PPIC PUBLIC POLICY INSTITUTE OF CALIFORNIA

AUGUST 2020

Ted Grantham,
Jeffrey Mount,
Eric D. Stein,
Sarah Yarnell
with research support from Gokce Sencan

Supported with funding from the S. D. Bechtel, Jr. Foundation and the funders of the PPIC CalTrout Ecosystem Fellowship

Making the Most of Water for the Environment

A Functional Flows Approach for California's Rivers

SUMMARY

CONTENTS

Policy recommendations from this report are available on the PPIC website.

In California, water and land management activities have substantially altered river flows and degraded river channels and their floodplains. The result has been a precipitous decline in native fish populations, including the collapse of valued salmon fisheries, and widespread imperilment of freshwater biodiversity. Environmental flows—flows in rivers and streams necessary to sustain ecosystem health—are essential to reversing these trends. Yet many rivers in California lack environmental flows. And for those rivers with such protections, environmental flows are typically established at static minimum levels, which fail to preserve the natural seasonal and interannual variability of flow that sustains healthy ecosystems. A new approach to managing environmental water is needed.

Building on previous PPIC work in this area, we recommend a "functional flows" approach for managing water for the environment. Functional flows refer to components of a river's flow that sustain the biological, chemical, and physical processes upon which native freshwater species depend. A functional flows approach does not mandate the restoration of natural flows or the maintenance of historical ecosystem conditions, but rather focuses on preserving key functions—such as sediment movement, water quality maintenance, and environmental cues for species migration and reproduction—that maintain ecosystem health. This approach also recognizes that suitable physical habitat is necessary to support the functions of flowing water.

By coupling physical habitat improvements with key aspects of flow variability, functional flows offer a more effective means of improving ecosystem health than conventional approaches. Managing environmental water as functional flows can also benefit people. A consistent, transparent, and science-based approach gives greater assurances to the public that investments in environmental water are justified. Resulting improvements in ecosystem health would also enhance fishing and recreational opportunities, as well as limit the risk of new Endangered Species Act listings and further regulatory restrictions on water users.

Elements of the functional flows approach have been put into practice in a few places, but implementation is in a nascent stage. Pilot studies and experimentation are needed to evaluate effectiveness and refine the approach. This means that robust, well-funded science and monitoring programs are essential to its success. Looking ahead, we suggest the functional flows approach can serve as a valuable tool for improving the health of freshwater ecosystems and building the long-term resilience of California's water management system.

Introduction

Freshwater scientists and natural resource managers have long recognized stream flow as a “master variable” in river ecosystems (Poff et al. 1997). Stream flow shapes the physical structure of river channels and floodplains, influences water quality, and affects the distribution and abundance of riverine species. Modification of rivers from dams, diversions, channelization, and land-use changes disrupts stream flow and the ecosystem functions those flows support. Flow alteration is a primary cause of freshwater ecosystem degradation throughout the world (Bunn and Arthington 2002), and in California has contributed to the loss of freshwater biodiversity, the collapse of native fish populations, and an extensive loss of wetlands and riverine habitats throughout the state (Frayer et al. 1989; Moyle et al. 2011; Howard et al. 2015).

There is growing awareness that protection of environmental flows—the quantity, quality, and timing of water required to support healthy river and stream ecosystems—is essential to conserving freshwater biodiversity, restoring fish populations, and supporting the many benefits people derive from freshwater ecosystems (Arthington et al. 2018).[1] However, efforts to secure environmental water in California’s rivers face many challenges. Allocating water to the environment is a contentious issue owing to perceived and real tradeoffs with competing water demands. Water allocation decisions are further complicated by the technical challenge of assessing environmental flow needs and the state’s complex regulatory framework that governs environmental water. The result is a fragmented and inconsistent approach to managing environmental water that has generally failed to protect ecosystem health, while also failing to resolve controversy over water used for environmental purposes.

There is an urgent need to rethink environmental water management in the state, especially as climate change and population growth intensify pressures on California’s water resources. Fortunately, there is growing interest in improving environmental water management. California’s Water Resilience Portfolio (2020) calls for “fuller, more dynamic integration of environmental protection into water management” and highlights the importance of “understanding the level of flow needed to support aquatic and riparian habitat on major streams.” The State Water Board, in collaboration with the California Department of Fish and Wildlife (CDFW), has also been advancing policies to establish or increase water allocations for the environment, and is supporting a multi-partner California Environmental Flows Workgroup to coordinate and improve the effectiveness of environmental water management statewide.[2]

As a key product of this effort, the California Environmental Flows Framework—also acknowledged in the Water Resilience Portfolio—establishes a technical process by which practitioners can develop environmental flow standards for rivers and streams across the state. The framework relies on “functional flows,” a scientific concept that emphasizes the biological, chemical, and physical functions of flowing water. Functional flows sustain ecosystem health by preserving essential patterns of flow variability that support physical processes and satisfy the habitat needs of native species. When coupled with the restoration of physical habitat, managing environmental water as functional flows represents a holistic approach for improving ecosystem health—one that delivers broad benefits for people and nature while also accommodating human demands on the system. For this

[1] In this report, the term “environmental flows” is used interchangeably with “environmental water.”

[2] The California Environmental Flows Workgroup was established in 2018 as part of the California Water Quality Monitoring Council (CA Senate Bill 1070)

reason, environmental and water supply organizations have both embraced functional flows as a tool for guiding environmental water management in the state.[3]

Yet there remains substantial uncertainty about how functional flows would be implemented in practice, including which technical methods should be used to estimate environmental water needs, the manner in which environmental water would be managed as functional flows, and what policies and regulations are needed to enable such an approach.

In this report, we describe the scientific underpinnings of functional flows and demonstrate how they could be used to guide the development of environmental flow standards. We also illustrate how functional flows could be implemented in distinct management settings, including dammed, undammed, and urban rivers. In each of these settings, we illustrate how environmental water could be managed as functional flows by releasing water from reservoirs, restricting diversions, and/or controlling discharges to rivers and streams. In particular, we explain how ecosystem water budgets—a dedicated volume of water used for ecosystem purposes, with characteristics of a senior water right—could provide greater flexibility in the way environmental water is managed. Finally, we discuss how a functional flows approach could be integrated into existing regulations to improve environmental water management in California.

This report builds on research on freshwater ecosystem management (Mount et al. 2019) and institutional responses during the 2012–2016 drought in California (Mount et al. 2017) and the Millennium Drought in Victoria, Australia (Mount et al. 2016). It was also informed by discussions with the California Environmental Flows Workgroup, which includes academic experts, federal and state staff, and representatives from environmental organizations.

The Need for a New Approach

Current approaches to managing environmental water have generally failed to achieve the desired goal of restoring and preserving ecosystem health. In many rivers with environmental flow protections, populations of native fishes and other sensitive aquatic species continue to decline (Moyle et al. 2011; Howard et al. 2015). There are several reasons why environmental water management has been ineffective.

First, water allocated to the environment often fails to restore critical aspects of flow variation needed to meet the needs of riverine species and support key ecosystem processes throughout the year. In California, environmental flows are typically expressed as minimum instream flow standards. These standards allocate fixed volumes of water for the environment, typically as a monthly or seasonal minimum flow threshold, above which water can be diverted or stored. This approach tends to mute the variability of flow, which naturally changes over time—whether due to storms, changing seasons, or differences between wet and dry years. All of California's freshwater species are adapted to this natural variability in flow and depend upon it to sustain viable populations. Natural flow variability is also essential for maintaining physical processes—particularly floods that create periodic connections between water and the landscape, but also seasonal dry periods that lead to a natural contraction in aquatic habitats, which can be important in limiting the distribution of invasive species.

[3] Scientists from environmental organizations including The Nature Conservancy, California Trout, and Trout Unlimited have recommended that functional flows be used to inform development of environmental flow standards (Yarnell et al. 2018). The Association of California Water Agencies has also advocated for a functional flows approach in setting Bay–Delta flow standards (Quinn 2018), and the Northern California Water Association has called for the use of "modern functional flows in the Sacramento Valley" (2019).

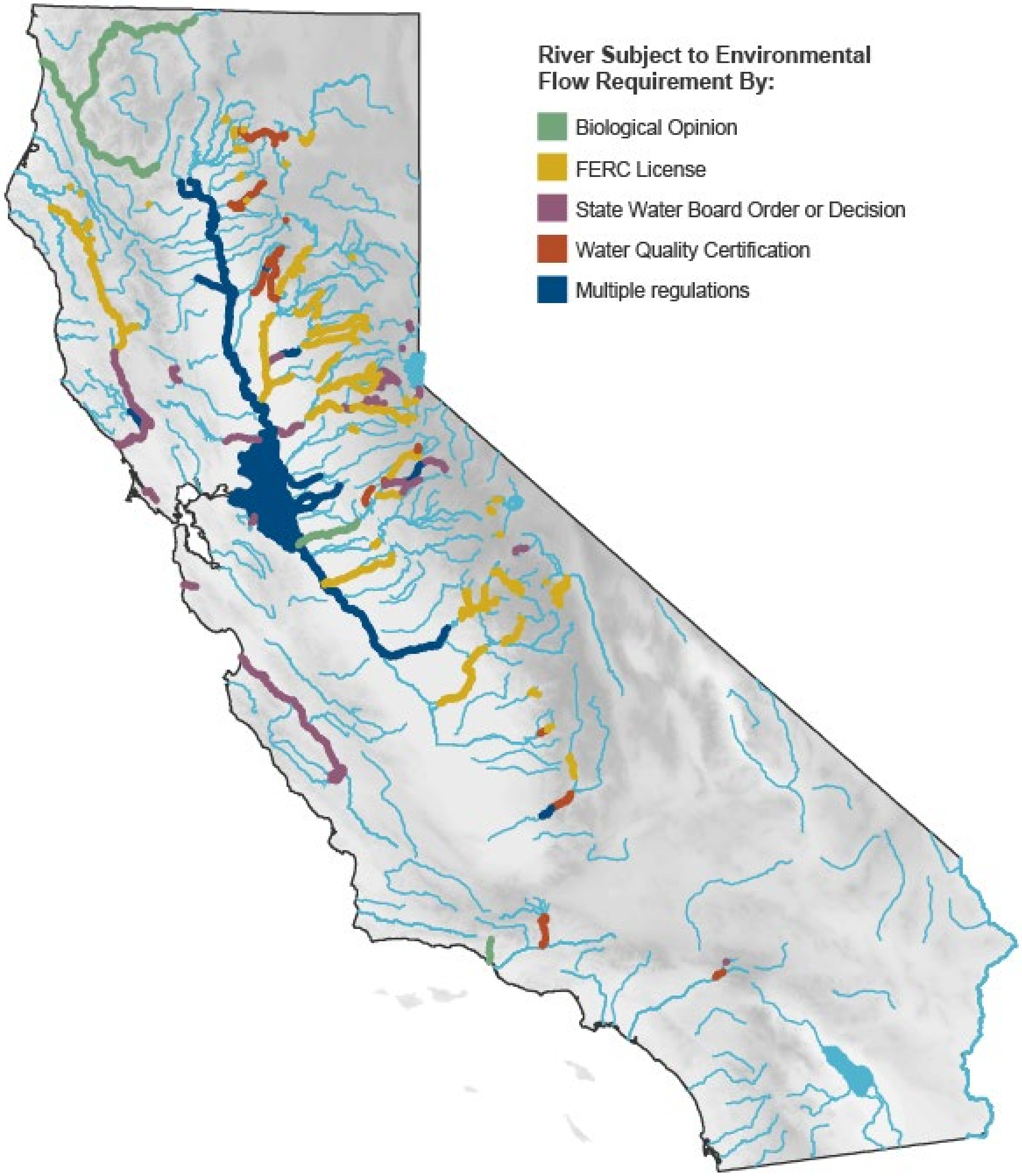
Second, the effectiveness of environmental water management has been limited by the narrow focus on protected species—or even specific life stages of those species—listed under the federal and state Endangered Species Acts. Environmental flow protections rarely account for the needs of non-listed species.

Third, environmental water management often fails to consider degraded physical habitat conditions, including modifications to the river and floodplains from bank armoring, channelization, levees, and other artificial structures. These physical changes limit the effectiveness of environmental water in meeting ecosystem goals.

Finally, environmental water is currently regulated and managed in a piecemeal fashion. A diverse array of regulations establish environmental flow protections. The most important are state and federal statutes to protect water quality and endangered species, but environmental water is also regulated under state and federal laws governing water rights and hydroelectric power generation. These legal tools have established environmental flow requirements on some rivers in California (Figure 1), but their application has been uncoordinated and inconsistent. As a result, it has been difficult to learn from successes and failures in environmental water management and, over time, to enhance the effectiveness of environmental flows. In our view, current approaches to allocating water to the environment fail to make the best use of water for conserving species and preserving the benefits derived from healthy freshwater ecosystems. This in turn makes it difficult to justify needed investments in freshwater ecosystem protection to the public and policy makers.

FIGURE 1

Diverse state and federal regulations have been used to establish environmental flows on California rivers



SOURCE: Modified from State Water Board (2020).

NOTES: This figure highlights various regulatory mechanisms used to establish environmental flow requirements in California, including Biological Opinions issued by the National Marine Fisheries Service or US Fish and Wildlife Service to comply with the federal Endangered Species Act; licenses issued by the Federal Energy Regulatory Commission (FERC) for hydropower projects; state Water Quality Control Plan requirements; and Water Right Orders and Decisions issued by the State Water Board.

What Are Functional Flows?

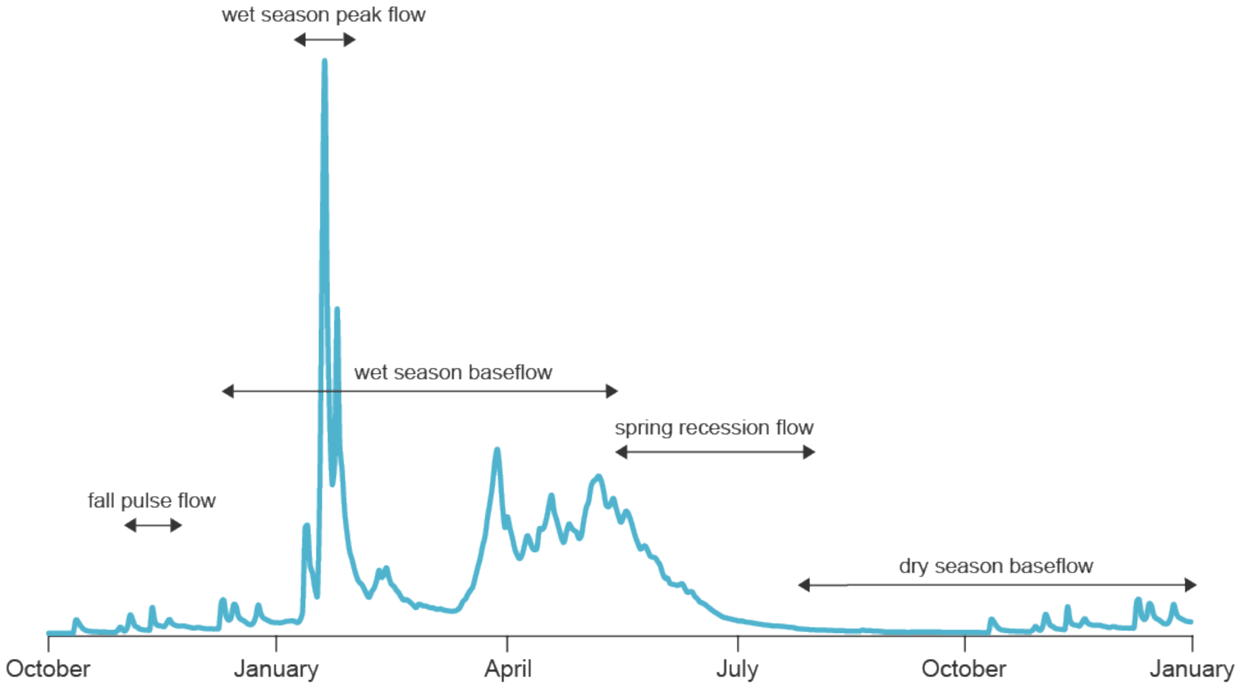
River ecosystems are shaped by the dynamic interaction between flowing water and the landscape. As flows rise and fall in response to rainfall and snowmelt runoff, rivers expand and contract, temporarily inundating banks and adjacent floodplains, and then receding back into their channels. High flows move sediment and woody debris, modifying stream channels and maintaining structural complexity that supports numerous plant and animal species. As flows recede during the dry season, waters warm and become more productive, stimulating plant growth and creating food for insects, fish, and birds. These predictable seasonal changes in flows also provide cues to native animals and plants for migration, breeding, rearing, and seed dispersal. By supporting the biological, chemical, and physical processes that native species have evolved with, functional flows focus on those components of the flow regime that are especially important to ecosystem health. Scientists have identified five such components for California's rivers (Figure 2). Their relevance to freshwater ecosystems is broadly supported by ecological theory and an extensive body of research (Yarnell et al. 2015, 2020). To summarize:

- **Fall pulse flows** are associated with the first major storm at the end of the dry season. The fall pulse flushes fine sediment from stream channels, making them more suitable for fish spawning. This an important environmental cue for the upstream migration of salmon and other native fishes.
- **Wet season peak flows** coincide with the largest storms of the winter. These high-flow events restructure habitat by scouring the river channel and banks, and redistributing sediment and wood. They also inundate floodplains that provide productive breeding and rearing habitat for fish, shorebirds, and waterfowl.
- **Wet season baseflows** maintain habitat connectivity in the periods between winter storms. They are essential to salmon egg incubation and the movement of migratory fish through the river network.
- **Spring recession flows** mark the transition from the wet to dry season and are characterized by a steady decline of flows over weeks or months. The spring recession is a prominent feature in all river types, but especially in rivers fed by snowmelt. It is a critical breeding cue for riverine frogs and native fishes, germination of cottonwoods, and migration of anadromous fish such as spring-run Chinook salmon.
- **Dry season baseflows** are sustained by groundwater inputs to rivers and are critical for maintaining aquatic habitat through summer. Native plants and animals have evolved to cope with this stressful period through diverse adaptations, whereas non-native species are often less tolerant of low or intermittent flows in the dry season.

These functional flow components can be identified in all of California's rivers, but their dimensions vary regionally. For example, the timing, magnitude, frequency, and duration of each component will be different for rivers in the Sacramento Valley, Sierra Nevada, and South Coast.[4] Flow components will also vary by water year type. However, each flow component can be expected to support critical ecosystem functions and collectively are important for maintaining ecosystem health.

[4] To examine the natural spatial and temporal variation in functional flows for California's rivers, visit the UC Davis E-flows site.

FIGURE 2
California rivers and streams exhibit five key functional flow components that support the physical, chemical, and biological functions needed to sustain ecosystem health



SOURCE: US Geological Survey stream flow data (USGS Station #11394500).

NOTES: This figure illustrates the seasonal periods in which five functional flow components occur, displayed in relation to daily flows (1958 water year) for an undammed section of the Middle Fork American River that is no longer gaged. The dimensions of these components vary by river type, but are important for supporting ecosystem functions in all rivers and streams in California.

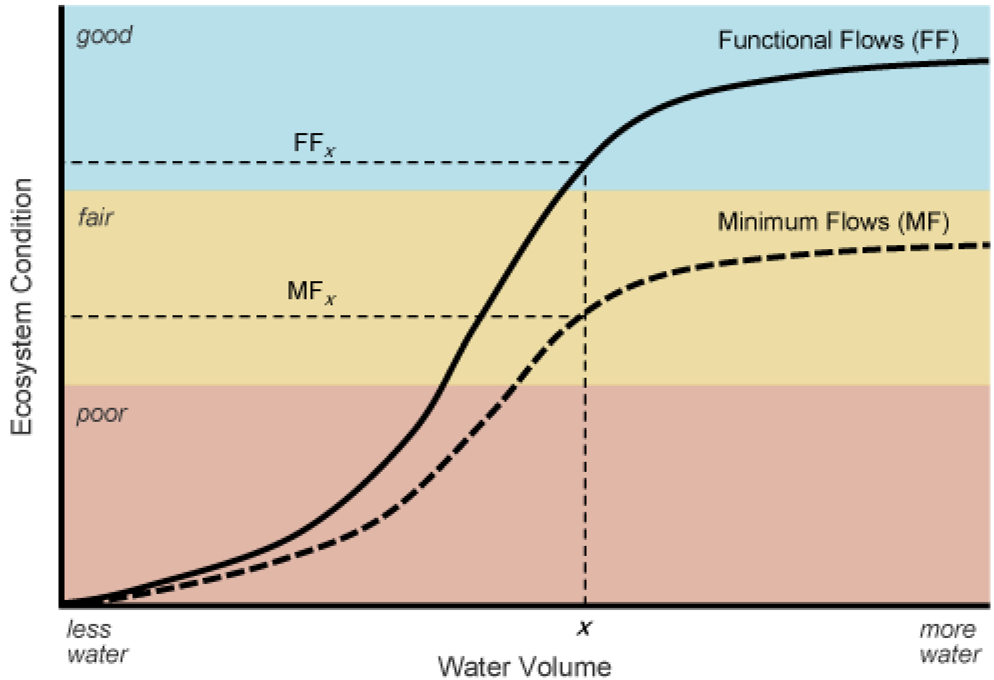
Functional Flows Require Water and Physical Habitat

Although water itself provides habitat for aquatic species, the way it interacts with channel beds, riverbanks, floodplains, and other structural features—known as *physical habitat*—is critical to supporting the ecosystem functions of flowing water. For example, wet season peak flows in rivers confined between levees will not support ecologically beneficial floodplain inundation. Water flowing through concrete-lined channels will provide limited habitat value for aquatic and riparian species and will fail to replenish groundwater that sustains dry season baseflow. Therefore, in many of California's altered rivers, physical habitat improvements—such as barrier removal, channel restoration, and floodplain reconnection projects—are needed to deliver the ecosystem benefits of functional flows.

In many systems, increasing the volume of water allocated to the environment could be expected to benefit ecosystems. However, improvements in ecosystem condition would likely diminish with increasing water volumes because of physical habitat constraints and other limiting factors, such as invasive species, poor water quality, and ocean conditions (Figure 3). By coupling physical habitat improvements with environmental water that preserves key aspects of flow variability, functional flows yield greater improvements in ecosystem conditions relative to conventional, minimum flows and therefore represent a more efficient approach to managing environmental water (Figure 3).

FIGURE 3

The functional flows approach achieves greater ecosystem benefits than minimum flows by preserving ecologically important flow variation and addressing physical habitat needs



NOTES: In this conceptual figure, increasing the volume of environmental water managed as either minimum flows (thick dashed line) or functional flows (solid line) improves ecosystem condition, although there are diminishing returns with increasing water allocations as result of physical habitat constraints and other limiting factors. Environmental water managed as minimum flows cannot achieve "good" ecosystem conditions, even at large water volumes. Any given volume of environmental water (x) managed as functional flows will achieve a better ecosystem condition (FF_x) than the same volume managed as minimum flows (MF_x). Functional flows consistently provide greater ecosystem benefits than minimum flows because the approach preserves key aspects of flow variability and considers the physical habitat needed to support ecosystem functions.

Many of California's rivers are disconnected from their floodplains by extensive networks of levees, such as along the San Joaquin River in the Central Valley (left). To enhance the ecosystem benefits of functional flows, physical habitat improvements are needed to reconnect rivers to the landscape, as illustrated by a floodplain restoration project on the lower Cosumnes River (right). Photo credit, left image: DWR; right image: Joshua Viers.

The functional flows approach considers how to integrate flow and non-flow interventions to most effectively improve ecosystem health. For example, ecosystem conditions below dams can be improved by coupling wet-season functional flows with the reintroduction of gravel for salmon spawning and the removal of barriers to improve fish passage. Maintaining cool temperatures of dry season baseflows can be achieved by changing flow volume and restoring healthy riparian vegetation to shade channels. Importantly, environmental flows that fail to consider physical habitat could have negative ecological effects. For example, in highly modified rivers with simplified river channels confined by levees, environmental flows that generate floods could cause undesirable channel erosion and potentially harm native fish.

Using Functional Flows to Develop Environmental Flow Standards

A functional flows approach can guide the assessment of environmental water needs and the development of environmental flow standards—legal requirements for environmental flows on rivers and streams. The process of assessing environmental water needs begins with setting goals for the desired ecosystem condition. The goals should be expressed as specific, measurable objectives developed through participatory planning processes, and could include objectives for water quality, native species diversity, or population targets for species of interest.[5] Objectives should ensure compliance with existing regulations for protected species and water quality, but should also consider more holistic goals for the recovery and maintenance of ecosystem health.

Once goals are established, the flows needed to support the desired ecosystem condition are assessed. There are many methods to guide such assessments (Williams et al. 2019), but under a functional flows approach the evaluation would focus on the five flow components associated with essential ecosystem functions, and the physical habitat necessary to support them. Detailed guidance for setting environmental flow standards following a functional flows approach is being developed through the California Environmental Flows Framework.[6] Steps described in the framework are summarized below:

1. **Assess functional flows needed to achieve ecosystem goals.** First, for each of the five functional flow components, target values are defined for their timing, magnitude, duration, frequency, and/or rate of change (Yarnell et al. 2020).[7] In systems with limited alteration of physical habitat, it can be assumed that natural flow conditions—those expected to occur in the absence of human activities—will support ecosystem objectives. In such cases, modeled natural flows can be used to set target values for each functional flow component. In rivers with significant physical alterations, more detailed, site-specific studies will be required to set functional flow targets. This entails evaluating the water and physical habitat required to support the functions associated with each component, which are collectively needed to achieve ecosystem goals.
2. **Develop a functional flow regime.** The target values for the five components are then synthesized into a *functional flow regime*—flows needed to maintain essential physical and ecological functions throughout the year and across years. Different functional flow targets may be defined for different water-year types (dry, moderate, and wet) to account for natural inter-annual variation in flow conditions. Importantly, the functional flow regime is distinct from the full natural flow regime—flows expected in the absence of

---

[5] The process of setting objectives for ecosystem condition and developing environmental flow standards should involve all parties who directly and indirectly derive benefit from a particular freshwater ecosystem, along with those who manage and regulate it. For more information on the process of setting ecosystem goals, see Mount et al. (2019).

[6] The California Environmental Flows Framework provides technical guidance for developing environmental flow standards following a functional flows approach. At this writing, the framework guidance document was still in development and expected to be released in late 2020.

[7] For example, the spring recession flow—a slow decline in flows between the wet and dry season—is defined by timing (when the recession period starts), magnitude (the flow at the start of the recession period), rate of change (the average daily change in flow over the recession period), and duration (the total length of time in which the recession occurs before transitioning into the dry season baseflow period).

human activities—because it only preserves natural variation in key flow components. Other aspects of the flow regime that are not associated with functional flow components may deviate from natural conditions.

3. **Assess alteration in flow.** Next, the functional flow regime is evaluated in relation to current flow conditions. Understanding the degree to which flows deviate from the functional flow regime helps to identify ecosystem functions that may be impaired and indicates the types of interventions that may be necessary to restore them. The alteration assessment also reveals where conflicts with other water management objectives may exist. If current conditions achieve targets for most of the functional flow components but consistently fail to achieve desired levels in dry season baseflow, for example, the causes of flow impairment during this period—and strategies for addressing them—can be the focus of further analysis in Step 4.

4. **Balance management objectives and develop environmental flow standards.** In any watershed, there are multiple competing objectives for water, and a unique regulatory, environmental, and social context that must be considered when developing environmental flow standards. Typically, regulatory agencies such as the State Water Board are responsible for setting flow standards that strike a balance between protecting ecosystem health and satisfying water supply demands and other management needs. This is best done through a formal decision analysis aimed at identifying management actions that minimize conflict among objectives. Such actions could include changes in reservoir operations, diversion schedules, and regulated discharges, but also physical habitat improvements in order to maximize ecosystem benefits, while still providing for human uses. For example, lowering the elevation of floodplains along a river through re-contouring the land could limit the total volume of water required to support floodplain functions, making more water available for alternative uses.

5. **Implement and adaptively manage functional flows.** There will inevitably be uncertainty in ecosystem responses to the implementation of environmental flows. This is because ecosystems are influenced by a broad suite of factors—extreme events, non-native species invasions, pollution, and fishing pressures, among others—that are difficult to account for when predicting the effects of water management. As a result, environmental flows will be most effective in achieving ecosystem objectives when implemented in an adaptive management framework, in which ecological and physical responses to functional flows are carefully monitored. Insights from monitoring could guide changes in flow standards over time and would also make it possible to adapt to changing ecosystem conditions from climate change.

Implementing Functional Flows

California has a remarkable diversity of river types, reflecting natural environmental variation (in geology, hydrology, plants and animals, and climate), differences in regional land use, and distinct water demands. Management objectives for rivers—along with ecosystem conditions—also differ regionally. Nevertheless, a functional flows approach can be used to improve environmental water management in rivers throughout the state. To implement functional flows in California, it is likely that the total volume of water allocated to the environment would be increased, at least in particular times of year. In some cases, existing environmental water allocations could be shifted to other periods, potentially mitigating impacts to human uses. Implementation of functional flows would also likely require physical habitat improvements, especially in rivers affected by large dams but also those influenced by urbanization, agriculture, and other intensive land use pressures.

To illustrate what implementation of functional flows might look like in practice, it is helpful to separate rivers into three general classes:

- **Rivers regulated by large dams** capable of storing a significant amount of annual runoff;
- **Undammed rivers** that preserve natural runoff patterns but are potentially affected by diversions; and
- **Rivers in urbanized settings**, often with extensive flood control structures, diversions, and intensive management of stormwater and wastewater discharges.

In each of these river types, it is possible to distinguish the natural flow regime (flows expected in the absence of human activities), the current flow regime (flows under current managed conditions), and the functional flow regime. In dammed rivers, functional flows would primarily be managed through reservoir releases, whereas in undammed rivers they would primarily be managed by restricting water diversions. In urban rivers, functional flows would likely be managed through a combination of reservoir re-operation, diversion restrictions, and management of discharges from wastewater treatment plants and stormwater infrastructure.

Functional Flows in Dammed Rivers

Dams exist on nearly all of California's large rivers and are operated for multiple, often competing purposes, including flood protection, hydropower generation, and water storage for municipal and agricultural uses. To satisfy these objectives, dam operations mute the natural flow variability downstream (Zimmerman et al. 2018). In addition to altering flow regimes, extensive land use changes below dams have transformed the physical structure of California's rivers—especially in valleys, where the construction of levees along riverbanks has restricted or eliminated the natural connection between the river and its floodplain.

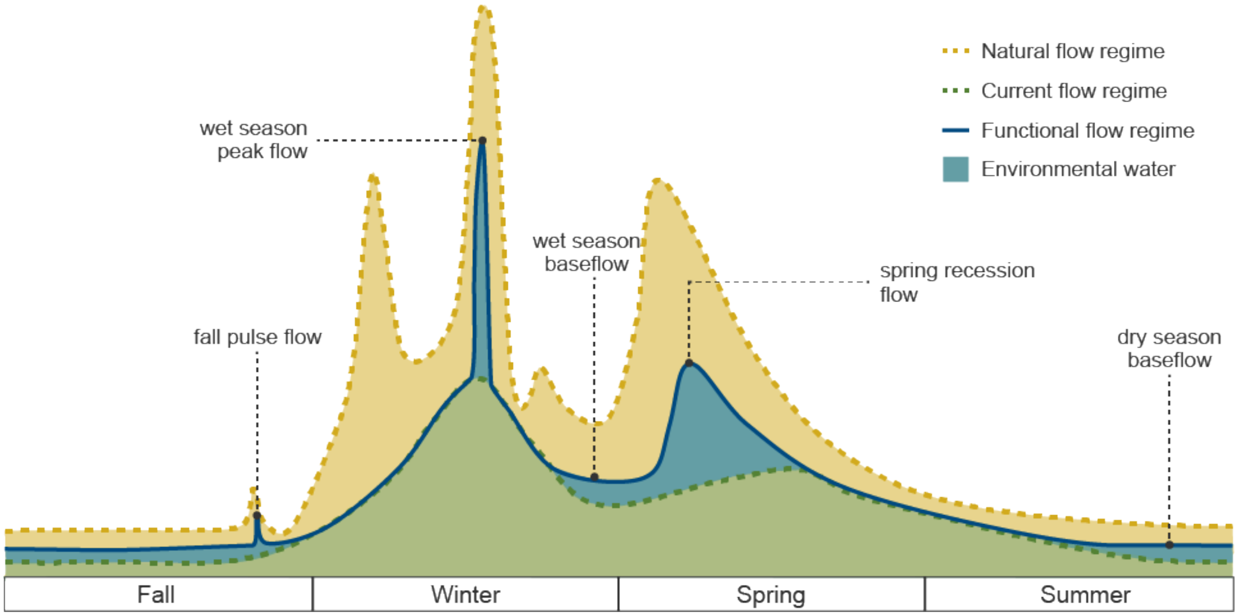
In dammed rivers, functional flows would be primarily managed by changing dam operations. Water would be released from storage to satisfy specific functional flow targets throughout the year. For example, water releases could be used to mimic a fall pulse flow, a winter peak flow event, and the spring flow recession (Figure 4). Additional environmental water could also be released in summer to maintain dry season baseflow targets. Managing for functional flows may also require restrictions on water diversions downstream of dams, particularly during periods of high water demand from irrigated agriculture. It may be necessary to curtail direct surface water diversions and limit groundwater withdrawals to ensure adequate flows. In some cases, diversions could be modified to direct water to floodplains behind levees to provide habitat for birds, fish, and other aquatic species.[8]

---

[8] Aquatic scientists have been working with farmers in the Sacramento Valley to manage flooded agricultural fields behind levees to provide habitat for migratory birds and, more recently, fish. These artificial floodplain habitats have been shown to be highly productive and compatible with agricultural production, and potentially deliver other benefits, such as groundwater recharge. For more information, visit the Migratory Bird Conservation Project and the Nigiri Project websites.

FIGURE 4

In dammed rivers, functional flows would be managed by releasing stored water from reservoirs



SOURCE: Modified from Mount et al. (2017, 2019).

NOTES: This figure illustrates a hydrograph typical of a regulated river in the Central Valley of California. The current managed flow regime (dashed green line) has reduced flow throughout the year relative to the natural flow regime (dashed brown line), as a result of water storage and consumptive use. Higher flows in winter and spring reflect uncaptured flow and managed flow releases to satisfy downstream water users and existing regulations. Environmental water (shaded blue area) could be allocated at specific times of year through releases of stored water to create a functional flow regime (blue line). The functional flow regime would deviate from the natural flow regime, with a significant proportion of annual discharge still available for storage and consumptive use.

Some of California's dammed rivers already incorporate elements of a functional flows approach. For example, since 2000, a negotiated settlement under the Putah Creek Accord modified dam operations to enhance flows in Lower Putah Creek when they are most beneficial to native fishes.[9] The managed flow regime includes pulse flow releases in fall to attract migrating salmon, elevated spring flows to support fish spawning and rearing, and sustained summer flows to prevent channel drying. The flow regime established under the Accord has been remarkably successful in restoring native fish and suppressing non-native fish populations (Kiernan et al. 2012). The Trinity River and Yuba River are also examples of rivers where flow release schedules from large dams were modified to mimic portions of the natural hydrograph to restore ecosystem functions (although not all functional flow components are supported).[10]

[9] For more information, visit the Putah Creek Council website.

[10] For more information, visit the Trinity River Restoration Program and Yuba River Accord websites.

Flow in Putah Creek is primarily controlled by releases from Berryessa Reservoir (top right), which passes through a narrow stream corridor that winds through agricultural lands in Solano County to the City of Davis (lower left). The Putah Creek Accord has led to the successful recovery of native fishes, such as the Sacramento pikeminnow, held by UC Davis professor Peter Moyle (right), who guided development of environmental flow recommendations aimed at supporting ecosystem functions in Putah Creek. Photo credit, right: Google Earth; left, Jacob Katz.

In each of these systems, environmental flows were coupled with physical habitat improvements to enhance ecosystem benefits. In Putah Creek, for example, Chinook salmon failed to breed in high numbers despite favorable flows under the Accord because spawning gravels had become hardened by prolonged periods of stable flows. Recently, the streambed was mechanically disturbed, which created a more hospitable gravel bed and significantly boosted salmon spawning in the creek. In the Trinity River, extensive river channel engineering created off-channel habitats for juvenile salmonids, increased habitat complexity, provided spawning gravels, and lowered the floodplain to increase connectivity with the river over a greater range of flows. Similar habitat improvements are planned for the Yuba River.[11]

Functional Flows in Undammed Rivers

Functional flows would be managed differently in rivers with few or no dams, such as in the north coast region of California. Human water needs in these systems are generally met by direct surface water diversions or withdrawals from groundwater and upland springs. Diversions typically represent a small fraction of the total annual flow of a river, because most flow occurs in winter, when demand is limited. But concentrated diversions in late spring and summer—when flow is at its lowest levels—can have significant ecological impacts.

In undammed rivers, managing for functional flows will require regulating river diversions to increase flows when needed (Figure 5). This might involve modifying the timing and location of specific diversions, as well as restricting the collective diversion volume or rate for all water users on a river. While the State Water Board has imposed restrictions on diversions to protect environmental flows, such as under the North Coast Instream Flow Policy and Cannabis Cultivation Policy, these regulations only affect water users applying for new water rights. These policies prohibit water users from diverting water in the dry season and encourage the development of small, off-stream storage that can fill in the winter, when water is abundant. The flow impacts from winter

---

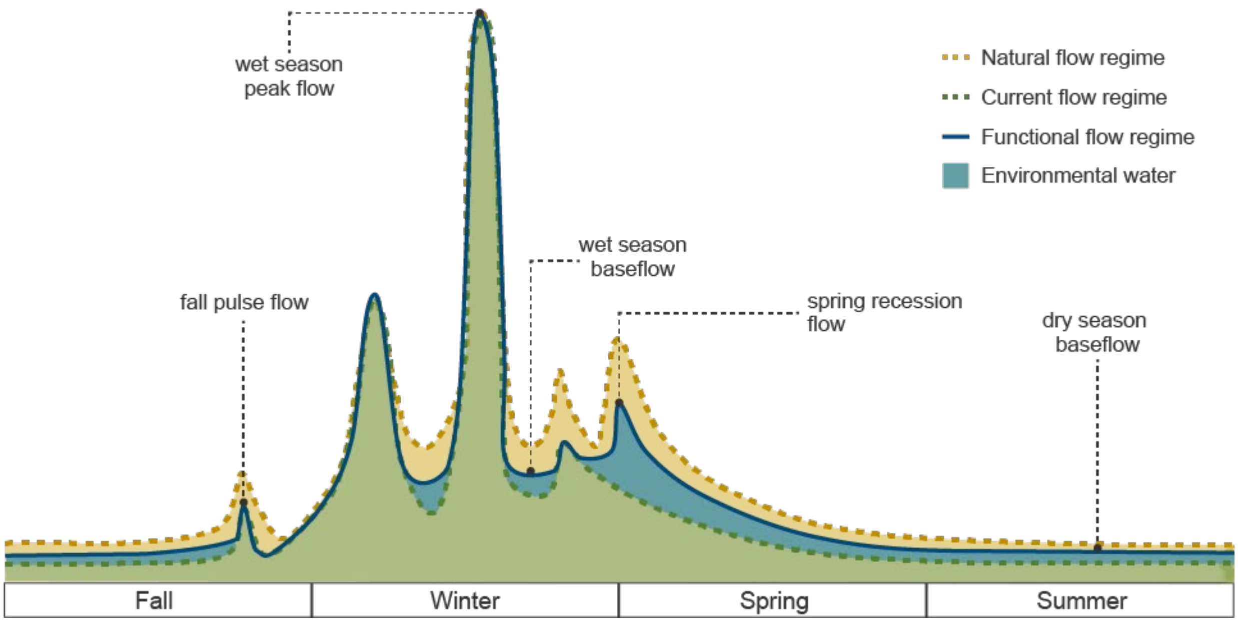
[11] For more information, visit the South Yuba River Citizens League website on Yuba River restoration projects.

diversions are less of an ecological concern than dry season diversions, although wet season baseflows can be negatively affected. Restrictions on existing water rights holders have rarely been applied at the basin scale to protect environmental flows. New approaches are being explored for managing multiple water diverters throughout a watershed, but have yet to be put into practice. For example, in the South Fork Eel River, researchers have shown that setting a maximum rate of diversion relative to long-term daily flow conditions can minimize alteration to natural flows, thereby supporting ecosystem processes and native species needs while also satisfying human water demands (Mierau et al. 2017).

Curtailing groundwater pumping may also be required to manage functional flows in undammed rivers. In many rivers, groundwater pumping has the potential to deplete stream flow, particularly in summer. For example, on the Scott and Shasta Rivers—tributaries to the Klamath River—groundwater feeds into and is recharged by flow in the channel (Foglia et al. 2018). To maintain functional flows in these rivers, seasonal curtailment of groundwater pumping—potentially coupled with managed aquifer recharge—may be needed to protect summer baseflows.[12] These groundwater management strategies will also be needed for groundwater sustainability plans in places where pumping has undesirable effects on river flows, as required by the Sustainable Groundwater Management Act (Rohde et al. 2018).

FIGURE 5

In undammed rivers, functional flows would be managed by restricting diversions



NOTES: This figure illustrates the current (managed) flow regime (dashed green line) characteristic of an undammed river in north coastal California, in which diversions for agricultural use cause a reduction in flows relative to the natural flow regime (dashed brown line), especially in spring, summer, and fall. Winter peak flows greatly exceed human demands and are not impaired. However, diversions for off-stream storage deplete wet season baseflows. A functional flow regime (blue line) would be established by restricting diversions to restore summer and winter baseflows and to preserve the spring recession. The total volume of environmental water needed to restore functional flows is shown as the shaded blue area.

Although not subject to the significant physical effects of dams, undammed rivers often suffer from other forms of physical habitat alteration. For example, past logging and mining activities across the state have deposited

[12] The California courts have recognized that the state has authority to curtail groundwater pumping to protect water flows, salmon spawning, and other public trust uses in the Scott River system (California Courts of Appeal 2018).

massive volumes of sediment into the state's rivers and streams, filling pools and spawning gravels with fine sediment and widening river channels. On many rural, undammed streams, grazing activity has also degraded riparian and aquatic habitat, and landowners have artificially straightened stream channels and lined them with riprap. These legacy effects continue to impair ecosystem health. These impacts have motivated a broad range of physical habitat restoration actions that could be coupled with functional flows, including the introduction of large boulders to promote pool formation, riparian vegetation recovery to stabilize banks and provide shading, and reduction of sediment inputs from roads.

Functional Flows in Urban Rivers

Urban streams have been extensively channelized, placed in concrete culverts, or buried underground. Flows are altered by stormwater runoff, wastewater discharges, and water imported from elsewhere. In many places, treated wastewater discharge and urban runoff in the dry season have converted intermittent streams into novel, perennially flowing habitats. In others, water storage, diversions, and groundwater withdrawals have reduced water in streams and resulted in prolonged periods of low or zero flow.

Despite these unique features, a functional flows approach can be used to improve environmental water management in urban rivers. Even more so than in other contexts, the challenge for developing environmental flow standards in urban rivers is setting management objectives that consider how flow and physical habitat can be managed together to most effectively improve ecosystem health. Restoring functional flows in degraded channels will not provide ecosystem benefits, nor will physical habitat restoration in the absence of water. Desired ecosystem conditions are also likely to deviate from those present historically. Restoring historical assemblages of native species may or may not be feasible. And owing to widespread physical changes to urban rivers, the natural flow regime will often be an inappropriate reference for setting management goals. Thus, setting objectives should account for contemporary environmental goals (e.g., protection or recovery of sensitive species currently present) and will likely require intensive stakeholder engagement and careful evaluation of current and potential future conditions.

Depending on existing flow and habitat conditions, it is also likely that different streams within a watershed will have different management objectives. The Upper Santa Ana watershed in Southern California, for example, currently supports fish, plant, and animal populations protected by federal and state Endangered Species Acts. The maintenance of habitat for some of these protected species now requires that flows be artificially maintained or enhanced by wastewater discharges. As a result, a coalition of wastewater treatment facilities are seeking to coordinate their discharge operations, which includes piping wastewater discharge from one drainage to another to achieve ecosystem management objectives.[13] In other urbanized streams in the region, it may be desirable to restrict wastewater discharges and other artificial sources of water in order to restore an intermittent flow regime more characteristic of its historical state (Figure 6). This would not only support native species adapted to intermittent streams, but potentially would also make water available for alternative uses.

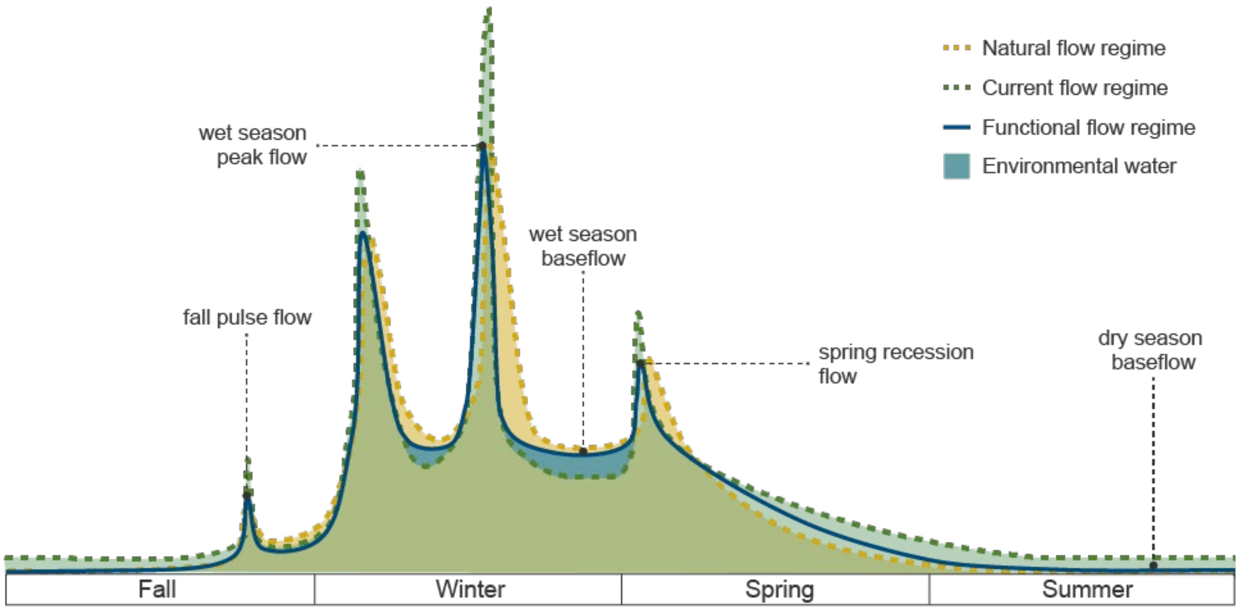
In urbanized settings, functional flows would be implemented through a combination of water management activities, including releasing water from storage, restricting diversions, and regulating wastewater and stormwater discharges. A functional flows approach in urban rivers also requires addressing watershed degradation. For example, an important driver of channel alteration in urbanized watersheds is unnaturally high peak flows caused by widespread impervious surfaces and stormwater infrastructure that rapidly move large volumes of runoff to the river channel. To mitigate these impacts and maintain high flows within a range

[13] These efforts are part of the Upper Santa Ana River Habitat Conservation Plan—a multi-agency effort to manage water supply, wastewater, and stormwater while improving biological conditions in tributaries to the Upper Santa Ana River.

beneficial to the aquatic ecosystem, stormwater infrastructure must be improved to slow runoff and promote infiltration (e.g., through wetland restoration). Other types of physical habitat improvements within and adjacent to the river channel—such as channel recontouring, floodplain reconnection projects, and installation of artificial structures to add habitat complexity and control erosion—may also be needed.

FIGURE 6

In urban rivers, implementation of functional flows requires changes in stormwater infrastructure and wastewater management



NOTES: The figure illustrates a typical urbanized stream in Southern California. Urbanization has increased summer baseflows with discharges from wastewater treatment plants, converting a naturally intermittent stream flow (dashed brown line) to a perennial stream under the current flow regime (dashed green line). Storms produce higher-magnitude winter peak flows relative to the natural flow regime due to stormwater infrastructure that quickly delivers runoff to the channel. However, water diversions and storage in the winter reduce winter baseflows below natural conditions. A functional flow regime (blue line) in this system would require that summer and fall wastewater discharges be reduced to support native species adapted to the naturally intermittent flow regime. Elevated winter peak flows that degrade physical habitat and harm target species could potentially be reduced through watershed revegetation and/or retention basins to slow stormwater runoff. In this example, environmental water from reservoir releases or diversion curtailments would be allocated during winter baseflow periods to support passage of migratory fish, such as Southern California steelhead.

Governance Framework for Implementing Functional Flows

Previous PPIC reports have recommended that California adopt the principles and practices of ecosystem-based management—an approach that seeks to manage water, land, and plants and animals to achieve a desired ecosystem condition that ultimately benefits both native biodiversity and the diverse human uses of freshwater (Mount et al. 2017, 2019). These reports highlight functional flows as a key tool for guiding ecosystem-based management and describe the governance requirements for implementing such an approach. Here we describe governance elements that are particularly relevant for putting functional flows into practice.

Ecosystem Water Budgets and Trustees

The use of functional flows to improve the health of ecosystems requires dedicated water supplies for the environment. We recommend that such water be formally set aside in an *ecosystem water budget*.[14] This budget would be established by estimating the total volume of water required to satisfy environmental flow standards developed through a functional flows approach. These budgets would established be at the watershed scale, taking into account ecosystem management objectives, current water uses, and institutional arrangements.[15] The ecosystem water budget would function like a high-priority water right and would control a volume of water sufficient for satisfying functional flow needs. In dammed rivers, the ecosystem water budget would be allocated by releasing water from reservoirs. In undammed rivers, the budget would be allocated primarily by restricting diversions. Water budgets in urbanized rivers would be allocated through reservoir operations, diversion restrictions, and by regulating stormwater or wastewater discharge.

We recommend that an independent ecosystem trustee or board of trustees be established and given the authority to manage ecosystem water budgets to achieve functional flows.[16] The trustee would be responsible for preparing and publicly vetting annual ecosystem watering plans. These plans would describe actions for managing the ecosystem water budget, along with their expected ecological benefits. The annual watering plans would provide a general allocation schedule for environmental flows (based on water supply forecasts), but the trustee would have some ability to seasonally modify the timing and magnitude of environmental water allocations. For example, environmental water allocations might be timed to take advantage of storm events or to mitigate the effects of heat waves. The trustee would also have the authority to sell, trade, or store environmental water for future use. Environmental water management would be constrained by infrastructure, regulations, and operational requirements to satisfy other goals; these would be accounted for in the planning process through consultation with regulatory agencies and other water users. Watering plans would be integrated into overall water management decision making and would provide transparency in how and why environmental water is allocated. This would also reduce uncertainty for the water-user community and help build public awareness around the need for, and benefits of, environmental flows.

Finally, the trustee would be responsible for adaptive management to ensure that environmental water is used efficiently and in a manner that is responsive to new information and changing environmental conditions. A functional flows approach is beginning to be used in some places in California, but it has yet to be widely adopted. It will likely be necessary to refine the approach for different contexts, using robust science and monitoring programs to evaluate ecological responses to management actions, facilitate experimentation, and guide adaptation of environmental water management. Such programs must be supported by reliable funding and scientific expertise.

---

[14] Functional flow regimes could be managed through detailed operational schedules for reservoirs, diversions, and discharges that would vary across seasons and years. However, this prescriptive approach would lack the flexibility of water budgets, which allow for water trading, selling, and storage—which in turn enable adaptive management.

[15] A watershed management unit would ideally encompass large individual rivers and their tributaries, but will depend on ecosystem objectives, jurisdictional boundaries of responsible entities, and preferences of watershed community organizations.

[16] A model for ecosystem trustees has been developed in Victoria, Australia, as described in Mount et al. (2016, 2017).

Planning and Integration with Existing Regulations

To our knowledge, there are no legal barriers to implementing functional flows or the governance and regulatory frameworks needed to support the functional flows approach.[17] Existing water management planning and regulatory proceedings could be readily adapted to incorporate functional flows.[18] These include:

- **Water quality and water rights proceedings.** The State Water Board and Regional Water Boards have broad authority to set flow and water quality standards that protect freshwater. California's Porter-Cologne Act and the federal Clean Water Act authorize the water boards to restrict diversions, regulate water use, and control the discharge of pollutants to rivers and streams. Under Article X, Section 2 of the California Constitution, statutory law, and the Public Trust Doctrine, the State Water Board's authority extends to administering water rights, determining what uses of water are reasonable and beneficial, and modifying water rights to ensure the protection of water quality, fish and wildlife, recreation, and other public trust values. In each of these proceedings, the state could integrate environmental flow standards that follow a functional flows approach.
- **Administration of state and federal Endangered Species Acts (ESAs).** The ESAs prohibit the unauthorized "taking" (killing, capturing, or harming) of any protected species, as well as actions that could place the species in jeopardy of extinction. The federal ESA also requires federal agencies that operate, license, or fund water projects to consult with the National Marine Fisheries Service and US Fish and Wildlife Service to ensure their activities do not adversely affect listed species or their habitat. These consultations typically result in Biological Opinions, which guide project operations and can include environmental water requirements to recover listed species. ESAs have provisions that allow for more holistic approaches to managing freshwater ecosystems, beyond single-species actions. In particular, federal Habitat Conservation Plans (HCPs) and state Natural Community Conservation Plans (NCCPs) seek to improve conditions to address conservation needs of multiple species. Functional flows are essential for sustaining habitat for many listed aquatic and riparian species and could become the cornerstone of these efforts.
- **Federal Energy Regulatory Commission (FERC) licensing.** All non-federal hydroelectric power projects must be licensed by FERC, which requires that environmental water needs for fish and wildlife be given "equal consideration" to energy production. Issued licenses include provisions for environmental flows that must be incorporated in dam operations. Many FERC dams in California are undergoing re-licensing, or will be required to do so in the next decade. Using a functional flows approach to guide actions and set new licensing terms has the potential to improve overall ecosystem conditions and to better align environmental water management under state and federal regulations.
- **Sustainable Groundwater Management Plans.** The Sustainable Groundwater Management Act (SGMA) requires that groundwater sustainability agencies prepare and implement plans to achieve sustainable groundwater management by the early 2040s. SGMA requires protection of wetland and river ecosystems that can be adversely affected by groundwater pumping. Functional flows for groundwater-dependent ecosystems could be incorporated as performance measures in these plans.

Broad adoption of a functional flows approach could help harmonize these regulatory processes and increase the consistency and effectiveness of environmental water management in California. This will require stronger cooperation between agencies, water users, and other stakeholders, which has proven difficult to accomplish in the past. To facilitate such cooperation, we recommend the development of sustainable watershed management plans that set goals for ecosystem condition, establish metrics, identify beneficiaries, and describe management actions and responsibilities (Mount et al. 2019). These plans, established at the watershed scale, would not only provide a roadmap for coordinated management, but could also become the basis for setting water quality

---

[17] See discussion of legal issues associated with ecosystem-based management, ecosystem water budgets, and functional flows in Gray et al. (2019).

[18] In addition to the regulations described above, other laws relevant to environmental flows in California include the California Fish and Game Code 5937, California Water Code Section 1707, and the federal and state Wild and Scenic Rivers Acts.

objectives, such as in water quality control plans administered by the water boards, state NCCPs, and federal HCPs.

Conclusions

Sustainable management of water resources remains one of California's, and indeed the world's, grand challenges. California will continue to face intense competition for scarce water resources, forcing decision makers to grapple with difficult tradeoffs. Environmental water will remain a contentious issue, particularly as the effects of climate change become more pronounced and further stress the state's freshwater ecosystems.

Improving the effectiveness of environmental water management will help mitigate these stresses. The proposed functional flows approach offers a means of holistically assessing environmental water needs—an essential starting point for informing water allocation strategies. The approach gains efficiencies by focusing on the protection of key flow components that support native species and their habitat needs, and the many benefits that people derive from healthy ecosystems. It also recognizes the important role of physical habitat in supporting ecosystem functions. If implemented through ecosystem water budgets, as we recommend, the proposed approach would also create new opportunities for environmental water to be traded, sold, stored, and flexibly managed—similar to any other water right. This flexibility can support cooperative solutions among water users and, critically, would allow for adaptive management to maintain desired ecosystem condition over time and under a changing climate.

Collectively, the functional flows approach can help build resilience in California's water management system more broadly, advancing the goals of the 2020 Water Resilience Portfolio. Wider use of environmental flows will likely mean less water available for human uses in some places. However, by establishing a transparent, science-based approach, environmental water managed for functional flows provides greater assurances that water is being used effectively, and brings greater certainty over supply reliability for water users. The potential improvement in ecosystem health resulting from more effective environmental water management would also bring significant public benefits through improved water quality and recreational opportunities. It would limit the likelihood of regulatory disruption from additional Endangered Species Act listings. Finally, by seeking to coordinate water management and physical habitat restoration, the functional flows approach would create a strong incentive for multi-benefit projects that satisfy both human and ecosystem needs.

The functional flows approach described here does not address all pressures on the environment nor the need for broader reforms to advance freshwater ecosystem-based management in California. Recommendations on technical methods and desired governance features to implement functional flows will likely require refinement as future pilot projects and scientific studies are completed. Nevertheless, functional flows offer clear improvements to the status quo, and can serve as a valuable tool for restoring ecosystem health in rivers throughout the state for the benefit of people and nature.

REFERENCES

Arthington, Angela, Anik Bhaduri, Stuart Bunn, Sue Jackson, Rebecca Tharme, Dave Tickner, Bill Young, Mike Acreman, Natalie Baker, Samantha Capon, Avril Horne, Eloise Kendy, Michael McClain, LeRoy Poff, Brian Richter, and Selina Ward. 2018. "The Brisbane Declaration and Global Action Agenda on Environmental Flows." *Frontiers in Environmental Science* 6:45.

Bunn, Stuart E. and Angela H. Arthington. 2002. "Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity." *Environmental Management* 30: 492-507.

California Courts of Appeal. 2018. Environmental Law Foundation *v.* State Water Board, 26 Cal. App. 5th 844, 237 Cal. Rptr. 3d 393.

Frayer, Ed, Dennis Peters, and Ross Pywell. 1989. *Wetlands of the California Central Valley: Status and Trends 1939 to mid-1980s*. US Fish and Wildlife Service, Region 1.

Foglia, Laura, Jakob Neumann, Douglas Tolley, Steve Orloff, Richard Snyder, and Thomas Harter. 2018. "Modeling Guides Groundwater Management in a Basin with River–Aquifer Interactions." *California Agriculture* 72: 84-95.

Gray, Brian, Karrigan Bork, and Jennifer Harder. 2019. *Legal Analysis of Ecosystem-Based Management and Recommendations for Reform*, in Appendix A to *Path Forward for California's Freshwater Ecosystems*. Public Policy Institute of California.

Howard, Jeanette, Kirk Klausmeyer, Kurt Fesenmyer, Joseph Furnish, Thomas Gardali, Ted Grantham, Jacob Katz, Sarah Kupferberg, Patrick McIntyre, Peter Moyle, Peter Ode, Ryan Peek, Rebecca Quiñones, and Scott Morrison. 2015. "Patterns of Freshwater Species Richness, Endemism, and Vulnerability in California." *PLoS One* 10.

Kiernan, Joseph D., Peter B. Moyle, and Patrick K. Crain. 2012. "Restoring Native Fish assemblages to a Regulated California Stream Using the Natural Flow Regime Concept." *Ecological Applications*: 1472-1482.

Mierau, Darren, William Trush, Gabriel Rossi, Jennifer Carah, Matthew Clifford, and Jeanette Howard. 2017. "Managing Diversions in Unregulated Streams Using a Modified Percent-of-Flow Approach." *Freshwater Biology* 63: 752-768.

Mount, Jeffrey, Brian Gray, Caitrin Chappelle, Jane Doolan, Ted Grantham, and Nathaniel Seavy. 2016. *Managing Water for the Environment During Drought: Lessons from Victoria, Australia*. Public Policy Institute of California.

Mount, Jeffrey, Brian Gray, Karrigan Bork, James Cloern, Frank Davis, Ted Grantham, Letitia Grenier, Jennifer Harder, Yusuke Kuwayama, Peter Moyle, Mark Schwartz, Alison Whipple, and Sarah Yarnell. 2019. *A Path Forward for California's Freshwater Ecosystems*. Public Policy Institute of California.

Mount, Jeffrey, Brian Gray, Caitrin Chappelle, Greg Gartrell, Ted Grantham, Peter Moyle, Nathaniel Seavy, Leon Szeptycki, and Barton "Buzz" Thompson. 2017. *Managing California's Freshwater Ecosystems: Lessons from the 2012–16 Drought*. Public Policy Institute of California.

Moyle, Peter, Jacob Katz, and Rebecca Quiñones. 2011. "Rapid Decline of California's Native Inland Fishes: A Status Assessment." *Biological Conservation* 144: 2414-2423.

Northern California Water Association. 2019. *Modern Functional Flows to Benefit Fish and Wildlife Throughout the Sacramento Valley*.

Poff, N. LeRoy, J. David Allan, Mark B. Bain, James R. Karr, Karen L. Prestegaard, Brian D. Richter, Richard E. Sparks, and Julie C. Stromberg. 1997. "The Natural Flow Regime." *BioScience* 47: 769-784.

Quinn, Timothy. 2018. "State Must Reconsider Unimpaired Flows Approach." Voices on Water, Association of California Water Agencies.

Rohde, Melissa M., Sandi Matsumoto, Jeanette Howard, Sally Liu, Laura Riege, and E. J. Remson. 2018. *Groundwater Dependent Ecosystems under the Sustainable Groundwater Management Act: Guidance for Preparing Groundwater Sustainability Plans.* The Nature Conservancy.

State of California. 2020*. California Water Resilience Portfolio: In Response to Executive Order N-10-19*.

State Water Board. 2020. Existing Instream Flow Requirements in California.

Williams, John G., Peter B. Moyle, J. Angus Webb, and G. Mathias Kondolf. 2019. *Environmental Flow Assessment: Methods and Applications*. John Wiley & Sons.

Yarnell, Sarah, Alyssa Obester, Ted Grantham, Eric Stein, Belize Lane, Rob Lusardi, Julie Zimmerman, Jeanette Howard, Sam Sandoval-Solis, Rene Henery, and Erin Bray. 2018. "Functional Flows for Developing Ecological Flow Recommendations." *California WaterBlog*, December 9.

Yarnell, Sarah, Geoffrey Petts, John Schmidt, Alison Whipple, Erin Beller, Clifford Dahm, Peter Goodwin, and Joshua Viers. 2015. "Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities." *BioScience* 65: 963-972.

Yarnell, Sarah, Eric Stein, J. Angus Webb, Ted Grantham, Rob Lusardi, Julie Zimmerman, Ryan Peek, Belize Lane, Jeanette Howard, and Samuel Sandoval-Solis. 2020. "A Functional Flows Approach to Selecting Ecologically Relevant Flow Metrics for Environmental Flow Applications." *River Research and Applications* 36: 318-324.

Zimmerman, Julie, Daren Carlisle, Jason May, Kirk Klausmeyer, Theodore Grantham, Larry Brown, and Jeanette Howard. 2018. "Patterns and Magnitude of Flow Alteration in California, USA." *Freshwater Biology* 63: 859-873.

ABOUT THE AUTHORS

Ted Grantham is an adjunct fellow at PPIC's Water Policy Center, and the first PPIC CalTrout Ecosystem Fellow. He is a cooperative extension specialist and an adjunct professor in the Department of Environmental Science, Policy, and Management at the University of California, Berkeley. His research explores the effects of climate change and water management on freshwater ecosystems. He holds a PhD in environmental science, policy, and management from the University of California, Berkeley, and a BS in biological sciences from Stanford University.

Jeffrey Mount is a senior fellow at the PPIC Water Policy Center. He is an emeritus professor in the Department of Earth and Planetary Sciences and founding director of the Center for Watershed Sciences at the University of California, Davis. He is a geomorphologist who specializes in the study of rivers, streams, and wetlands. He has served on many state and federal boards and commissions that address water management issues in the West. He has published more than a hundred articles, books, and other publications, including the seminal book *California Rivers and Streams* (UC Press). He holds a PhD and MS in Earth Sciences from the University of California, Santa Cruz.

Eric Stein is the head of the Biology Department at the Southern California Coastal Water Research Project (SCCWRP), where he oversees a variety of projects related to instream and coastal water quality, hydromodification, and monitoring and assessment of aquatic resources, including wetlands, streams, and estuaries. His research focuses on effects of human activities on the condition of aquatic ecosystems, and on developing tools to better assess and manage those effects. He holds a PhD in environmental science and engineering, an MEd in science education, and a BS in biology—all from the University of California, Los Angeles.

Sarah Yarnell is an associate professional researcher at the Center for Watershed Sciences at the University of California, Davis. She conducts interdisciplinary research that applies understanding of river ecosystem processes to managed systems, with a focus on the development and maintenance of riverine habitat for native aquatic species. She is currently working with colleagues to apply a functional flows approach to the development of environmental flow criteria throughout California. She holds a PhD in hydrologic sciences and an MS in geology, both from the University of California, Davis.

ACKNOWLEDGMENTS

We wish to thank the many individuals who provided us with information and insight on managing water for the environment. Special thanks to Ellen Hanak, who gave us expert guidance and reviews. Thanks, too, to the following individuals for very helpful reviews of a draft version of this report: Julie Zimmerman, Albert Ruhi, Bryan McFadin, Bronwen Stanford, Brian Gray, and Chad Loflen. Lori Pottinger provided expert editorial guidance. The authors alone are responsible for any errors or omissions.

We would also like to thank the funders of this work: the S. D. Bechtel, Jr. Foundation and the donors of the PPIC CalTrout Ecosystem Fellowship—Gary Arabian, the Morgan Family Foundation, Nick Graves, John Osterweis, the Rosenberg Ach Foundation, and the Water Funder Initiative Water Campaign.

PUBLIC POLICY INSTITUTE OF CALIFORNIA

The Public Policy Institute of California is dedicated to informing and improving public policy in California through independent, objective, nonpartisan research.

Public Policy Institute of California
500 Washington Street, Suite 600
San Francisco, CA 94111
T: 415.291.4400
F: 415.291.4401
PPIC.ORG/WATER

PPIC Sacramento Center
Senator Office Building
1121 L Street, Suite 801
Sacramento, CA 95814
T: 916.440.1120
F: 916.440.1121