements in environmental flow assessment: an example from the upper Ganga River, India. Water Int. 39, 81–96.

Lytle, D.A., Merritt, D.M., 2004. Hydrologic regimes and riparian forests: a structured population model for cottonwood. Ecology 85, 2493–2503.

Lytle, D.A., Poff, N.L., 2004. Adaptation to natural flow regimes. Trend. Ecol. Evol. 19, 94–100.

Mackay, S.J., Arthington, A.H., James, C.S., 2014. Classification and comparison of natural and altered flow regimes to support an Australian trial of the Ecological Limits of Hydrologic Alteration framework. Ecohydrology 7, 1485–1507.

Maheu, A., Poff, N.L., St-Hilaire, A., 2016. A classification of stream water temperature regimes in the conterminous United States. River Res. Appl. 32, 896–906.

Martin, D.M., Labadie, J.W., Poff, N.L., 2015. Incorporating social preferences into the ecological limits of hydrologic alteration (ELOHA): a case study in the Yampa-White River basin, Colorado. Freshw. Biol. 60, 1890–1900.

Mathews, R., Richter, B.D., 2007. Application of the indicators of hydrologic alteration software in environmental flow setting. J. Am. Water Resour. Assoc. 43 (5), 1–14.

Matthews, J., Aldous, A., Wickel, B., 2009. Managing water in a shifting climate. Am. Water Works Assoc. 101 (8), 29, 99.

McClain, M.E., Sabalusky, A.L., Anderson, E.P., Dessu, S.B., Melesse, A.M., Ndomba, P.M., et al., 2014. Comparing flow regime, channel; hydraulics and biological communities to infer flow-ecology relationships in the Mara River of Kenya and Tanzania. Hydrol. Sci. J. 59, 801–819.

McManamay, R.A., Orth, D.J., Dolloff, C.A., 2012. Revisiting the homogenization of dammed rivers in the southeastern US. J. Hydrol. 424, 217–237.

McManamay, R.A., Orth, D.J., Dolloff, C.A., Mathews, D.C., 2013. Application of the ELOHA framework to regulated rivers in the Upper Tennessee River Basin: a case study. Environ. Manage. 51, 1210–1235.

McManamay, R.A., Bevelhimer, M.S., Kao, S.C., 2014. Updating the US hydrologic classification: an approach to clustering and stratifying ecohydrologic data. Ecohydrology 7, 903–926.

Merritt, D.M., Scott, M.L., Poff, N.L., Auble, G.T., Lytle, D.A., 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshw. Biol. 55, 206–225.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., et al., 2008. Stationarity is dead: whither water management? Science 319, 573–574.

Mims, M.C., Olden, J.D., 2012. Life history theory predicts fish assemblage response to hydrologic regimes. Ecology 93 (1), 35–45.

Mims, M.C., Olden, J.D., Shattuck, Z.R., Poff, N.L., 2010. Life history trait diversity of native freshwater fishes in North America. Ecol. Freshw. Fish 19, 390–400.

Monk, W.A., Wood, P.J., Hannah, D.M., Wilson, D.A., 2007. Selection of river flow indices for the assessment of hydroecological change. River Res. Appl. 23, 113–122.

Moyle, P.B., 2014. Novel aquatic ecosystems: the new reality for streams in California and other Mediterranean climate regions. River Res. Appl. 30, 1335–1344.

Muth, R., Crist, L.W., LaGory, K.E., Hayse, J.W., Bestgen, K.R., Ryan, T.P., et al., 2000. Flow and temperature recommendations for endangered fishes in the Green River downstream of Flaming Gorge Dam. Final report FG-53 to the Upper Colorado River Endangered Fish Recovery Program. US Fish and Wildlife Service, Denver, Colorado. Larval Fish Laboratory Contribution 120.

Myers, N., 1993. Biodiversity and the precautionary principle. Ambio 22, 74–79.
National Water Commission of Mexico, 2012. Norma Mexicana 2012. NMX-AA-159-SCFI-2012. Que establece el procedimiento para la determinacioìn del caudal ecoloìgico en cuencas hidroloìgicas. Establishing the procedure for environmental flow determination in hydrological basins. Comisión Nacional del Agua, Conagua.
Nel, J.L., Turak, E., Linke, S., Brown, C., 2011. Integration of environmental flow assessment and freshwater conservation planning: a new era in catchment management. Mar. Freshw. Res. 62, 290–299.
Newcombe, C.P., Jensen, J.O.T., 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. N. Am. J. Fisheries Manage. 16, 693–727.
Newson, M.D., Newson, C.L., 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Prog. Phys. Geogr. 24 (2), 195–217.
Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308 (5720), 405–4088.
O'Keeffe, J., Hughes, D., Tharme, R., 2002. Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method. Verh. Internat. Verein. Limnol. 28, 84–92.
Olden, J.D., Naiman, R.J., 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshw. Biol. 55, 86–107.
Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Appl. 19, 101–121.
Olden, J.D., Hogan, Z.S., Vander Zanden, M.J., 2007. Small fish, big fish, red fish, blue fish: size-biased extinction risk of the world's freshwater and marine fishes. Glob. Ecol. Biogeogr. 16, 694–701.
Olden, J.D., Kennard, M.J., Pusey, B.J., 2008. Species invasions and the changing biogeography of Australian freshwater fishes. Glob. Ecol. Biogeogr. 17, 25–37.
Olden, J.D., Konrad, C.P., Melis, T.S., Kennard, M.J., Freeman, M.C., Mims, M.C., et al., 2014. Are large-scale flow experiments informing the science and management of freshwater ecosystems? Front. Ecol. Environ. 12, 176–185.
Olden, J.D., Poff, N.L., Douglas, M.R., Douglas, M.E., Fausch, K.D., 2004. Ecological and evolutionary consequences of biotic homogenization. Trends Ecol. Evol. 19, 18–24.
Opperman, J., Grill, G., Hartmann, J., 2015. The power of rivers: finding balance between energy and conservation in hydropower development. Technical report. Available from: http://dx.doi.org/10.13140/RG.2.1.5054.5765. The Nature Conservancy, Washington, DC.
Overton, I.C., Smith, D.M., Dalton, J., Barchiest, S., Acreman, M.C., Stromberg, J.C., et al., 2014. Implementing environmental flows in integrated water resources management and the ecosystem approach. Hydrol. Sci. J. 59, 860–877.
Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S.E., Hoff, H., Lebel, L., et al., 2013. Environmental flows and water governance: managing sustainable water uses. Curr. Opin. Environ. Sustain. 5, 341–351.
Palmer, M.A., Lettenmaier, D.P., Poff, N.L., Postel, S., Richter, B., Warner, R., 2009. Climate change and river ecosystems: protection and adaptation options. Environ. Manage. 44, 1053–1068.
Parasiewicz, P., 2007. The MesoHABSIM model revisited. River Res. Appl. 23, 893–903.
Petts, G.E., Calow, P., 1996. River Flows and Channel Forms. Blackwell Science, Oxford, UK.
Poff, N.L., 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshw. Biol. 36, 71–91.
Poff, N.L., 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. J. N. Am. Benthol. Soc. 16, 391–409.
Poff, N.L., 2009. Managing for variability to sustain freshwater ecosystems. J. Water Resour. Plan. Manage. 135, 1–4.
Poff, N.L., 2014. Rivers of the Anthropocene? Front. Ecol. Environ. 12, 427.

Poff, N.L., Hart, D.D., 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience 52, 659–668.
Poff, N.L., Matthews, J.H., 2013. Environmental flows in the Anthropocene: past progress and future prospects. Curr. Opin. Environ. Sustain. 5, 667–675.
Poff, N.L., Schmidt, J.C., 2016. How dams can go with the flow: small changes to water flow regimes from dams can help to restore river ecosystems. Science 353 (6304), 7–8.
Poff, N.L., Ward, J.V., 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Can. J. Fish. Aquat. Sci. 46, 1805–1818.
Poff, N.L., Ward, J.V., 1990. Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. Environ. Manage. 14, 629–645.
Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., et al., 1997. The natural flow regime. BioScience 47, 769–784.
Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., et al., 2003. River flows and water wars: emerging science for environmental decision making. Front. Ecol. Environ. 1, 298–306.
Poff, N.L., Brown, C.M., Grantham, T.E., Matthews, J.H., Palmer, M.A., Spence, C.M., et al., 2016. Sustainable water management under future uncertainty with eco-engineering decision scaling. Nat. Clim. Change 6, 25–34.
Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. USA 104, 5732–5737.
Poff, N.L., Olden, J.D., Pepin, D.M., Bledsoe, B.P., 2006a. Placing global streamflow variability in geographic and geomorphic contexts. River Res. Appl. 22, 149–166.
Poff, N.L., Olden, J.D., Vieira, N.K.M., Finn, D.S., Simmons, M.P., Kondratieff, B.C., 2006b. Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. J. N. Am. Benthol. Soc. 25, 730–755.
Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., et al., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw. Biol. 55, 147–170.
Puckridge, J.T., Sheldon, F., Walker, K.F., Boulton, A.J., 1998. Flow variability and the ecology of large rivers. Mar. Freshw. Res. 49, 55–72.
Rahel, F.J., Olden, J.D., 2008. Assessing the effects of climate change on aquatic invasive species. Conserv. Biol. 22, 521–533.
Reidy Liermann, C.A., Olden, J.D., Beechie, T.J., Kennard, M.J., Skidmore, P.B., Konrad, C.P., et al., 2012. Hydrogeomorphic classification of Washington State rivers to support emerging environmental flow management strategies. River Res. Appl. 28, 1340–1358.
Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., et al., 1988. The role of disturbance in stream ecology. J. N. Am. Benthol. Soc. 7, 433–455.
Richter, B.D., Thomas, G.A., 2007. Restoring environmental flows by modifying dam operations. Ecol. Soc. 12 (art. 12).
Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10, 1163–1174.
Richter, B.D., Baumgartner, J.V., Wigington, R., Braun, D.P., 1997. How much water does a river need? Freshw. Biol. 37, 231–249.
Richter, B.D., Davis, M.M., Apse, C., Konrad, C., 2012. A presumptive standard for environmental flow protection. River Res. Appl. 28, 1312–1321.

Rogers, K.H., 2006. The real river management challenge: integrating scientists, stakeholders and service agencies. River Res. Appl. 22, 269−280.

Rolls, R.J., Arthington, A.H., 2014. How do low magnitudes of hydrologic alteration impact riverine fish populations and assemblage characteristics? Ecol. Indic. 39, 179−188.

Rood, S.B., Gourley, C.R., Ammon, E.M., Heki, L.G., Klotz, J.R., Morrison, M.L., et al., 2003. Flows for floodplain forests: a successful riparian restoration. BioScience 53, 647−656.

Roux, D.J., Foxcroft, L.C., 2011. The development and application of strategic adaptive management within South African National Parks. Koedoe 53(2), Art. # 1049, 5. Available from: http://dx.doi.org/10.4102/koedoe.v53i2.1049.

Rowntree, K., Wadeson, R., 1998. A geomorphological framework for the assessment of instream flow requirements. Aquat. Ecosyst. Health Manage. 1, 125−141.

Ruhi, A., Holmes, E.E., Rinne, J.N., Sabo, J.L., 2015. Anomalous droughts, not invasion, decrease persistence of native fishes in a desert river. Glob. Change Biol. 21, 1482−1496.

Sanderson, J.S., Rowan, N., Wilding, T., Bledsoe, B.P., Miller, W.J., Poff, N.L., 2012. Getting to scale with environmental flow assessment: the watershed flow evaluation tool. River Res. Appl. 28, 1369−1377.

Shenton, W., Bond, N.R., Yen, J.D.L., Mac Nally, R., 2012. Putting the "ecology" into environmental flows: ecological dynamics and demographic modelling. Environ. Manage. 50, 1−10.

Smakhtin, V.U., Anputhas, M., 2006. An assessment of environmental flow requirements of Indian river basins. IWMI Research Report 107. International Water Management Institute, Colombo, Sri Lanka.

Solans, M.A., de Jalón, D.G., 2016. Basic tools for setting environmental flows at the regional scale: application of the ELOHA framework in a Mediterranean river basin. Ecohydrology 9, 1517−1538. Available from: http://dx.doi.org/10.1002/eco.1745.

Solans, M.A., Poff, N.L., 2013. Classification of natural flow regimes in the Ebro Basin (Spain) by using a wide range of hydrologic parameters. River Res. Appl. 29, 1147−1163. Available from: http://dx.doi.org/10.1002/rra.2598.

Speed, R., Binney, J., Pusey, B., Catford, J., 2011. Policy measures, mechanisms, and framework for addressing environmental flows. ACEDP Project Report. International Water Centre, Brisbane, QLD.

Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A., et al., 1996. A general protocol for restoration of regulated rivers. Regul. Rivers Res. Manage. 12, 391−413.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. J. Climatol. 18, 1136−1155.

Stewart-Koster, B., Bunn, S.E., Mackay, S.J., Poff, N.L., Naiman, P.J., Lake, P.S., 2010. The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. Freshw. Biol. 55, 243−260.

Strayer, D.L., Dudgeon, D., 2010. Freshwater biodiversity conservation: recent progress and future challenges. J. N. Am. Benthol. Soc. 29, 344−358.

Tennant, D.L., 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1 (4), 6−10.

Tharme, R.E., 1996. A review of international methodologies for the quantification of the instream flow requirements of rivers. Water law review report for policy development. Department of Water Affairs and Forestry, Pretoria, South Africa.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Appl. 19, 397−441.

Tharme, R.E., King, J.M., 1998. Development of the Building Block Methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. Water Research Commission Report No. 576/1/98. Water Research Commission, Pretoria, South Africa.

Thompson, J.R., Laizé, C.L.R., Green, A.J., Acreman, M.C., Kingston, D.G., 2014. Climate change uncertainty in environmental flows for the Mekong River. Hydrol. Sci. J. 59 (3–4), 935–954.
Thompson, L.C., Escobar, M.I., Mosser, C.M., Purkey, D.R., Yates, D., Moyle, P.B., 2012. Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. J. Water Resour. Plan. Manage. 138, 465–478.
USAID, 2016. Environmental flows in Rufiji River Basin assessed from the perspective of planned development in Kilombero and Lower Rufiji sub-basins. Technical assistance to support the development of irrigation and rural roads infrastructure project (IRRIP2). United States Agency for International Development, final report.
Verberk, W.C.E.P., van Noordwijk, C.G.E., Hildrew, A.G., 2013. Delivering on a promise: integrating species traits to transform descriptive community ecology into a predictive science. Freshw. Sci. 32, 531–547.
Walschburger, T., Angarita, H., Delgado, J., 2015. Hacia una gestión integral de las planicies inundables en la Cuenca Magdalena-Cauca. In: Rodríguez Becerra, M. (Ed.), ¿Para Dónde va el río Magdalena? Riesgos Sociales, Ambientales y Económicos del Proyecto de Navegabilidad. Friedrich Ebert Stiftung, Foro Nacional Ambiental, Bogotá, Colombia.
Wantzen, K.M., Ballouche, A.Z., Longuet, I., Bao, I., Bocoum, H., Cissé, L., et al., 2016. River culture: an eco-social approach to mitigate the biological and cultural diversity crisis in riverscapes. Ecohydrol. Hydrobiol. (in press). Available from: http://dx.doi.org/10.1016/j.ecohyd.2015.12.003.
Warner, A.T., Bach, L.B., Hickey, J.T., 2014. Restoring environmental flows through adaptive reservoir management: planning, science, and implementation through the Sustainable Rivers Project. Hydrol. Sci. J. 59, 770–785.
Webb, C.T., Hoeting, J.A., Ames, G.M., Pyne, M.I., Poff, N.L., 2010. A structured and dynamic framework to advance traits-based theory and prediction in ecology. Ecol. Lett. 13, 267–283.
Webb, J.A., De Little, S.C., Miller, K.A., Stewardson, M.J., Rutherfurd, I.D., Sharpe, A.K., et al., 2015. A general approach to predicting ecological responses to environmental flows: making best use of the literature, expert knowledge, and monitoring. River Res. Appl. 31, 505–514.
Wiens, J.A., Hayward, G.D., Safford, H.D., Giffen, C. (Eds.), 2012. Historical Environmental Variation in Conservation and Natural Resource Management. John Wiley & Sons, Ltd, Chichester, UK.
Wilding, T.K., Bledsoe, B., Poff, N.L., Sanderson, J., 2014. Predicting habitat response to flow using generalized habitat models for trout in Rocky Mountain streams. River Res. Appl. 30, 805–824.
Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., et al., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 351, 128–129.
Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., et al., 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. BioScience 65, 358–371.
Yarnell, S.M., Petts, G.E., Schmidt, J.C., Whipple, A.A., Beller, E.E., Dahm, C.N., et al., 2015. Functional flows in modified riverscapes: hydrographs, habitats and opportunities. BioScience 65, 963–972.
Yen, J.D.L., Bond, N.R., Shenton, W., Spring, D.A., Mac Nally, R., 2013. Identifying effective water-management strategies in variable climates using population dynamics models. J. Appl. Ecol. 50, 691–701.
Zhang, Y., Arthington, A.H., Bunn, S.E., Mackay, S., Xia, J., Kennard, M., 2012. Classification of flow regimes for environmental flow assessment in regulated rivers: the Huai River Basin, China. River Res. Appl. 28, 989–1005.