Environmental Flow Assessment

Methods and Applications

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WILEY Blackwell

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ADVANCING RIVER RESTORATION AND MANAGEMENT

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Series foreword

Advancing river restoration and management

The field of river restoration and management has evolved enormously in recent decades, driven largely by increased recognition of ecological values, river functions and ecosystem services. Many conventional river-management techniques, emphasizing strong structural controls, have proven difficult to maintain over time, resulting in sometimes spectacular failures, and often a degraded river environment. More sustainable results are likely from a holistic framework, which requires viewing the "problem" at a larger catchment scale and involves the application of tools from diverse fields. Success often hinges on understanding the sometimes complex interactions among physical, ecological and social processes.

Thus, effective river restoration and management require nurturing the interdisciplinary conversation, testing and refining of our scientific theories, reducing uncertainties, designing future scenarios for evaluating the best options, and better understanding the divide between nature and culture that conditions human actions. It also implies that scientists should communicate better with managers and practitioners, so that new insights from research can guide management, and so that results from implemented projects can, in turn, inform research directions.

This series provides a forum for "integrative sciences" to improve rivers. It highlights innovative approaches, from the underlying science, concepts, methodologies, new technologies and new practices, to help managers and scientists alike improve our understanding of river processes, and to inform our efforts to steward and restore our fluvial resources better for a more harmonious coexistence of humans with their fluvial environment.

G. Mathias Kondolf,
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University of Lyon, CNRS

Preface

In a 2010 review, Arthington et al. remarked that: "There is now wide recognition that a dynamic, variable water regime is required to maintain the native biodiversity and ecological processes characteristic of every river and wetland ecosystem. Yet it remains a challenge to translate this 'natural flow regime' paradigm into quantitative environmental flow prescriptions for individual reaches from source to sea" (citations omitted). This book is about methods and approaches for meeting this challenge.

Environmental flow assessment is largely about flow, as the name suggests, but not just about flow. Other biotic and abiotic factors influence flowing water ecosystems, and environmental flow assessment (EFA) needs to take them into account. And, EFA is a social process, probably more than a scientific process. We treat EFA mostly as a kind of applied ecology, but we do not ignore the complications arising from human nature.

People working on EFA have diverse backgrounds, so we expect the same of readers of this book. Some will see themselves primarily as managers, rather than as scientists or engineers, and many will be familiar mainly with one region or even one stream system. Therefore, we have included material that will seem elementary to some readers, mostly to emphasize the variety of stream ecosystems that are the subject of assessments. Similarly, although we expect that many readers will already know a lot about EFA, we have tried to avoid assuming that they do. And, we do not try to be comprehensive. For example, we say little about riparian systems, and almost nothing about estuaries, although dealing with them is an important part of the overall problem. Rather, we try to elaborate an approach or point of view that can be applied generally.

We take a more critical attitude about methods for EFA than other books on the same subject, such as Locke et al. (2008) or Arthington (2012). We make recommendations, but we explain the shortcomings of the methods we recommend, as well as of those we don't. Part of our motivation in writing this book is concern about careless use of models in EFA, and we deal with that at length. Reluctance to criticize others' work is generally an admirable trait, but not in science, where it is part of the job, provided it is not mean-spirited.

It is an unhappy truth that many scientific papers have been published that should not have been, and many published research findings are false (Ioannidis 2005). There are various reasons for this, and a major one is flawed statistical analyses, especially overreliance on and misuse of statistical significance tests. Ioannidis wrote about the biomedical literature, but the same applies in environmental sciences. For example, Bolker et al. (2009) found problems with 311 of 537 applications of generalized linear mixed models in articles on ecology and evolution, and our impression is that papers on EFAs tend to exhibit a lower level of statistical understanding, and to receive poorer reviewing on statistical matters, than papers in related fields. We discuss and illustrate statistical problems with methods for EFA and related studies, but at a conceptual level, without getting into the technical details.

Geographically, the western USA, and especially California, is overrepresented in the book, as are salmonids. This seems parochial, and it is, but the western USA is highly diverse geographically, salmonids have diverse life-histories, and most of the literature on EFA deals with salmonids. Since three of us have lived and worked in California for decades, we are more familiar with EFA as it is actually done in California than elsewhere, so our California bias results largely from following the advice to "write what you know." However, we are broadly familiar with EFA elsewhere, and recommend an approach developed in Australia.

On language, we follow more recent (and more appropriate) usage and refer to "environmental flows" instead of "instream flows," but we do not intend any change in meaning with this terminology. We have tried to write in plain language, and to avoid overly technical or overblown academic writing such as the following, which we did not make up: "Temporary streams naturally experience flow intermittence and hydrologic discontinuity that act to shape fish community structure," or worse: "Thus, theoretically, although habitat suitability curves underpinning area-weighted suitability indices apparently invite the intervention of modeling approaches, the more complex and less-definite relations between physical habitat and ecological response may reduce this potential, with correspondence at best, treated probabilistically." Why would anyone who has something to say use such language? We expect that some readers will disagree with some of what we write, but we have tried to write it clearly.

With one exception, separate authorship is not listed for the various chapters, although **r**eaders with any sense of language will notice immediately that the writing styles varies. Each chapter has a main author, but each of us has read, commented on, and approved the others. The exception, Chapter 8, Dams and Channel Morphology, was written by fluvial geomorphologist Mathias Kondolf and collaborators from his research group in Lyon, France: Remi Loire, Hervé Piégay, and Jean-Réné Malavoi, who are thus listed as co-authors for the chapter.

Overall, our somewhat lofty goal is to give users (and students) of environmental flow methods a better understanding of the tools they are using, and especially where they may fall short. Methods for EFA are constantly evolving, especially analytical tools. Practitioners would be well served to be more critical of existing well-used methods, and to investigate alternatives coming on line. The more EFAs reflect reality, the more likely they will provide useful information, to the benefit of both flowing-water ecosystems and human populations that derive so much benefit from them.

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CHAPTER 1

An introduction to environmental flows

Summary

Environmental flows are flows in a river required to sustain aquatic ecosystems and other beneficial uses of free-flowing rivers. Environmental flow assessment is a general term for studies that can inform management of flows. Such assessments are surprisingly difficult to do right, constrained by the natural variability of the environment through which rivers flow and the diverse needs of organisms that live there. They are also made difficult by social constraints that pit human demands for water against those of the environment, and by aspects of human behavior.

1.1 What are environmental flows?

The 2007 Brisbane Declaration of the 10th International River Symposium and Environmental Flows Conference states that: "Environmental flows describes the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon those ecosystems." We will use this definition, taking "freshwater ecosystems" to include riparian areas. "Instream flows" is an older term that means much the same thing, but we prefer "environmental flows" because it implies a broader view of what should be assessed; instream flow assessments historically have been concerned mainly with the physical environment of only a few species, especially salmonids. We take environmental flow assessment (EFA) to be the process of trying to translate the Brisbane definition into usefully precise estimates of environmental water needs and the effects of modified flows on ecosystems and human well-being, to inform decisions such as:

- Whether to reserve some portion of the flow in a stream for environmental uses, and if so, how much, and on what kind of schedule;
- How effects of an existing project on streams or estuaries can be mitigated (or not) by releases of environmental flows or restrictions on water withdrawals;
- Whether and how to modify existing water projects to improve environmental conditions;
- Whether and how to build a new water project.

Environmental flow assessment is hard to do well. This book is about the scientific and social difficulties with EFA and how to address them as best one can. In this chapter, we first explain why EFA is so difficult, and address problems with the EFA literature.

Environmental Flow Assessment: Methods and Applications, First Edition. John G. Williams, Peter B. Moyle, J. Angus Webb and G. Mathias Kondolf.

1.2 Why EFA is so hard; scientific issues

1.2.1 Stream ecosystems are dynamic and open

Twenty-some years ago, three of the authors of this book participated in a small workshop on environmental flow assessment at the University of California at Davis, which concluded that "…currently no scientifically defensible method exists for defining the instream flows needed to protect particular species of fish or aquatic ecosystems" (Castleberry et al. 1996). Despite major progress with analytical and statistical methods over the last 20 years, especially those described in Chapter 9, we still believe that at best an EFA should be regarded as a first cut, to be implemented within the context of adaptive management. Why is this problem so hard? Scientists have a truly wonderful understanding of the nature of energy and matter, the evolution of the universe, the atomic structure and properties of molecules, the structure and activities of cells, the origin of species and the evolutionary relationships among organisms, and much more. Why, then, is it so hard to assess the consequences of taking some of the water out of a stream, or changing the timing or temperature with which water flows down the stream?

The reasons have been known for some time: ecosystems are open, dynamic systems that are "…in a constant state of flux, usually without long-term stability, and affected by a series of human and other, often stochastic, factors, many originating outside of the ecosystem itself" (Mangel et al. 1996, p. 356). For such reasons, Healey (1998) argues that questions such as "How much can a river's hydrology be altered without endangering its ecological integrity?" are trans-scientific, sensu Weinberg (1972); trans-scientific questions: "… can be stated in the language of science but not answered by the traditional means of science." These ideas have been restated recently by Harris and Heathwaite (2012) and by Boyd (2012, p. 307): "Predicting the dynamics of real ecosystems – or even of components of these ecosystems – will remain beyond the reach of even the best ecosystem models for the foreseeable future."

A long-term study on the South Fork Eel River in Northern California (Box 1.1) illustrates these points. Although the highly predictable seasonality of flow is a major factor structuring the food web in that river, year-to-year variation in the timing and magnitude of high-flow events results in substantial variation in the structure of the food web and its response to mobilization of the bed by high flows; for practical purposes, predictions of the response can only be probabilistic, not deterministic.

As another example, consider the valuable and well-managed sockeye salmon fishery in Bristol Bay, Alaska, for which long-term catch records are available for three major fishing districts, corresponding to areas of spawning and rearing habitat. The catch is a good proxy for the number of spawning fish, known since about 1950 (Hilborn et al. 2003). Although there has been little human disturbance in the spawning and rearing areas except for climate change, the relative contributions to the catch from the different districts has varied widely over time, as described by Hilborn et al. (2003, p. 6567):

> The stability and sustainability of Bristol Bay sockeye salmon have been greatly influenced by different populations performing well at different times during the last century. Indeed, no one associated with the fishery in the 1950s and 1960s could have imagined that Egegik would produce over 20 million fish in 1 year, nor could they imagine that the Nushagak would produce more than the Kvichak, as it has in the last 4 years. It appears that the resilience of Bristol Bay sockeye is due in large part to the maintenance of all of the diverse life history strategies and geographic locations that comprise the stock. At different times, different geographic regions and different life history strategies have been the major producers. If managers in earlier times had decided to focus management on the most productive runs at the time and had neglected the less productive runs, the biocomplexity that later proved important could have been lost.

Hilborn et al. (2003) were thinking of fisheries management, but the same point would apply to

Box 1.1 Variable Effects of High Flows on a River Ecosystem

Eighteen years of field observations and five summer field experiments in a coastal California river suggest that hydrologic regimes influence algal blooms and the impacts of fish on algae, cyanobacteria, invertebrates, and small vertebrates. In this Mediterranean climate, rainy winters precede the biologically active summer low-flow season. *Cladophora glomerata*, the filamentous green alga that dominates primary producer biomass during summer, reaches peak biomass during late spring or early summer. *Cladophora* blooms are larger if floods during the preceding winter attained or exceeded "bankfull discharge" (sufficient to mobilize much of the river bed, estimated at 120 $m^3 s^{-1}$). In 9 out of 12 summers preceded by large bed-scouring floods, the average peak height of attached *Cladophora* turfs equaled or exceeded 50 cm. In five out of six years when flows remained below bankfull, *Cladophora* biomass peaked at lower levels. Flood effects on algae were partially mediated through impacts on consumers in food webs. In three experiments [with caged fish] that followed scouring winter floods, juvenile steelhead (*Oncorhynchus mykiss*) and …[coastal roach, *Hesperoleucus venustus*] suppressed certain insects and fish fry, affecting persistence or accrual of algae depending on the predator-specific vulnerabilities of primary consumers [that were] capable of suppressing algae during a given year. During two post-flood years, these grazers were more vulnerable to small predators (odonates and fish fry, which… [steelhead stocked in the cages always suppressed] … [As a result, the abundant grazers] had adverse effects on algae in those years. During one post-flood year, all enclosed grazers capable of suppressing algae were consumed by steelhead, which therefore had positive effects on algae. During drought years, when no bed-scouring winter flows occurred, large armored caddisflies (*Dicosmoecus gilvipes*) were more abundant during the subsequent summer. In drought-year experiments, stocked fish had little or no influence on algal standing crops, which increased only when *Dicosmoecus* were removed from enclosures. Flood scour, by suppressing invulnerable grazers, set the stage for fish-mediated effects on algae in this river food web. Whether these effects were positive or negative depended on the predator-specific vulnerabilities of primary consumers that dominated during a given summer. (Power et al. 2008, p. 263 edited for clarity)

managing the freshwater habitat in these regions; there have been major geographical shifts in productivity in this undisturbed habitat, and no one knows why.

1.2.2 Fish evolve

We are used to thinking of evolution as a slow process, but this is not always the case. Stearns and Hendry (2004) wrote that: "A major shift in evolutionary biology in the last quarter century is due to the insight that evolution can be very rapid when populations containing ample genetic variation encounter strong selection (citations omitted)." It is now clear that significant evolution can occur within the time spans commonly considered in EFA, and fish populations may respond to changes in the environment in unexpected ways. For example, in several California rivers, releases of cold water from the lower levels of reservoirs have created have good habitat for large trout. The steelhead populations in these rivers apparently have evolved toward a resident life-history in response (Williams 2006). Where hatcheries "mitigate" for habitat lost above dams, salmonids evolve greater fitness for reproduction in hatcheries, and lower fitness for reproducing in rivers (Myers et al. 2004; Araki et al. 2007; Christie et al. 2014); significant domestication can occur in a single generation (Christie et al. 2016). If hatchery fish mix with naturally spawning fish in the river below the dam, the population of naturally spawning fish below the dam that can be supported by a given flow regime will be reduced as fitness declines.

1.2.3 Streams adjust

Alluvial or partially alluvial streams create their own channels. Anything that substantially changes flow or sediment transport in a stream, such as a new dam, will provoke geomorphic adjustments in channel size and form that will change the physical habitat, compromising assessments based on the pre-project habitat.

1.2.4 Climate changes

Long-term climate records and paleoclimatic data from tree rings and other sources show that climates have always varied over decades and centuries, and now greenhouse gas emissions are driving rapid change. One predictable change, already evident in flow data, is more winter runoff and less snowmelt runoff in mountain streams. Precipitation may increase or decrease, depending upon the region, and may become more variable. Thus, the amount and temporal distribution of water available to be allocated between instream and consumptive uses will change, as will the temperature of the water. Methodologically, climate change confounds analytical methods that assume that the statistical properties of flow data will be stationary, i.e. not change over time (Milly et al. 2008). Predicting climate change at any particular location is even more difficult than predicting global change (Deser et al. 2012), so uncertainty about climate will add substantially to the uncertainties already faced in EFAs.

Even without major human influences, climates and flow regimes vary substantially over time, especially in arid and semi-arid regions, as shown by a plot of the 30-year running average discharge in the Arroyo Seco River in California. (Figure 1.1). Thus, the particular period of record that is available for analysis can make a major difference (Williams 2017). Probably the most famous example of this is the Colorado River Compact of 1922, which allocated the water from the Colorado River among the various states of the USA in the basin. The allocation was based on unusually high flows in the early twentieth century, and so seriously over-allocated water from the river, as noted by the National Research Council (2007, pp. 99, 103):

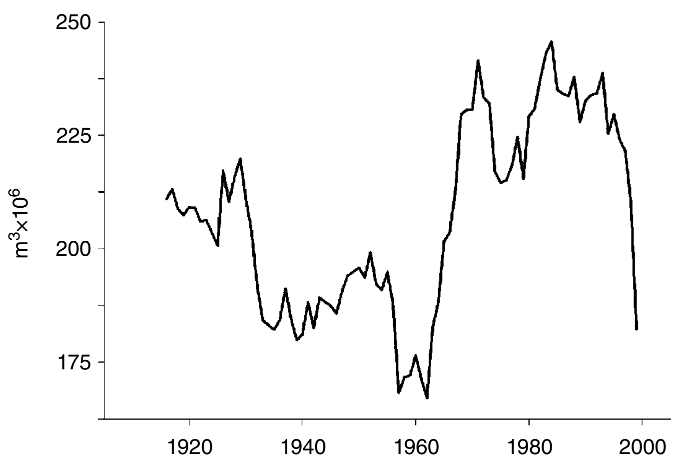

Figure 1.1 Thirty-year running average discharge in the Arroyo Seco River in central California. There has been no significant development in the basin. Data from the USGS gage 11152000. Source: John Williams.

> From the vantage point of the early 21st century, there is now a greater appreciation that the roughly 100 years of flow data within the Lees Ferry gage record represents a relatively small window of time of a system that is known to fluctuate considerably on scales of decades and centuries. (p. 99). … Long-term Colorado River mean flows calculated over these periods of hundreds of years are significantly lower than both the mean of the Lees Ferry gage record upon which the Colorado River Compact was based and the full 20th century gage record (citation).

1.2.5 Populations vary

Populations of fish and other aquatic organisms can be highly variable in time and space (e.g. Dauwalter et al. 2009), even in stable stream environments (e.g. Elliott 1994). This makes it hard to determine population trends or whether changes in flows have done any good or harm (Korman and Higgins 1997; Williams et al. 1999). This is particularly true for anadromous fish, populations of which may be strongly affected by ocean conditions that vary from year to year (e.g. Lindley et al. 2009). Within short sections of streams, abundance can vary strongly over periods of days (e.g. Bélanger and Rodríguez 2002), so assessments of habitat quality based on fish density can be unstable.

1.2.6 Habitat selection is conditional

Environmental flow assessments are often based on the assumptions that providing more of the kind of habitat where fish are found will increase the population of fish. The assumption may be sound, provided that it is tempered by biological understanding, by appropriate choice of spatial scale in the assessment, and by the recognition that habitat selection is conditional; in other words, fish can only select habitat that is available to them, and habitat selection at fine spatial scales can be affected by many factors, including habitat at coarser spatial scales, population density, competition, season, water temperature, cloud cover, and even discharge (Chapter 7). It is also necessary to consider how much of a particular kind of habitat a population of a given size needs, and to recognize that other factors altogether may determine abundance. Habitats affect populations through their effects on births, deaths, growth, and migration.

1.2.7 Spatial and temporal scales matter

The response times of the resources of concern complicate EFAs. Biotic communities may take decades to respond detectably to management actions, or the response may change over time. For example, the population of Sacramento River spring Chinook salmon initially increased after the construction of Shasta Dam (Eicher 1976), but later collapsed (Williams 2006), probably because of interbreeding with fall Chinook salmon. This problem is particularly acute for fish that use spatially dispersed and distinct habitats over the course of their life cycles, when only some of the habitats are affected by the actions.

Even if the inquiry concerns physical habitat, response times may still present problems. Events such as scouring floods that seem to destroy habitat in the short term may create other habitat, such as deep pools, in the long term. Anything that substantially changes sediment transport in a stream, such as a new dam that blocks sediment transport or modifies flows, will provoke geomorphic adjustments in channel size and form that will change the physical habitat.

Spatial scales also matter, for example in assessments of habitat selection (Cooper et al. 1998; Welsh and Perry 1998; Tullos et al. 2016). Factors that seem to drive habitat selection at a fine spatial scale may explain relatively little at a coarser spatial scale (Fausch et al. 2002; Durance et al. 2006; Bouchard and Boisclair 2008). As an additional complication, organisms can select habitat at multiple scales. In a classic observational study, Bachman (1984, p. 9) wrote that:

> The mean home-range size of 53 wild brown trout was 15.6 m^2 (SE, 1.7) as determined from minimum-convex polygons encompassing 95% of the scan sighting of each fish each year. … Typically, foraging sites were in front of a submerged rock, or on top of but on the downward-sloping rear surface of a rock

> … From there the fish had an unobstructed view of oncoming drift. While a wild brown trout was in such a site, its tail beat was minimal … indicating that little effort was required to maintain a stationary position even though the current only millimeters overhead was as high as 60–70 $cm\,s^{-1}$. Most brown trout could be found in one of several such sites day after day, and it was not uncommon to find a fish using many of the same sites for three consecutive years.

Thus, the trout selected habitat on a scale of centimeters with respect to the rock, on a scale of meters with respect to incoming drift, and a scale of tens of meters with respect to home range; further study might have shown selection of home ranges on a scale of hundreds or thousands of meters.

1.3 Why EFA is so hard: social issues

1.3.1 Social objectives evolve

Like ecosystems, societies are not stable equilibrium systems; social attitudes and objectives also evolve, as do environmental laws and regulations, and the evolution is rapid relative to the duration of major water-development projects. We are old enough to remember the resurgence of environmental concern in the 1960s that laid the basis for much of current environmental law in the USA, such as the Clean Water Act, the Endangered Species Act, and the National Environmental Policy Act. Environmental concerns also affected judicial decisions. For example, in 1971, in *Marks v. Whitney* (6 Cal.3d 251), a decision about tidelands in Tomales Bay, the California Supreme Court broadened the uses that are protected by the Public Trust to include providing environments for birds and marine life, and scientific study. This decision did not come from abstract legal reasoning, but rather from the political mood of the time. In pertinent part, the decision states that:

> Public trust easements are traditionally defined in terms of navigation, commerce and fisheries. They have been held to include the right to fish, hunt, bathe, swim, to use for boating and general recreation purposes the navigable waters of the state, and to use the bottom of the navigable waters for anchoring, standing, or other purposes (citations omitted). The public has the same rights in and to tidelands. … The public uses to which tidelands are subject are sufficiently flexible to encompass changing public needs. In administering the trust the state is not burdened with an outmoded classification favoring one mode of utilization over another (*citations omitted*). There is a growing public recognition that one of the most important public uses of tidelands – a use encompassed within the tidelands trust – is the preservation of those lands in their natural state, so that they may serve as units for scientific study, as open space, and as environments which produce food and habitat for birds and marine life, and which favorably affect the scenery and climate of the area. …

This broadening of trust uses was extended to navigable lakes and streams and their tributaries in 1983 in *National Audubon Society v. Superior Court* (33 Cal.3d 419), concerning environmental flows in Rush Creek, a tributary to Mono Lake. The Audubon decision and the environmental attitudes it reflected also gave new life to existing legislation affecting environmental flows, such as Fish and Game Code sec. 5937, discussed in Chapter 2. Changing social attitudes also change the practical effect of environmental laws. Monticello Dam on Putah Creek in California releases water for re-diversion 10 km downstream. These releases support a trout fishery, which, together with recreational uses of the reservoir, was long thought to meet any environmental obligations arising from the project, including Fish and Game Code sec. 5937. Over time, however, native fishes that were formerly regarded as "trash fish" came to be valued, and litigation resulted in revised environmental flow releases to protect them (Moyle et al. 1998).

Similar changes have developed elsewhere, although the nature and pace of the change has varied among nations and regions. South Africa, for example, experienced sudden advances in the relevant law and methods for EFA in the euphoric period after Nelson Mandela ushered in a peaceful end to