

Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities

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Building on previous environmental flow discussions and a growing recognition that hydrogeomorphic processes are inherent in the ecological functionality and biodiversity of riverscapes, we propose a functional-flows approach to managing heavily modified rivers. The approach focuses on retaining specific process-based components of the hydrograph, or functional flows, rather than attempting to mimic the full natural flow regime. Key functional components include wet-season initiation flows, peak magnitude flows, recession flows, dry-season low flows, and interannual variability. We illustrate the importance of each key functional flow using examples from western US rivers with seasonably predictable flow regimes. To maximize the functionality of these flows, connectivity to morphologically diverse overbank areas must be enhanced in both space and time, and consideration must be given to the sediment-transport regime. Finally, we provide guiding principles for developing functional flows or incorporating functional flows into existing environmental flow frameworks.

Keywords: hydrology, river ecology, water resources, land-use management, geology

During the past three decades, flow management of regulated rivers has increasingly considered downstream effects on the environment. Early approaches to defining stream flows that benefit the environment (hereafter called *e-flows*) focused on quantifying a single minimum instream flow sufficient to maintain aquatic species during crucial low-flow periods. These recommendations did not address the role of stream flow in maintaining species during other periods—or in habitat maintenance and formation—and riparian ecosystem needs (Petts 1996). However, consideration of the impacts of different aspects of the flow regime on the entire river ecosystem was first proposed by Hill and colleagues (1991), who described the various ecological links associated with different flow magnitudes: low flows, bank-full flows, overbank flows, and extreme valley-inundating floods. Petts (1996), Richter and colleagues (1996), and Poff and colleagues (1997) introduced ecological and geomorphological relationships to other attributes of the flow regime, including the timing, duration, frequency, and rate of change of flows. Following these and other advances in river science, an “*e-flows imperative*” to sustain healthy river ecosystems (Petts 2009) emerged at the beginning of the twenty-first century. Today, resource managers and river scientists recognize the importance of the natural flow regime

(Poff et al. 1997), the role of flow variability as a driver of ecosystem processes (Naiman et al. 2008), and the inherent interplay among river structure, physical processes, and ecological patterns (Fremier and Strickler 2010, Wohl 2012).

The early twenty-first century has seen expansion in the variety of approaches to implementing *e-flows* (Arthington 2012). These advances have ranged from simple prescriptions applicable to rivers where few baseline data are available to complex data-driven approaches, such as the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al. 2010). The former approaches include strategies such as limiting withdrawals to a fixed proportion of the natural flow (Richter et al. 2012) and downscaling the entire flow regime by reducing flow magnitudes but sustaining the normal seasonal pattern of flow variations (Hall et al. 2011). The latter approaches specifically advocate that flow recommendations be based on the mechanistic relationships between flows and ecological outcomes. However, in heavily modified riverscapes (*sensu* Ward 1998, Fausch et al. 2002), restoring a natural flow regime is a particular challenge because of competing water demands (Aceman et al. 2014). Mimicking a natural flow regime in modified riverscapes will not yield successful ecological outcomes unless such flows trigger functional processes. For example, the

restoration of peak flows will not regenerate habitats if the river is starved of sediment or if the river channel is highly confined (Wohl et al. 2015). Given these constraints, we propose that a more effective approach is to identify and restore aspects of the flow regime that support key ecosystem functions and drive geomorphological and ecological processes.

Riverine ecosystems and their species are adapted to processes and patterns that stem from not only the flow regime but also the associated disturbance regime, which promotes ecological feedbacks between biological and physical processes (Lytle and Poff 2004). It is well recognized that functioning river systems exhibit temporal variability in flow (Naiman et al. 2008), sediment flux, and channel morphology (Beechie et al. 2010), and these physical dynamics interact with biological communities at multiple scales (Petts 2009). Simply stated, the design of a more natural flow regime without consideration of the implications for sediment transport and channel–floodplain geomorphology is likely to have limited success in river management and restoration.

Here, we build on the latest e-flows science to propose a functional-flows approach to managing rivers in highly modified riverscapes. We expand consideration of e-flows to not only address the ecological function of particular flows (Acreman et al. 2014) but also to explicitly emphasize sediment erosion, transport, and deposition to maintain and rehabilitate geomorphologically important instream and floodplain habitats, as was advocated most recently by Wohl and colleagues (2015). We suggest that e-flow design and implementation should focus on specific functional flows (*sensu* Escobar-Arias and Pasternack 2010) that support natural disturbances, promote physical dynamics, and drive ecosystem functions (Arthington et al. 2010). We define these functional flows, discuss their geomorphic implications in the context of floodplain connectivity and sediment mass balance, suggest how they might be combined into a functional flows framework or incorporated into existing e-flow frameworks, and provide several guiding principles for the flow management of highly modified rivers. We illustrate our approach with examples from rivers throughout western North America that have marked flow seasonality, widely variable sediment supply regimes, and variable sensitivity to hydrological change, typically exhibiting relatively short relaxation times for channel morphology response to flow regulation (Petts and Gurnell 2013)—thereby providing examples applicable to other rivers worldwide.

What is a highly modified riverscape?

We consider *highly modified rivers* to be those that (1) have a high proportion of their total length converted to reservoirs, (2) have a high proportion of their total annual stream flow diverted and/or managed for societal uses, (3) have a high proportion of their total annual stream flow stored in reservoirs, and/or (4) have a large proportion of their total length channelized or lined by levees. These four characteristics rarely occur in the same river, but even one of these characteristics can greatly affect the riverscape, particularly

in terms of sediment transport and floodplain extent, and constrain e-flow implementation and ecosystem restoration potential. For example, the Columbia River meets the first criterion, and e-flows can only be applied to the remaining reaches of the channel network. In these short river reaches, specific flow regimes, specific target species, and particular life-history habitat requirements can be relatively easily linked to limited e-flow allocations, because fewer demands are placed on these short reaches. In contrast, the Colorado River meets the third criterion, with reservoirs that can store many times the annual average runoff and long river segments between reservoirs. Here, e-flow recommendations must be balanced with the interests of multiple stakeholders concerned about different river resources in different parts of the river. Extensive e-flows negotiations over several decades have been implemented, debated, and revised in order to meet these competing demands (Melis et al. 2012). Opportunities for e-flow implementation are particularly constrained on the lower Colorado River, where all of the stated criteria for a highly modified river are met. In fact, no flow typically occurs downstream from Morelos Dam in Mexico, and the Colorado River rarely flows into the Gulf of California. In each of these types of highly modified rivers, the limited availability of water to support e-flows makes it impossible to restore a full natural flow regime, suggesting that the restoration of key flow components that drive geomorphological and ecological functions may be a more efficient and effective strategy.

The functionality of flows in the riverscape

Variable flow regimes that transport differing sediment sizes at multiple discharges produce dynamic habitat mosaics that change in space and time (Stanford 2006) but can remain consistent in terms of overall abundance and area of habitat types (Ward et al. 2002). Temporally variable flow regimes interact with spatially variable river channel and floodplain forms to support high biodiversity (Ward 1998, Wohl 2012). When these dynamic spatiotemporal interactions are limited by flow alterations, blocked by channel levees, or perturbed by sediment deficit or surplus, rivers can become homogeneous, and biodiversity decreases (Moyle and Mount 2007, Wohl et al. 2015).

In large alluvial rivers, the extended residence time of floodwaters within riparian wetlands diversifies the vegetative structure and increases primary productivity (Ahearn et al. 2006), whereas increased shoreline complexity can provide greater diversity of fish habitat (Moore and Gregory 1988). Such conditions require both the flows to produce the necessary timing of connectivity, as well as the space for the development of geomorphic configurations (figure 1). Only when interactions between flow and the riverscape are maintained can these diverse ecological processes be sustained over time (Fausch et al. 2002). However, these morphologic attributes and related physical processes are often the first to be lost when floodplains are confined by levees and channels are simplified.

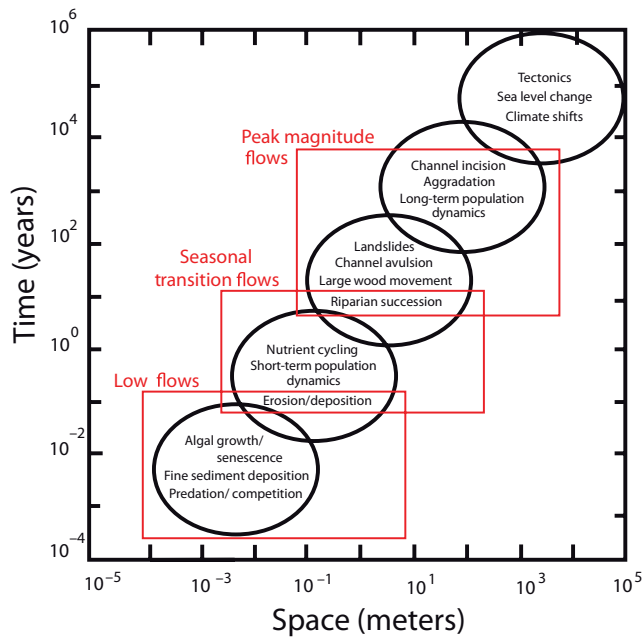


Figure 1. Examples of interrelated physical and ecological riverine processes at varying spatial and temporal scales. Key functional flows supporting specific processes are shown in boxes.

Hydrogeomorphic processes are not only influenced by active floodplains but also by the balance between the sediment supplied from the watershed and the ability of the river to move the sediment (Lane 1955). Channels differ in form because of differences in sediment transport capacity and sediment supply (Wohl et al. 2015), as well as variations in riparian vegetation, the presence of coarse legacy substrate and bedrock, floodplain extent, and large woody debris (Petts and Gurnell 2013). In headwater areas, geomorphic diversity is primarily driven by the mobilization of coarse bed material in various aquatic habitats; therefore, the magnitude of stream flow and the availability of sediment are key factors. However, as one moves downstream in the drainage network, the proportion of fine sediment and the total bed material load typically increases, and consideration of bed material mass balance becomes key (Church 2002). Here, geomorphic diversity and aquatic habitats can only be maintained if the duration of high flows is sufficient to maintain the flux of bed material supplied from further upstream.

In regulated rivers with large dams, the upstream sediment supply is typically trapped behind the dams, creating a sediment mass balance deficit downstream. If the relationship between flood duration, which correlates with total transport capacity, is not in balance with the limited sediment available below the dam, subsequent scour and bed degradation can occur, such as in the immediate 25 kilometers (km) downstream from Glen Canyon Dam on the Colorado river (Grams et al. 2007). Conversely, if a regulated river has large sediment inputs from unregulated tributaries

or lacks transport capacity because of large flow diversions, such as in the Rio Grande in the Big Bend region of Texas and Chihuahua (Dean and Schmidt 2013), the sediment mass balance may be perturbed into surplus. Short duration floods are insufficient to transport large volumes of residual sediment downstream, limiting the geomorphic diversity and maintenance of associated instream channel habitats.

Achieving greater river functionality in highly modified riverscapes requires the enhancement of dynamic spatio-temporal interactions. Recent emphasis on process-based restoration has drawn attention to the connections between hydrologic and geomorphic dynamics (Beechie et al. 2010, Wohl et al. 2015). In general, greater floodplain benefits accrue when physical habitat restoration, sediment transport, and flow regimes are considered together. In some locations, levee setbacks or reclaimed farmland adjacent to the channel have been coupled with e-flows to restore floodplain dynamics (e.g., Greco and Larsen 2014). In other cases, coarse sediment has been added to the river to promote sediment transport and redistribution of bed material to create instream habitat diversity (e.g., Gaeuman 2014). Incorporating a process-based view of how flows interact with the riverscape is more likely to produce a self-sustaining and resilient river ecosystem (Beechie et al. 2010). Furthermore, a process-based view allows for future climate or land use changes to be taken into account versus empirical approaches that rely on assumptions of stationarity and static management prescriptions (Null and Viers 2013).

In many contemporary riverscapes, opportunities for process-based restoration may be found at tributary junctions along the drainage network, locations where the valley morphology naturally widens, where access to the historic floodplain is politically possible, or where sediment can be actively recruited into the channel, creating a diversity of bed material sizes. Considered “biological hotspots” (Benda et al. 2004), tributary junctions are zones of geomorphological and hydraulic diversity with enhanced channel dynamics, increased channel width, increased local sediment supply, and low-energy backwater habitats with thermal upwelling benefits. Similarly, areas with channel widening that promote local deposition and bar development or areas with local sediment inputs that provide coarse substrate in a fine-grained channel bed can provide hotspots of habitat diversity within a more uniform river reach (Yarnell 2008). These various types of hotspots may be seen as loci of core populations and assemblages that can buffer aquatic and riparian metacommunities against environmental change, providing stable sources of dispersers to recolonize peripheral habitats following a major disturbance. In highly modified rivers with complex water demands and limited “room for the river” (Warner and van Buuren 2011), functional flows maximize the benefits from limited environmental flow allocations. This may be achieved by focusing on the ecological and geomorphological functionality of particular aspects of the flow regime, considering geomorphic context and emphasizing spatiotemporal diversity at key locations

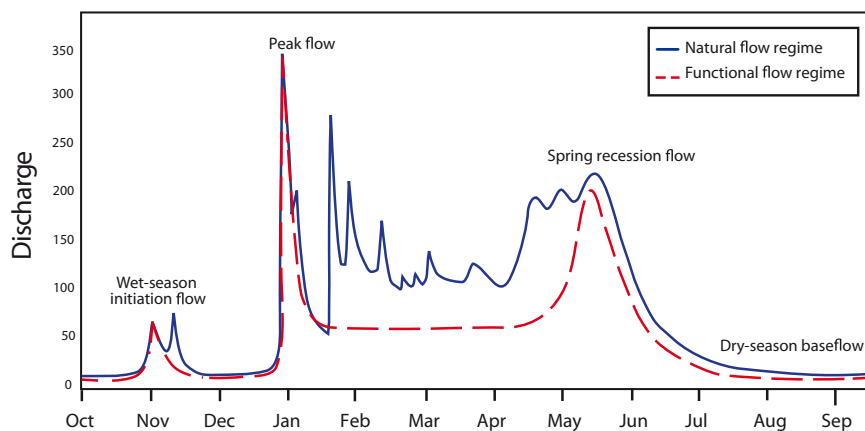


Figure 2. Natural and functional flow regimes in a Mediterranean–montane climate, where spring occurs April to June. Peak flows are typically rain-driven events in winter, whereas a pronounced snowmelt pulse occurs in spring. The functional flow regime retains key components of the natural hydrograph that support physical and ecological processes across the riverscape.

in the riverscape, such as adjacent floodplains or tributary junctions.

Defining functional flows

A *functional flow* is a component of the hydrograph that provides a distinct geomorphic or ecological function (*sensu* Escobar-Arias and Pasternack 2010). These functions may include geomorphic processes (Escobar-Arias and Pasternack 2010), ecological processes (Ward et al. 2002), or biogeochemical processes (Vidon et al. 2010). Such processes in rivers and associated biotic interactions operate in three dimensions—longitudinally, laterally, and vertically—and are intimately tied to the timing, duration, and frequency of natural flows. Therefore, functional flows must attempt to reflect the natural patterns of flow variability.

Most rivers in the western US have a distinct season of high-magnitude flow, with low flows dominating the remainder of the year. In Mediterranean-montane environments of the Pacific region, winter precipitation events create rain-driven floods at low and moderate elevations and spring snowmelt floods from high elevation snowpack. Streams draining the Rocky Mountains into the Missouri and Colorado Rivers have a well-defined spring snowmelt flood season, whereas the southern Rocky Mountain and southwest mountain regions have a pronounced spring snowmelt season and a later summer flood season associated with the North American monsoon. For many native species adapted to these cyclic flow regimes, high flows present significant abiotic pressures (e.g., high main-stem velocity, high turbidity), whereas intermediate and low flows present significant biotic pressures (e.g., competition, predation) (Lytle and Poff 2004, Yarnell et al. 2010). However, flood and drought cycles, their seasonal transitions, and their associated temperature changes provide breeding, migration, and other life-history cues for most endemic species.

Recognizing that e-flow recommendations mimicking the full natural flow regime are not likely to be implemented in highly developed rivers where societal demands are well established, we attempt here to identify the most essential functional flows that support physical and biotic processes, emphasizing their timing, duration, rate of change, and frequency (figure 2). Below, we delineate five key components of the flow regime that drive ecosystem processes and should be incorporated into the existing environmental flow framework.

Wet-season initiation flows. Whether the onset of high flows begins with the first substantial rains of late fall in the Pacific region or with the first substantial melting of the winter snowpack, as in the

Rocky Mountains, the transition from dry season to wet season signals the start of a dramatic annual shift in riverine conditions. The first high flows of the season typically have higher suspended sediment concentrations as sediments accumulated on hillslopes and in channels during the dry season are flushed downstream. In some landscapes, these “initiation flows” kick-start ecological processes such as nutrient cycling (Ahearn et al. 2006) and provide key ecological cues for native species, such as upstream migration in the Pacific region (Sommer et al. 2011, Kiernan et al. 2012) and spawning in semiarid rivers (Propst and Gido 2004). The timing of these first high flows is essential for life-history cues, whereas the magnitude and duration are important for revitalizing the riverscape by reconnecting channel–riparian–floodplain habitats, flushing organic matter and fines from gravel spawning beds, increasing soil moisture, and reactivating exchanges with the hyporheic zone (Stubbington 2012).

The timing of wet-season initiation flows should coincide, to the degree possible, with the onset of wet-season precipitation or initial snowmelt runoff. For many native species, this first turbid flow event provides a key life-history cue to migrate upstream and begin spawning. In the California Delta, at the confluence of the Sacramento and San Joaquin Rivers, the endangered Delta smelt (*Hypomesus transpacificus*) is a short-lived endemic minnow that resides in the Delta estuary and relies on “first flush” pulses of more turbid, lower salinity, colder water in the fall to cue their upstream migratory response (Sommer et al. 2011). Similarly, the Colorado pikeminnow (*Ptychocheilus Lucius*) in the Colorado River initiates migration for spawning in response to the flow and temperature cues associated with the initial increase of the spring snowmelt pulse (Schmidt and Brim-Box 2004). Alterations to the timing of or complete lack of this key flow event can be detrimental to the life-history strategies of these native species.

The magnitude of an initiation flow should be such that connectivity with the riparian zone is established and organic matter can be flushed from the channel substrate. The buildup of organic material and fines can impede the success of salmonid spawning in gravel beds (Kemp et al. 2011) and over time can contribute to increased vegetation encroachment and decreased substrate diversity in the main channel. On many rivers, such flushing flows that remove sand from riffles and organic fines from pools and riparian edgewater areas can be effective at or above 60% bankfull depth. The duration of flushing flows should be adequate to cue species migration or initiate nutrient exchange in floodplains. In California's Cosumnes River floodplain, for example, Ahearn and colleagues (2006) observed that the timing and intensity of the first flushing flow of the season, which typically lasted only a few days, determined water chemistry patterns throughout the watershed.

On some rivers, wet-season initiation flows can be accomplished by simply letting the first sediment-laden flood of the season or the initial rise of the snowmelt flood pass through reservoirs to reflect the natural passage through the watershed. This may be more easily accomplished in rivers with small storage reservoirs that are quickly filled, but even in highly regulated rivers, where large reservoirs can store the full annual flow, wet-season initiation pulse flows can be designed to match unregulated reference conditions. In Putah Creek, California, a more natural flow regime was implemented that included fall pulse flows at the start of the wet season designed to initiate migration of native fish species (Kiernan et al. 2012). In combination with elevated spring spawning flows, the new flow regime resulted in an increase in native species abundance and a reduction in nonnative species throughout the upper 20 km of the 30-km stream.

Peak magnitude flows. Large-magnitude peak flows during the annual flood season typically transport a significant portion of the annual sediment load and restructure the channel and floodplain landforms, which create the habitat template of the river corridor ecosystem. These large-scale disturbances serve to reset natural processes such as succession (Ward 1998); to redistribute large volumes of sediment through scour and fill, creating channel bed, bank, and floodplain variability (Florsheim and Mount 2002); and to cause the mortality of exotic species not adapted to the disturbance regime (Kiernan and Moyle 2012). Channel-filling and overbank flows initiate nutrient cycling within the floodplain (Ahearn et al. 2006), scour vegetation encroaching the channel, and disperse seeds and wood fragments to rejuvenate riparian vegetation (Petts and Gurnell 2013). As such, peak flows serve as a primary driver for ecosystem processes that maintain habitat diversity over the long term.

The magnitude of a peak flow should be large enough to mobilize bed material and maintain in-channel bar forms, connect to overbank areas and floodplains, and occur with a frequency of 1–3 years depending on regional climate

conditions. Very large magnitude peak flows that cause extensive floodplain scour and fill and reset floodplain vegetation succession naturally occur every 10–20 years; however, such geomorphologically effective floods are typically incompatible with highly modified rivers, where the alluvial valley is developed for agriculture and residential communities. Without space within the river corridor for lateral channel migration, inundation of floodplain depressions, and backwater channels, the geomorphic functionality of peak flows is limited. Therefore, connections to the floodplain (e.g., levee breaches) and the expansion of overbank areas (e.g., levee setbacks) should be enhanced and maintained wherever possible.

The timing of a peak magnitude flow should occur within the natural season of high flows when native species have life-history strategies to survive and even capitalize on these large-scale floods. In California, native amphibians retreat to protected riparian areas during winter floods, whereas native juvenile fish occupy shallow low-velocity overbank habitats and avoid high-velocity conditions in the main channel (Yarnell 2008; Kiernan et al. 2012). Peak flows can provide ecologic cues for migration and spawning, as well as the flow volume needed to create a migration corridor. For example, Columbia River salmon use high spring snowmelt flows to migrate upstream to small streams suitable for spawning. Shifts in the timing of peak flows, particularly to seasons that naturally might be dominated by low flows, can be detrimental to the life-history strategy of these native species.

The duration of peak flows should allow ecologic processes such as floodplain activation, species migration, and spawning to occur. For example, Ahearn and colleagues (2006) showed that as flood pulse flows inundate the Cosumnes River floodplain, wetted soil promotes a bloom of phytoplankton, which in turn drives the secondary production of zooplankton. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) rearing in the floodplain feed on the zooplankton, leading to high growth rates (Jeffres et al. 2008). Simultaneously, native splittail (*Pogonichthys macrolepidotus*) use the inundated floodplain habitat for breeding, with larval fish emerging within several weeks. These ecological processes and cues are dependent on the sustained floodplain inundation of a minimum of three weeks and periodic connectivity between the topographically heterogeneous floodplain and the river.

Although the duration of a peak flow should also be sufficient to facilitate desired geomorphic processes, such as floodplain deposition, pool scour, or channel bar formation, the duration should not be longer than the time needed to transport the annual available supply of bed material. Particularly in rivers perturbed into sediment deficit, extended duration floods are likely to further erode sediment deposits that are already infrequent and can result in net erosion of the channel unless sediment supplies are augmented naturally by access to historic floodplains or artificially by gravel augmentation. For example, in the Colorado River,

controlled floods have been released from Glen Canyon Dam to mobilize the small amounts of sand supplied from unregulated tributaries and transfer the sediment to eddy sandbars that are of recreational and ecological importance (Melis et al. 2012). These floods have short durations of 2–7 days and are half the magnitude of the pre-dam annual flood in an effort to limit erosion of the remaining pre-dam fine sediment and redistribute only the sand supplied from the tributaries. In contrast, in rivers perturbed into sediment surplus, the flood duration must be sufficiently long to transport the annual accumulation of sediment and limit channel infilling. In the Rio Grande River along the US–Mexico border, sediment surplus conditions exacerbate the problems of fine sediment accumulation, particularly during short-duration flood pulses that attenuate quickly and rapidly deposit their sediment load, inducing the vertical aggradation of the floodplain and channel narrowing (Dean and Schmidt 2013).

The management of the magnitude, timing, and duration of peak flows is easier in rivers where reservoir volume is relatively small and natural high flows can spill downstream, where dams have the capacity to release high flows via controlled outlets or spillways, and where water-supply demands can be met. Challenges occur when reservoirs are large and rarely spill, when hydropower or water supply demands are highly seasonal and out of phase with the natural runoff, or when the infrastructure to release high flows is limited. In the Yuba River in California, peak winter runoff and spring snowmelt flows are captured for agricultural water supply during the low-flow summer season. Environmental flow negotiations have resulted in the release of spring high flows in all but the driest years, designed to support the rejuvenation and maintenance of Chinook salmon-spawning conditions on gravel–cobble bars (5 April 2015; www.yubaaccordrmt.com). In contrast, in the Colorado River basin, the annual snowmelt peak historically occurred in May and June, but the demands for hydropower—and therefore high flows from the powerhouses—are largest in December–January and July–August. Controlled floods to redistribute sediment are now scheduled (2012–2014) during the historically low-flow period in November to mobilize newly deposited sediments supplied from the unregulated tributaries. Although these controlled floods provide some geomorphic functionality to the Colorado River in Grand Canyon by rebuilding channel bars, the timing is out of phase with the natural flow regime.

Spring recession flows. The spring flow transition from high flow to low flow is often identified as a part of the hydrograph from which stream flows can be extracted without significant geomorphic and ecological effect (Schmidt and Potyondy 2004). However, the spring flow recession is predictable in its timing and rate of flow change and therefore provides distinctive annual cues for the reproduction and movement of native species (Yarnell et al. 2010), particularly in regions with highly seasonal climates. These cues are

primary ecologic drivers in population dynamics such that changes in the timing or shape of the flow recession can alter aquatic community composition and limit reproductive success (Marchetti and Moyle 2001). Gradually receding flows can also be a key factor in redistributing sediments mobilized by high peak flows (Yarnell et al. 2010). When sediments are recruited and entrained at high flows, slowly receding flows allow for continued sediment movement in deeper channel locations and gradual deposition throughout shallow channel habitats.

The initial magnitude of recession flows is typically associated with the spring snowmelt peak, and the rate of declining flow should mimic the natural gradual recession rates shown to provide suitable habitat conditions for native species (Yarnell et al. 2010). The character of water storages—ice, snow, groundwater, lake—determines the typical flow recession curve for each river basin. In the Sierra Nevada mountain range of California, daily spring flow recession rates were found to be consistent across latitude, elevation, and watershed area, with flows decreasing from 4–8% per day across the entire spring season (Yarnell et al. 2013). These recession rates are slow enough that suitable spring spawning habitat for native species, such as the riffle sculpin and the foothill yellow-legged frog, persists for two to four weeks in any one channel location, allowing the emergence from eggs before the habitat disappears as flows continue to decrease (Yarnell et al. 2013). In southwestern US rivers, the recruitment-box model for cottonwood germination suggests spring flow recession rates should not exceed 2.5 centimeters per day in order for cottonwood (*Populus* spp.) to germinate and young sapling roots to follow the receding water level (Mahoney and Rood 1998). These recession rates are such that the duration of receding flows sustains the persistence of various aquatic habitats used by native species for successful reproduction and therefore should be replicated in regulated rivers to the extent possible.

The timing of recession flows should coincide with natural climatic conditions (e.g., during spring snowmelt) when temperatures and precipitation regimes are changing. For many native spring spawners, the flow recession provides a cue that appropriate higher-flow spawning conditions will soon transition into warm, low-velocity habitats suitable for early life stages. The foothill yellow-legged frog (*Rana boylei*) is a river-breeding amphibian native to California and southern Oregon highly adapted to the natural seasonal flow regime (Yarnell 2008). Individuals breed annually in early spring following the start of the snowmelt recession, timing their reproduction to minimize the risk of egg scour from late-spring storms, and to maximize tadpole growth during summer low flows. Similarly, successful cottonwood recruitment requires not only an appropriately slow recession flow rate but also the appropriate timing to coincide with seed dispersal (Mahoney and Rood 1998). In order to successfully reproduce, the endangered Rio Grande silvery minnow (*Hybognathus amarus*) requires access to suitable floodplain habitat for spawning in late April and May and a

gradual flow recession with lateral connectivity to the main channel (Medley and Shirey 2013). In regulated rivers with altered spring and summer flow regimes, these native species populations have been extirpated or persist in very low numbers. The prescription of a flow regime that gradually ramps down from a spring high-flow event by appropriately mimicking the rate and timing of natural spring snowmelt recessions will provide the greatest opportunity for the successful reproduction of these and other native species.

The implementation of spring recession flows in regulated rivers is limited primarily by the system's infrastructure. If high spring flows are the result of spill over the dam, control valves or lower-level outlets must be used to appropriately ramp down flows from spill to baseflow. In some instances in the northern Sierra Nevada in California, this has required modifications to spill gates or changes in the low-level outlets of the dam (Yarnell et al. 2013). Although there can be potential costs to hydropower generation by extending spring flow releases in a recession, if the flows are timed appropriately to coincide with naturally occurring higher spring flows, the costs can be minimal or recouped by storage downstream (Rheinheimer et al. 2013). In rivers with a sediment surplus, the design of a flow recession should include consideration of the volume of sediment supplied by upstream reaches, whereas in rivers where sediment is limited, consideration of augmentation to local sediment sources may be needed to promote redistribution of sediment throughout the channel.

Dry-season low flows. The duration and magnitude of dry-season low flows are important drivers of riverine ecosystems, because most native species are adapted to survive these biologically stressful periods. The magnitude and duration of low flows dictate the extent and quality of physical habitat, thereby affecting the composition and distribution of riverine biota. As low flows restrict the connectivity of instream habitat, ecological-niche partitioning can occur with native species using low-flow refugia or exhibiting adaptive life-history strategies (Lee and Suen 2012). Artificially high baseflows can maintain connectivity, but often to the benefit of non-native species that are not adapted to the limiting conditions of natural low-flow periods (Kiernan and Moyle 2012). Extended constant base flows can also lead to silt accumulation in the channel bed, reducing instream channel diversity and species diversity (Moyle and Mount 2007).

Although the prescribed magnitude of low flows or minimum instream flows in regulated rivers is a well-studied and extensively debated topic (e.g., Jowett 1997), we suggest that the magnitude of low flows should be low enough to produce naturally limiting habitat conditions, such as floodplain disconnection, but still maintain natural stream characteristics, such as perenniality or ephemerality. On the lower Santa Clara River in southern California, geological controls on groundwater historically created an alternating pattern of perennial and intermittent reaches such that a heterogeneous mosaic of mesic and xeric riparian communities

occurred in close proximity (Beller et al. 2011). These differing stream reaches provided distinct ecological functions, including refugia from drought and flood, support of extensive willow-cottonwood forests in perennial reaches, and support of the now-regionally rare xeric alluvial scrub in intermittent reaches. Although the maintenance of natural spatial patterns of perennial or intermittent flow in summer can be an important component to supporting biodiversity, the duration and timing of low flows should reflect premodified conditions to the extent possible so as to limit stressful habitat conditions. The presence of diverse channel habitat that provides a variety of refugia during low flows is key to supporting native species. Although instream geomorphic diversity is created and maintained by sediment mobility at higher flood flows, instream habitat heterogeneity may be augmented by the addition of large woody debris, riparian vegetation, and other cover features that enhance the diversity of habitat available at low flows.

Interannual variability. Year-to-year variation is a key attribute of functional ecosystems that should be incorporated in all e-flow frameworks. Periodic disturbances from climatically driven high-flow events have been shown to reset successional stages in river systems (Ward 1998) and to regulate river food webs by decreasing the abundance of predator-resistant primary consumers, which supports more diverse food chains (Power et al. 2013). Therefore, the magnitude, timing, and duration of specific flow events should vary within their associated season, depending on the regional climatic conditions, and between years, depending on global climate conditions. When combined with spatial heterogeneity throughout the channel and floodplain, this interannual variability supports diversity in habitat conditions, associated recruitment opportunities and refugia from competition, and subsequent diversity in native species (Naiman et al. 2008, Petts and Gurnell 2013).

Functional flows can accommodate this variability by constituting a suite of hydrographs reflecting different strategies for wet, dry, and normal years (figure 3; Petts 1996). Occasional large-magnitude, long-duration floods should be planned for climatically wet years when water is plentiful, whereas smaller-magnitude, shorter-duration peak flows should occur in drier years. In most western US rivers, climate conditions cycle through periods of wetter and drier years, resulting in a diversity of flow conditions over the long term. Maintenance of this interannual variability in regulated rivers can also help to limit the spread of nonnative species that are less adapted to regional flow variation (Kiernan et al. 2012) and build greater resilience under continued land-use change and changing climate conditions (Viers and Rheinheimer 2011).

Considerations for management

Managing toward the recovery and maintenance of physical processes and connections in highly modified riverscapes requires more than applying simple hydrometric criteria to

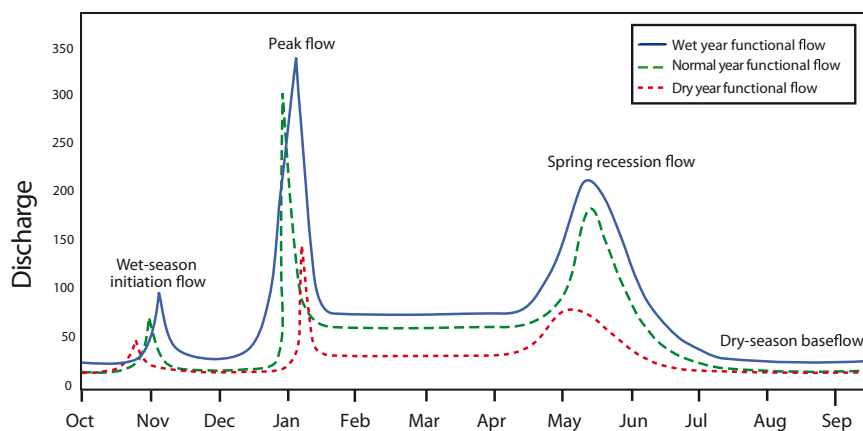


Figure 3. Climatically variable functional flow regimes in a Mediterranean–montane climate, where spring occurs April to June.

mimic the natural flow regime. Considering the interaction of hydrologic, geomorphic, and ecologic processes and the functions they serve is more likely to result in e-flow targets that better support self-sustaining ecosystems that are inherently diverse and adaptive (Florsheim and Mount 2002, Beechie et al. 2010). The specific functional flows presented here support many of the key processes that link riverine dynamics across space and time (see figure 1) and therefore can serve to restore ecological integrity and functionality in highly modified rivers. Resource managers have the opportunity to actively promote restoration by coupling a functional-flows approach with landform reconstruction to encourage connectivity within the riverscape and to initiate natural riverine processes (box 1).

A functional-flows approach focuses on flow and geomorphic components with process-based outcomes. This differentiates it from other e-flow approaches in that flow allocations are made with consideration of how the duration, timing, and rate of change of flows—rather than just the magnitude—are influenced by the geomorphic context and sediment supply conditions. However, functional flows can be readily incorporated into existing e-flow frameworks, such as regional Instream Flow Incremental Methodology (IFIM) approaches (e.g., Denslinger et al. 1998) or the ELOHA framework (Poff et al. 2010), in which consideration of geomorphic context may be mentioned but not developed. In the simplest terms, the IFIM framework is fundamentally a bottom-up approach (adding various flows to a static minimum as needed to achieve a desired outcome) versus ELOHA, which is a top-down approach (starting with the full natural flow regime and removing flow until there are ecological consequences). In both cases, the consideration of key functional flows either allows for specific flows to be added or places limitations on which flows should be removed. Indeed, in the most heavily modified catchments with competition from water users and regulated rivers supported by only a constant baseflow, the restoration of a naturalistic flow regime by the addition of key functional flows at the most ecologically significant times of the year, even if

not possible in drought years, may be the best option available at the present time.

Conclusions

Riverscapes are physical systems with a history. Under contemporary climate conditions, a river's physical character and dynamics reflect the interaction of hydrological processes and terrestrial vegetation dynamics superimposed on a valley structure, channel form, and sediment supply inherited from previous climatic conditions. However, centuries of land-use change, urban and industrial development, river impoundment and channelization, and water abstraction have imposed artificial flow regimes on

simplified river channels that are isolated from their floodplains and fixed in time. In these highly managed and modified river systems, there is a need for greater sophistication in designing and implementing flows that are optimized for multiple uses, including ecosystem services and functioning, water supply, hydropower generation, recharge of local aquifers, and flood control among others.

We suggest that functional flows, as are described herein, provide the best opportunity to encompass geomorphic and ecologic processes and functions alongside varied human needs when developing flow regimes in regulated river systems. At the simplest level, incorporating specific functional flows in rivers with little geomorphologic diversity and/or highly perturbed sediment regimes can provide some ecological benefits for discrete functions, such as high flows to support migratory pathways for fish or to maintain salinity profiles within the fluvial–estuarine transition. In rivers with some geomorphic diversity in channel width, sinuosity, and local bank variability, functional flows promote in-channel habitat heterogeneity and support a broader species assemblage. When functional flows in these rivers further inundate floodplain and overbank areas, large-scale geomorphic and sediment flux processes occur, enhancing physical and ecological diversity in space and time. Given the room for lateral channel–floodplain connections and the consideration of sediment transport conditions, restoration opportunities exist to transform rivers from the simplest forms with limited functions to more complex riverine mosaics with multiple ecosystem functions and services.

Because of the dependence of societies on developed riverscapes and the implications of climate change, the restoration of highly modified rivers to unimpaired conditions is an unrealistic concept. Managing rivers in a nonstationary world requires management strategies and policies that focus on preserving key functions and processes to sustain the dynamically evolving nature of river ecosystems. The functional-flows approach discussed herein provides a basis for the adaptation of current river regulation policies and the development of new strategies to meet such future needs.

Box 1. Five principles for management of highly modified rivers.

Guiding principles for management of rivers in highly modified riverscapes.

1. Hydrogeomorphic connections within the riverscape should be maintained or restored in order to achieve optimal ecosystem functionality. This requires peak flows equal to at least the channel-filling discharge that can access overbank areas and are of appropriate duration to move the annually delivered sediment supply. The more space given to a channel and its floodplain, the greater the ecological benefit from flood flows.

2. Transitions in flow between seasons should be retained. High turbidity wet-season initiation flows and spring recession flows have high ecological benefit across a riverscape.

3. Seasonality of baseflows should be retained. Higher baseflows in wet seasons support channel margin habitats and promote groundwater recharge, and lower baseflows in dry seasons create habitat partitioning and limit nonnative species. Variations in baseflows can help limit impacts from prolonged constant flows.

4. Flow regimes should reflect interannual climate variability. Larger peak flows, longer duration recessions, and higher baseflows should occur in wet years, whereas smaller, shorter, lower flows should occur in dry years. Within year variability may be necessarily limited in extreme years, such as prolonged drought or flood.

5. Water management for human uses should consider the seasonality of natural flows. Greater water abstraction, high flow releases to the river from hydropower, or water supply deliveries should occur during wetter months rather than drier months. A few floods should be retained at near full magnitude and duration, whereas others are removed for consumptive uses, rather than reducing all flood magnitudes.

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