*Chapter 16*

# STREAMS PAST AND FUTURE: FLUVIAL RESPONSES TO RAPID ENVIRONMENTAL CHANGE IN THE CONTEXT OF HISTORICAL VARIATION

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## 16.1 INTRODUCTION

Changes at the global scale jeopardize the sustainable management of biodiversity and ecosystem services in streams and rivers (Baron et al. 2002; Poff 2009). Climatic shifts, land-use changes and the spread of invasive species complicate the goal of balancing ecosystem protection with water-resource development. As the environmental drivers of riverine systems move outside of their historical range of variation, researchers and managers must confront the possibility of novel ecological states and their consequences for currently valued resources.

Unprecedented ecological conditions in rivers demand management strategies that balance knowledge of historical patterns with the rapid assimilation of new information. For example, stakeholders might ask whether a valued population of cold-water game fish will persist within its current range when winters are shorter and summers are warmer. Addressing this concern requires synthesizing historical information, such as evolved thermal tolerances within a natural flow context, with expectations regarding the population's physiological or behavioral adaptability in the face of contemporary factors that include interaction with introduced species, harvesting pressure, habitat loss or augmentation, and trends in nutrient or sediment inputs due to altered land-use practices. The task of integrating current observations with historical understanding poses challenges to the formulation of clear policy regarding the management of rivers and their watersheds. Fortunately, a general, process-based framework that builds from the study of many unique rivers provides the necessary conceptual foundation for addressing this task.

Riverine ecosystems are characterized by ongoing physical fluxes and numerous feedbacks that link organisms and their shared habitat (Allan & Castillo 2007; Box 16.1). Ecological states observed in rivers, such as population levels or nutrient concentrations,

### Box 16.1 Five principles of riverine ecosystem function.

River and stream ecosystems consist of strongly coupled biological and physical elements that interact in the context of specific climatic, physiographic, and biogeographic settings. Defining "ecological states" as population abundances, species assemblages, or biogeochemical concentrations, we can identify several critical characteristics of these systems.

**1.** Conditions in streams and rivers naturally vary between regions and within watersheds from headwaters to outlet. River networks also transition among different ecological states through time such as cycling between periods of high and low flows. Differences in these patterns of variation through time permit distinguishing rivers in terms of historical flow conditions and provide the basis for appropriate management targets.

**2.** Hydrologic, geomorphic, and biological processes combine to determine ecological states. As low points on the landscape, streams receive water, sediment, wood, and nutrients from the surrounding terrestrial landscape, and thereby integrate processes occurring throughout watersheds. Streams display feedbacks between these domains, such as the effect of riparian vegetation on sediment movement, but the physical attributes of a system often help determine the temporal scale of relevance to historically informed management.

**3.** Discharge, or streamflow, is often a particularly important determinant of ecological states in rivers and acts as a key control on sediment flux, temperature fluctuations, wood inputs, and nutrient concentrations. Flow regimes mediate between environmental drivers and ecosystem responses and may be manipulated to achieve desired ecological states. As a record of changes through time, adjusting a river's flow regime represents an explicitly historical approach to management.

**4.** Population, community, and biogeochemical dynamics in rivers and streams are innately linked. Management that alters the relative abundance of one or several species may alter nutrient or solute concentrations and vice versa. The pathways by which these interactions occur are likely to be complex, context-specific, and sometimes counterintuitive. These interactions warrant an experimental approach to manipulating rivers and streams.

**5.** River and stream systems can recover (sometimes rapidly) from degradation, if recovery efforts address the causes as well as the symptoms of detrimental forces. In addition to fostering appropriate habitat conditions, management that accounts for species' natural histories, in terms of demographic processes and biotic interactions, is more likely to achieve lasting success.

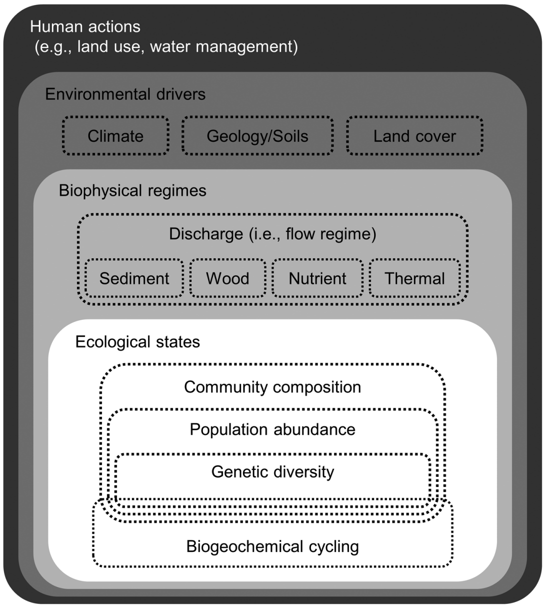


**Fig. 16.1** A conceptual representation of the hierarchical organization of stream and river ecosystems. Ecological states, such as community composition or genetic diversity, are proximately driven by biophysical regimes in flow, sediment, wood, nutrients, and temperature, with the latter also strongly influenced by the flow regime (the characteristic temporal sequence of measured discharge). In turn, these environmental regimes are controlled by atmospheric and terrestrial drivers. Ultimately, human actions can force each of the underlying environmental drivers and biophysical regimes.

are proximately driven by environmental regimes in flow, sediment, wood, and temperature (Box 16.1, Fig. 16.1). These environmental regimes are in turn controlled by broader atmospheric, terrestrial, and anthropogenic drivers such as precipitation, land use, and water management. This dynamic interplay creates tremendous spatial and temporal variation in river networks. Understanding and influencing these mediating regimes, even as they continue to shift, is critical to achieving desired ecological states. This perspective generates a focused set of mechanistic questions and research priorities concerning changes in historical relationships, for instance between fish populations and flow or temperature regimes.

Analyzing river ecosystems in terms of their characteristic biophysical variation, particularly their flow regimes, provides a sound basis for anticipating responses to rapid environmental change and can thereby suggest meaningful management actions. Accordingly, we focus on the relationship between drivers outside of their historical range of variation, altered flow regimes, and consequent ecological states. We caution, however, that management to manipulate flow regimes must be undertaken within the context of the many other complex factors that influence ecological integrity in rivers. For example, food web dynamics (e.g. Power et al. 2008), terrestrial subsidies (Baxter et al. 2005), or landscape influences (Allan 2004) may interact with changing flow regimes to influence the outcomes of a particular flow-based management action. In addition, we note that despite the necessity of historical knowledge, its insufficiency as a complete guide to the future poses a basic challenge to the formulation of effective management strategies in an uncertain future.

## Historical variation as a double-edged sword

The difficulty of accurately defining "novel" conditions in rivers illustrates the importance of historical information. Along with our increasingly detailed knowledge of river ecosystems has come an appreciation of the extent to which humans have modified the banks, channels, and biota we encounter. Reduced spawning runs of salmon have disrupted the flow of marine nutrient subsidies to riparian forests (Naiman et al. 2002). Widespread damming and land-use change have altered patterns of discharge and reduced connectivity throughout channel networks, with detrimental impacts for many organisms and ecosystem functions (Nilsson et al. 2005; Poff et al. 2007). Agricultural development, urbanization, and airborne deposition of contaminants have altered nutrient fluxes (Allan 2004), and non-native species introductions have disrupted community interactions (Rahel & Olden 2008). The magnitude and history of these changes can undermine the perception of natural baseline conditions.

Contemporary watersheds may also carry a legacy of human actions prior to the usual period of record captured by instrumented monitoring. Examples in North America include the continental-scale adjustment of flow and sediment regimes following widespread beaver trapping during the eighteenth and nineteenth centuries, the removal of large woody debris from channels to facilitate transportation, the catastrophic channel modifications from hydraulic mining and tie-drives, and the massive input and storage of sediment after widespread deforestation (Wohl 2005). Seen in the light of these changes, some current ecosystem states could be viewed as transient recovery phases rather than stable endpoints. Thus, knowledge of a river's past may reveal that the reference conditions that guide certain decisions are the product of human impacts as well as natural evolutionary and geomorphic forces (Wohl 2005; Humphries & Winemiller 2009; Fig.16.1).

Complicating the role of historical information is the recognition that "stationarity is dead" (Milly et al. 2008). Many current water-resource-management practices are grounded in the assumption that climatic drivers and associated fluvial processes have a stable and well-characterized statistical range of variation. Time series of discharge data extending back as far as the late nineteenth century are often used in defining present-day habitat distributions (e.g. floodplain boundaries, depth profiles) or in designing reservoir operation plans. Yet environmental drivers that have shifted outside of their historical range of variation weaken the premise that historical information supports predictions concerning future ecological states. In addition, many riverine ecosystems already have no apparent analog in the historical record and require treatment as such (e.g. cold, clear-water reaches below dams on rivers that were historically warm and turbid; highly salinized and acidified streams in urban areas). Failure to acknowledge these changes risks decisions that are encumbered by false expectations concerning relationships that have not persisted. Researchers and managers share a responsibility to consider how a non-stationary climate and further modification of channel structure, hydrology, and biological assemblages will combine to undermine current assumptions regarding riverine ecosystem dynamics.

Understanding the record of history is critical to effective management, but knowledge of past ecosystem forms and processes cannot eliminate uncertainty from the decision-making process. Stewardship of rivers requires that we consider the direction, magnitude, and variability of expected changes in the context of previous observations, but with a license to experiment. Grounding management experiments in a process-based framework that emphasizes the relevance of flow regimes to riverine ecosystem function (Box 16.1) will improve efforts to anticipate and adapt to projected climatic and socioeconomic changes.

## 16.2 FLOW REGIMES STRUCTURE ECOLOGICAL COMPLEXITY

Aquatic and riparian ecosystems are controlled by patterns of variation in key environmental regimes, particularly streamflow, sediment, nutrient concentrations, wood inputs, and temperature (Fig. 16.1). Streamflow varies in terms of its magnitude (how much flow?); duration (how long is a particular flow level sustained?); frequency (how often does a particular flow level occur?); rate of change (how quickly does the flow change?); and timing and predictability (when do particular flow levels occur?) (Poff et al. 1997). Differences in these dimensions of the flow regime, both within and between drainage networks, generate a physical habitat template (Southwood 1988) that selects for organisms with certain functional characteristics (Poff & Ward 1990; Townsend & Hildrew 1994; Poff et al. 2006b). For instance, a turbulent stretch of river is more likely to contain organisms with a preference for faster current velocity and coarse substrates; a calmer, forested section may be dominated by invertebrates with the ability to shred falling leaves; and a system dominated by frequent flooding will tend to contain mobile species with short generation times.

Flow dynamics "filter" species from a regional candidate pool according to traits for life history, physiology, morphology, and behavior. Regional or watershed-scale filters (e.g. annual minimum temperature, flood frequency) interact with localized, site-scale filters (e.g. velocity, depth, presence of predator/prey) to influence the distribution and abundance of organisms such as invertebrates and fish (Poff 1997; Fausch et al. 2002; Wiens 2002). In addition to these niche constraints, dispersal limitation and source-sink dynamics likely play a role in determining the composition of some stream communities and may also be subject to flow regimes (Lowe et al. 2006; Hitt & Angermeier 2008; Winemiller et al. 2010).

Streamflow directly filters ecological responses by constraining habitat dimensions and by setting the sequence of mortality-inducing disturbances for organisms of varying vulnerability. Flow also operates indirectly by influencing other physical regimes: temperature, sediment, wood inputs, and nutrient concentrations (Doyle et al. 2005; Fig. 16.1). Tracking changes through time in this "master variable" provides a perspective on observed ecological states in rivers that emphasizes the biological significance of a mixture of high and low flows (and their frequency, duration and timing), rather than a single minimum or average condition (Poff et al. 1997; Bunn & Arthington 2002). The plot of measured discharge against a given duration is known as a hydrograph, and the set of daily, weekly, yearly, or interannual hydrographs provides fundamental insight into a river's ecological function (Figs. 16.2 and 16.3). The "natural flow regime" is the distribution of flows that would occur in the absence of major development and which is associated with a characteristic set of ecological states in a river network (Poff et al. 1997; Fig. 16.2). The dynamism of rivers dictates that efforts to understand and manage them incorporate the patterns revealed in this key record of historical processes.

Species can adapt to natural flow regimes, especially when extreme events limit growth or reproductive success, so that critical behaviors, such as foraging, mating, dispersal, and establishment, come to follow closely a characteristic sequence of flows (Lytle & Poff 2004; Lytle et al. 2008). The tight relationship between the structure and function of river ecosystems and flow-regime characteristics, both natural and altered, is well documented (Bunn & Arthington 2002; Poff & Zimmerman 2010). For example, flashy streams (with rapid transitions between high and low flows) favor habitat and diet generalists (Poff & Allan 1995; Roy

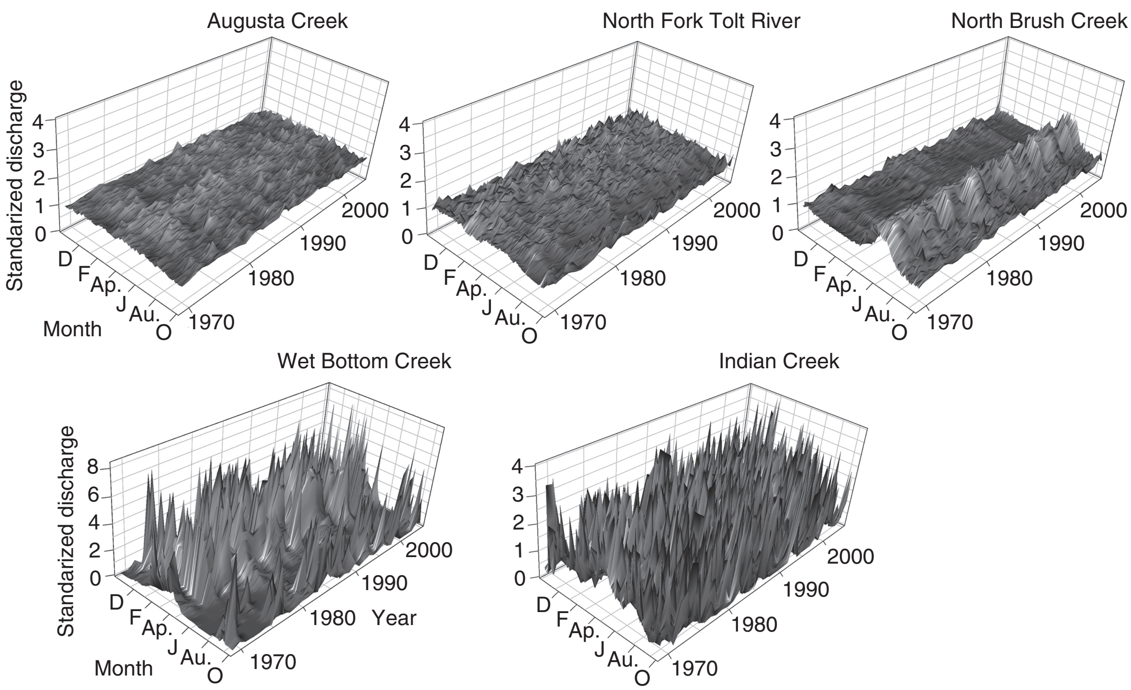


**Fig. 16.2** Hydrographs illustrating regional differences in flow regime. Daily flow is shown for the 1969–2005 water years. All five streams drain catchments of similar size (90–125 $km^2$), and flow was normalized to enable comparison between sites (natural-log-transformed and divided by mean daily flow). The three upper hydrographs represent perennial streams, and the lower two represent intermittent streams. Following the stream classification terminology of Poff (1996), Wet Bottom Creek in Arizona is a "harsh intermittent" stream that experiences extended periods of zero flow punctuated by large flow events caused by sporadic, intense rainstorms. Indian Creek is a "flashy intermittent" stream in Illinois subject to short periods of zero flow. Augusta Creek is a "superstable groundwater" stream in Michigan buffered from short-term variation in precipitation by a large groundwater input. North Fork Tolt River in Washington is a "winter rain" system. North Brush Creek in Wyoming is a classic "snowmelt" stream.

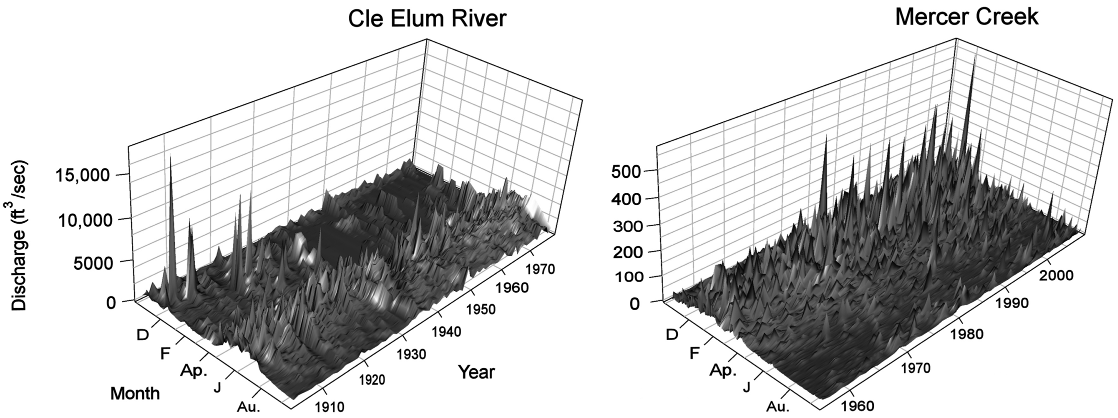


**Fig. 16.3** Human influences on flow regimes. Hydrograph of Cle Elum River (left panel) on the east slope of the Cascade Range in Washington, showing the influence of a storage dam on natural variation in flow. This hydrograph encompasses the water years 1904–1978. Cle Elum River is naturally a "rain-and-snow" stream that shows peak flows from both winter rains and spring snowmelt. In 1933, an irrigation dam constructed upstream of the gage reduced winter peak flows and raised late summer low flows. Hydrograph of Mercer Creek (right panel) in Bellvue, Washington, showing a subtle effect of urbanization on a small stream. Over the period of record (1956–2009), the population of Bellevue grew from 7658 (1950) to 109 569 (2000), which is reflected in the increasing frequency and intensity of high flows seen in the winter since the 1970s. Annual flood events (flows exceeding the 75th percentile flow) increased from 31 to 49, on average, between 1955 and 2000.

et al. 2005), peak flows sustain the recruitment of native riparian vegetation (Merritt & Poff 2010), and timing of high flows relative to species' life histories can prevent invasion of non-native fish (Fausch et al. 2001) or modify entire food webs (Power et al. 2008).

Consequently, the natural flow paradigm argues that alteration of these sequences will likely affect the biological communities and overall integrity in rivers and riparian zones (Poff et al. 1997; 2010; Arthington et al. 2006; Fig. 16.3). Patterns of flows clearly regulate the basic dynamics of riverine ecosystems – the challenge is to transform a historically informed understanding of flow–ecology relationships into mechanistic models that project how fluvial systems will respond to novel conditions associated with rapid climate change.

## 16.3 FLOW REGIMES AS A MANAGEMENT TARGET

Changing regional precipitation and temperature patterns will necessitate action to maintain desired ecological states and ecosystem goods and services. In contrast to climate, geology, or physiography, streamflow within a drainage network can be manipulated to mitigate global-scale changes. Management actions, such as revegetation and dam reoperation, can influence watershed hydrology, delaying or diminishing undesirable effects associated with climate change. For instance, releases of stored winter rains could compensate to some degree for reduced snowmelt runoff peaks in a warming mountainous region. Careful adjustment of flow regimes begins with measurement of the existing and potential flows in a river. This information permits formulating flow targets and assessing progress toward them (Richter et al. 2006). Given the foundation provided by these data, several general issues are relevant to the design of site-specific plans.

Political and economic constraints are often as relevant to the design of environmental regime adjustments as the limits of ecological knowledge. Whenever possible, we encourage identifying the actions most likely to lead to desirable ecological states and then reconciling these alternatives with societal needs, perhaps iteratively (Palmer et al. 2009; Poff 2009). Such a process involves translating policy objectives (e.g. "clean water," "biodiversity") into implementation methods (e.g. intercept storm runoff with adequate riparian buffers; maintain connectivity via flows

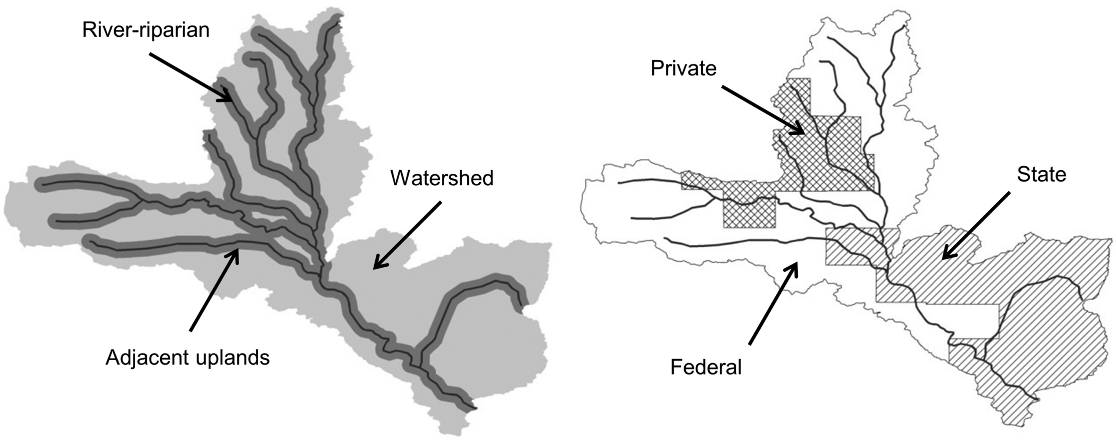


**Fig. 16.4** Hypothetical watershed illustrating scale and boundary issues. The left panel indicates three scales of relevance to management, and the right panel indicates how these scales might intersect with ownership divisions. Changing environmental regimes will manifest as altered ecological states at several scales within a river network, and sensitivity to the scale hierarchy will improve mitigation and adaptation efforts. When political boundaries do not align with ecological boundaries at various scales, coordination and cooperation among landholders will be required to ensure habitat connectivity and to prevent contradictory management activities.

that allow access to floodplains and side channels). Including acceptable ranges of variation around targeted average levels of a desired ecosystem state is critical to designing approaches that are robust to both climatic and socioeconomic change (Landres et al. 1999). Management plans that accommodate natural variability will establish the importance of flexibility and may stand a greater chance of meeting their criteria for success over time.

## Key considerations for strategic management

Three additional concerns factor into planning appropriate environmental regimes: mismatches between institutional jurisdictions and ecologically meaningful boundaries (Cumming et al. 2006), hierarchical spatial scales of influence (Poff 1997; Poole 2002), and the persistence and connectivity of habitat (Fausch et al. 2002; Pringle 2003).

Eliminating boundary mismatches will be impossible in many circumstances, but they nonetheless inform flow-regime interventions (and most other manipulations) because most global changes are unlikely to follow existing political boundaries or organizational divisions. Successfully mitigating the effects of environmental drivers that have departed from their historical range is likely to involve new partnerships between public and private authorities, with greater coordination and cooperation between agencies, stakeholders, and researchers (Cash et al. 2006; Fig. 16.4). For example, irrigators and wildlife authorities might seek ways to incentivize water delivery that preserves a semblance of critical spawning or seeding cues even as other changes diminish these flow-regime elements.

The branching structure and habitat orientation imposed by unidirectional flow distinguish the effects of scale in river systems, producing ecological states that are the result of local factors nested within the network context (Poole 2002; Grant et al. 2007; Rodriguez-Iturbe et al. 2009). For example, species assemblages and nutrient cycling in a particular reach reflect the interaction of flows with the channel substrate and hydraulic geometry (i.e. pool vs riffle), with the surrounding riparian area (i.e. extensive floodplains vs confined canyons), with neighboring up- and downstream reaches, and with more distant terrestrial portions of the watershed (Ward 1989; Fausch et al.

2002; Wiens 2002). Sensitivity to the effects of hierarchical scale can improve management interventions by informing the feasibility of counteracting large-scale mismatches with relatively small-scale interventions (Fig. 16.4). For instance, constructing pools for a fish species that requires them may incur significant, lasting costs if the species does not fit within the regional thermal profile or if watershed-wide land-use change produces an unsuitable sediment regime (Pretty et al. 2003). Selective timber harvesting throughout a watershed might diminish soil erosion relative to clear cutting, but a simultaneously intensive riparian grazing program could counteract benefits to aquatic organisms by promoting bank destabilization. Similarly, reshaping channel profiles with heavy machinery may not yield the desired biodiversity outcomes if the surrounding species pool has been significantly depleted, is blocked by movement barriers, or includes aggressive invasive species. These examples are certainly not intended to discourage local efforts, but rather to emphasize the need to consider the consequences of possible actions – flow manipulations or otherwise – across multiple spatial scales (Bond & Lake 2003; Brown et al. 2011; Fig. 16.4).

Attention to the habitat patch networks that correspond to spatial variation in flows can also enhance the design of robust management strategies. Stream-dwelling organisms depend on heterogeneous conditions that support foraging and reproduction and that act as refugia during disturbance events (Schlosser 1991; Palmer et al. 1995; Magoulick & Kobza 2003). Refugia exist at multiple scales, from interstitial spaces between cobbles and localized thermal habitats to landscape features such as tributary and side channels. Connectivity between these patches is necessary to permit adequate gene flow, tracking of spatiotemporally varying resources, and the possibility of regional "rescue" following local extirpation (i.e. metapopulation dynamics) (Fagan 2002; Falke & Fausch 2010; Winemiller et al. 2010). Flow regimes can mediate how in-channel infrastructure and watershed land use influence both the movement of organisms and the extent or accessibility of habitat (Stanford et al. 1996; Pringle 2003). Manipulating flows or fluvial forms to protect refugia and their connectivity may aid some species in their struggle to adapt (Magoulick & Kobza 2003; Matthews & Wickel 2009; Palmer et al. 2009). For example, the importance of pools and hyporheic zones for stream organisms in existing arid areas might justify efforts to promote such habitats in streams expected to shift from continuous to intermittent flow (Humphries & Baldwin 2003).

## Niches lost, niches gained

Complete information is never available when confronting riverine management issues both because of logistical limitations and because of the ongoing evolution of ecological systems. Nonetheless, an adaptive, experimental approach that accounts for the concerns outlined above positions managers to handle novel trends and fluctuations in environmental drivers. We propose that shifting climate and land-use drivers will affect riverine ecosystems in three conceptually distinct ways (Fig. 16.5). First, currently occurring niches – the endpoint of the multiscaled, multidimensional

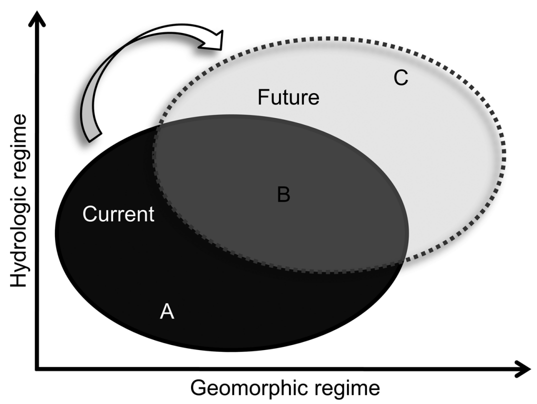


**Fig. 16.5** Shifts in the range of variation of environmental regimes will alter available niches in rivers. Hydrologic and geomorphic regimes in river networks may transition from a current range of variation (black) to a future one (white). Multiple interacting regimes form niches in streams and rivers, but are reduced here to these two dimension for simplicity. The three zones (A–C) represent ecological states (i.e. "niches") within the current and future biophysical regimes: zone A (black) denotes entirely lost ecological states under future hydro-geomorphic regimes; zone B (gray) depicts states that persist either locally or regionally; and zone C (white) corresponds to "novel" states that have never existed within the current range of variation. The types of changes on a particular river will help determine management strategies. Respectively, these might involve intensive flow manipulation to preserve lost hydrologic cues, ongoing monitoring for further shifts, or a program of experimentation to determine new best practices.

filtering processes described above – may be entirely lost from a region of interest (zone A in Fig. 16.5). Second, such niches may be relatively unchanged in a current location or regionally retained but geographically displaced (zone B in Fig. 16.5). Third, entirely new or regionally novel niches may emerge (zone C in Fig. 16.5).

Real river ecosystems will almost certainly mix these simplified scenarios (Fig. 16.6), especially if flow regimes buffer countervailing effects from altered large-scale drivers. Yet, they constitute useful cases for thinking about changes in flow-regime components. For instance, large or discontinuous shifts in the mean or variance of maximum daily flows might correspond to niche loss or gain. Figure 16.6 illustrates this as the loss of black and gain of white segments in a hypothetical river network. By contrast, smaller shifts in maximum daily flows might result in a relatively minor spatial niche displacement, as illustrated by the transition of some segments from black to gray in Fig. 16.6.

The persistence of a flow regime associated with a valued species or desirable ecosystem state presumably constitutes the best-case scenario. Under these circumstances, management can strive to "do no harm" by focusing on monitoring or maintenance to ensure that

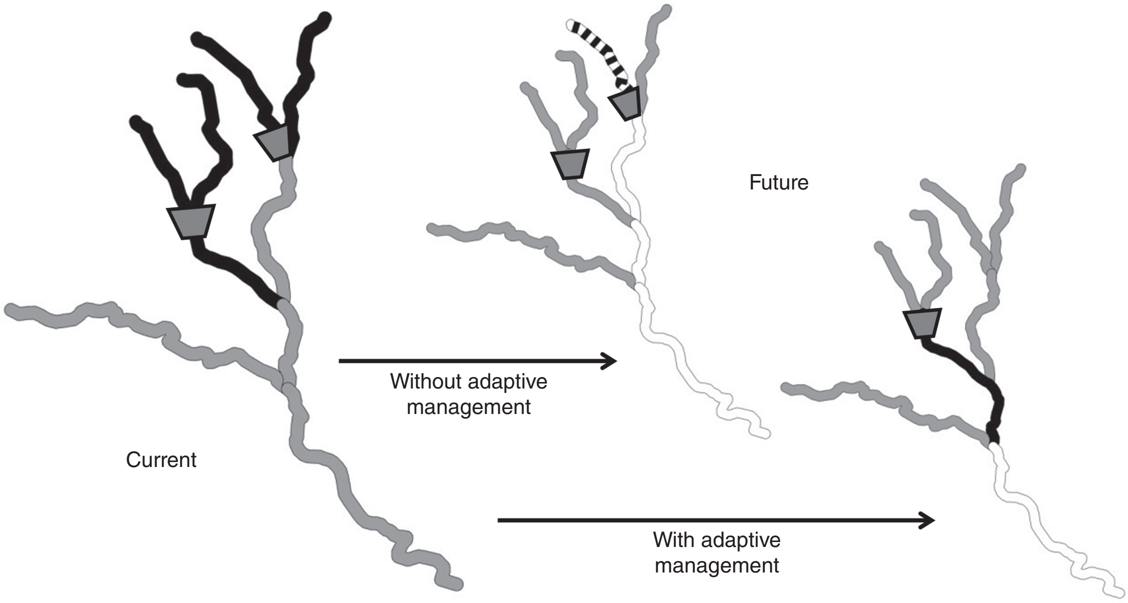


**Fig. 16.6** Altered ecological states in the river network. Colors correspond to Fig. 16.5: black segments represent lost conditions, gray denotes persistence, and white the emergence of novel states. Gray trapezoids represent water infrastructure such as dams and diversions. Current environmental regimes (left panel) support distinct species assemblages adapted to a particular range of variation. Shifts in the range of variation may occur in the absence of management adjustments (upper right panel) or within an adaptively managed watershed (lower right panel). Even without adaptive management (upper right), certain segments could retain desired ecological states (gray stays gray), but some segments would likely change states (black becomes gray) while others are entirely lost ("extinction" of black). Dam operation could further disconnect the network, obstructing colonization from other segments (black becomes dashed). In contrast, adaptive management (lower right) that includes re-operation of an existing dam might permit the local preservation of an otherwise vulnerable ecological state (black stays black), or its regional persistence in other segments farther downstream (gray becomes black). Additionally, dam removal could allow colonization from other portions of the network (black becomes gray rather than dashed). The adaptive management scenario broadens the potential number of ecological states within the network to include those that might otherwise be lost and those that match stakeholder values.

further global change does not drive the system past a flow threshold at which the target niche is lost. In a similarly optimistic vein, flow-regime changes could also deliver management benefits if an undesirable ecosystem state is replaced by a desirable one (e.g. niche changes leading to reduction of the detrimental effects caused by an invasive species).

Unfortunately, in many cases, the niche consequences of flow-regime changes will be considered detrimental. The difficulty of trying to "go against the flow" by artificially sustaining desired conditions will generate tough choices between complex and costly logistics and the need to communicate to stakeholders that it is unreasonable to preserve existing states. As an example, consider a shift from a spring-snowmelt to winter-rain flow regime, resulting in an earlier and lower magnitude annual peak flow (e.g. North Brush Creek to North Fork Tolt River in Fig. 16.2). The persistence of a species with reproductive timing that is adapted to predictable, yearly peak flows will then depend on its ability to adjust to new cues phenotypically or genetically or on managers' ability to deliver flows that sufficiently mimic the current sequence (Schlaepfer et al. 2002; Lytle & Poff 2004). If the altered peak flow timing exceeds the species' adaptive capacity, and over-allocated water resources in the basin preclude adequate flow manipulation, then regional extirpation is plausible. Species already facing unfavorable flow regimes, such as Plains cottonwood (*Populus deltoides*) in western US rivers, are at potentially greater risk under this scenario (Stella et al. 2006; Merritt & Poff 2010).

Entirely new niches present yet another set of challenges. The scope of continental or global flow regimes may provide precedents for locally novel circumstances (e.g. present day arid-region streams serving as models for systems undergoing desertification), but when no such precedent is available, managers will need to incorporate predictive modeling and a diversified program of trial and error. No single method will constitute the best response to the loss, creation, or displacement of niches within river and stream ecosystems. Legal constraints or early indications of irreversible damage may call for intensive manipulations. Careful monitoring of a system that adjusts on its own may be most appropriate in other circumstances. Successful resource management and conservation will creatively pursue a combination of approaches with clear evaluation standards and will avoid entrenchment by shifting resources to those that deliver the greatest ecological return.

## Classification to enhance dialogue and decisions

A flow-regime paradigm emphasizes the importance of variability, but the complexity of patterns in rivers can become overwhelming, particularly when social or political mandates presume managers act within straightforward, tractable systems. Classification of flow types (e.g. snowmelt vs rainfall, perennial vs intermittent) affords a means of dealing with some of this complexity while retaining essential relationships between flow pattern and ecological outcome. Differences in precipitation, vegetation, and topography support the differentiation of regimes in terms of biologically relevant hydrograph components (e.g. frequency of peak and low flows, seasonality; Fig. 16.2). This facilitates the association of certain regime types with targeted ecological outcomes across similar reaches, sub-watersheds, or basins, and can expedite efforts to monitor progress toward these goals (Arthington et al. 2006; Poff et al. 2010). Flow-regime classification can also play a role in the reconstruction of appropriate hydrographs when large dams and extensive land-use modification mask the underlying natural variation (Fig. 16.3). Representative typologies have been developed for the United States (e.g. Poff 1996), New Zealand (Biggs et al. 1990), Australia (Kennard et al. 2010), and France (Snelder et al. 2009) as well as various other nations.

Classifications are defined by recent historical climatic conditions, and this raises the issue of their applicability to future conditions. Climate change is projected to modify historical flow regimes significantly (Doll & Zhang 2010) and may induce entirely novel hydro-climatological conditions (Williams et al. 2007). In some instances, this will necessitate the revision of flow-regime types, and this possibility constitutes a strong argument for the maintenance and expansion of the gauge networks that provide critical data for any flow-based approach. Many watersheds, however, are likely to experience shifts in temperature and precipitation patterns that are within the total range of all systems considered for classification (e.g. among all types shown in Fig. 16.2). That is, novel conditions for a particular river may or may not be novel at some broader scale (e.g. continental). In some cases, a river or stream may transition between currently recognizable flow-regime classes, such that management of the newly altered system can take advantage of knowledge regarding existing systems with similar hydrologic properties. For example, anticipating a transition from perennial to ephemeral flows (Seager et al. 2007), managers in a drying region might consult with those who have already experienced the challenges of sustaining desired ecological states under periodic drought conditions.

Certain forms of water-resource infrastructure have distinct signatures in the hydrograph, and typologies may include patterns such as the regular discharge spikes associated with "hydropeaking" (releases from hydropower installations that follow from the intensity of electrical demand). Classification may also help prioritize resources by indicating if and how a flow regime is already subject to significant human alteration (Bunn & Arthington 2002; Graf 2006; Poff et al. 2006a; 2007; Fig. 16.3). In some instances, climatic shifts may be of less relevance to desired ecological states, and climate-related mitigation programs may or may not adequately address impacts related to other types of change. For example, consistent, intermediate-magnitude flows below an irrigation dam might harm a native species accustomed to sporadic or seasonal fluctuations in discharge or allow non-native species preferring stabilized flows to flourish (Marchetti & Moyle 2001). In this case, an assessment of the ecological consequences of altered precipitation in the basin would need to begin with an account of the dam's impacts and the degree of flexibility in its operation.

Efforts to apply a flow classification approach to pressing issues in river management have progressed rapidly and continue to be refined with the availability of new data and analysis tools. The ecological limits of hydrologic alteration (ELOHA) framework seeks to integrate scientific knowledge regarding the importance of heterogeneity in the hydrologic, geomorphic, and biological attributes of fluvial environments with social priorities for the use and protection of those systems (Poff et al. 2010). Incorporating the needs of multiple stakeholders, the ELOHA process provides a means of quantitatively relating flows to ecological states at a regional scale, thereby generating a context for changes in a particular watershed. Poff et al. (2010) describe the steps of the ELOHA framework in detail. Briefly, they include building a hydrologic foundation, classifying segments appropriately, constructing defensible flow-response models, evaluating uncertainty, and building toward consensus among stakeholders. Our emphasis here has been on flow regimes, but because of the importance of the interaction between discharge and the geomorphic context, ELOHA involves local geomorphic subclassification to better stratify ecological responses. Although the ELOHA methodology will not be suited to all issues in riverine ecosystem management, its recent implementations demonstrate the value of addressing novel environmental conditions in terms of flow (http://conserveonline.org/workspaces/eloha). The approach enables managers facing climatic or land-use uncertainty to refine their expectations for ecological responses by conducting a scenario analysis using flow-response models developed for a region. ELOHA also embodies the more general goal of framing resource management and conservation decisions within the understanding of basic ecological processes gained through research and historical analysis.

## 16.4 SUMMARY

In this chapter, we have argued that a process-based understanding of river ecology (Box 16.1, Fig. 16.1) offers a means of effectively evaluating resource-management options in the face of rapid global change. Contemporary ecological states in rivers reflect a hierarchical set of drivers (Fig. 16.1) with characteristic ranges of variation over a recent historical period. These relationships provide the basis for anticipating rivers' responses as their drivers depart from these historical ranges. Monitoring and adjusting the properties of key environmental regimes, particularly the flow regime, will provide an opportunity for management to mitigate or adapt to large-scale shifts. Recognizing the importance of variable flows and their interaction with multiscaled habitat networks is critical to developing management strategies that sustain the heterogeneity required for diverse, functioning river ecosystems. Despite the political and economic costs of an experimental approach to management, operational flexibility is vital to successfully integrating knowledge of rivers' past with their ongoing alteration. We remain hopeful that the dedication and ingenuity of the many managers committed to ecological and socioeconomic health will overcome the difficulties posed by a rapidly changing world.

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