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The California Environmental Flows Framework: Meeting the Challenges of Developing a Large-Scale Environmental Flows Program

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Environmental flow programs aim to protect aquatic habitats and species while recognizing competing water demands. Often this is done at the local or watershed level because it is relatively easier to address technical and implementation challenges at these scales. However, a consequence of this approach is that ecological flow criteria are developed for only a few areas as dictated by funding and interest with many streams neglected. Here we discuss the collaborative development of the California Environmental Flows Framework (CEFF) as an example process for developing environmental flow recommendations at a statewide scale. CEFF uses a functional flows approach, which focuses on protecting a broad suite of ecological, geomorphic, and biogeochemical functions instead of specific species or habitats, and can be applied consistently across diverse stream types and spatial scales. CEFF adopts a tiered approach in which statewide models are used to estimate *ecological flow needs* based on natural functional flow ranges, i.e., metrics that quantify the required magnitude, timing, duration, frequency, and/or rate-of-change of functional flow components under reference hydrologic conditions, for every stream reach in the state. Initial flow needs can then be revised at regional, or watershed, scales based on local constraints, management objectives, and available data and resources. The third tier of CEFF provides a process for considering non-ecological flow needs to produce a final set of *environmental flow recommendations* that aim to balance of all desired water uses. CEFF was developed via a broad inclusive process that included technical experts across multiple disciplines, representatives from federal and state agencies, and stakeholders and potential end-users from across the state. The resulting framework is therefore not associated with any single agency or regulatory program but can be applied under different contexts, mandates and end-user priorities. The inclusive development of CEFF also allowed us to achieve consensus on the technical foundations and commitment to applying this approach in the future.

Keywords: functional flows, ecohydrology, flow metrics, flow-ecology relationship, interagency agreement

INTRODUCTION

For decades, river scientists have been working to understand the quantity, quality, and timing of flows needed to sustain healthy river ecosystems. This work has resulted in the development of approaches for defining enviornmental flows that recognize the importance of natural flow variability and ecosystem functions (Poff et al., 2010; Richter et al., 2012; Horne et al., 2017). In addition to the direct, predictable impacts of flow changes on ecological condition (Poff et al., 1997; Bunn and Arthington 2002; Arthington 2012), researchers have increasingly recognized the role of other factors in mediating the relationship between flow and ecology, including the physical form and structure of the stream channel, impairments to water quality, and biological interactions among species (Beechie et al., 2010; Wohl et al., 2015; Yarnell et al., 2015; Mazor et al., 2018). As a result, researchers and water resource managers have advocated for holistic environmental flow assessment methods designed to support physical, chemical, and biological functions of streams that, in turn, sustain ecosystem health (Poff and Matthews 2013; Palmer and Rui 2019; Tickner et al., 2020). Despite these scientific advances, assessing environmental flows in a holistic manner faces significant obstacles. Many of the holistic approaches used to develop ecological flow needs (or requirements) are extremely complicated and difficult to implement, require significant funding, and are limited to local sites and not readily transferable (Chen and Olden, 2018). Thus, managers continue to use relatively simple affordable tools that focus on the needs of a single species or life stage and fail to address the spatial complexity and/or temporal variability required for a healthy river ecosystem (Arthington et al., 2006; Meitzen et al., 2013; Horne et al., 2019).

In addition to the technical challenges of assessing environmental flows, implementation faces significant socio-economic and regulatory barriers. In most rivers, ecosystem water needs must be balanced with legal requirements, public health and safety requirements, and social values and priorities for water, including other human uses. The process of developing environmental flow recommendations often requires lengthy public proceedings that can take years to resolve. As a result, only a small fraction of the world's rivers has formal protections of environmental flows (Smakhtin et al., 2004; Tickner et al., 2020). There remains a need to accelerate implementation and improve the effectiveness of environmental flows in supporting the ecological health of rivers and streams (Reid et al., 2019; van Rees et al., 2021). In particular, water managers need a consistent approach for transforming complex environmental data into scientifically defensible, easy-to-understand environmental flow recommendations that are effective in supporting a broad range of ecosystem functions and preserving the multitude of benefits provided by healthy rivers and streams.

The challenges of developing ecologically protective, implementable, environmental flow recommendations can be exacerbated in drier climates, regions that support sensitive species or habitats, and areas with high levels of competition for water resources (Arthington et al., 2012; Horne et al., 2017; Tickner et al., 2020b). California is emblematic of these challenges due to its expansive water infrastructure and over-allocated surface water supplies (Grantham and Viers 2014), in addition to high regional-scale diversity of climate, geology, and elevation that supports diverse stream types with highly variable flow regimes (Ode et al., 2016; Lane et al., 2017). Intense human water-use pressures, coupled with high geographic diversity, broad range of management needs (e.g., urban water supply, agriculture, forestry, fisheries management, species protection), and a complex and highly fractured governance structure has resulted in piecemeal approaches to establishing environmental flow recommendations across the state, making development of a statewide environmental flows program particularly daunting.

In 2017, a collaborative team of agency personnel, academic researchers, and non-governmental organization scientists from across the state of California formed an Environmental Flows Workgroup to create a framework for developing environmental flow recommendations statewide. The goal of the workgroup was to develop a shared, scientifically defensible approach to protecting river ecosystems that would be flexible enough to be used statewide by a variety of different stakeholder groups. The workgroup also explicitly sought to incorporate a holistic understanding of flows needed to sustain the physical, biological, and chemical functions of streams in a way that was easily accessible to managers. Finally, the workgroup focused on building an inclusive process that incorporated feedback throughout to ensure that the final product was useful and useable by the target end user community. The workgroup built on a 2014 review of methods for establishing environmental flow needs (Dahm et al., 2014), that included consideration of the Instream Flow Incremental Methodology (IFIM) and the Ecological Limits of Hydrologic Alteration (ELOHA). The review recommended a regional approach that draws from the strengths from these two methods and includes a hydrologic classification and analysis, site specific fieldwork and extrapolation, definition of environmental flow regime, interaction between scientists and stakeholders, as well as an adaptive management protocol.

The result of this effort is the California Environmental Flows Framework (CEFF; CEFWG 2020). While developed for California, CEFF provides a case study to illustrate how large-scale environmental flow programs can be designed in a technically defensible and practically implementable manner. This paper presents the guiding principles and approach underlying CEFF and describes a process for stakeholder coordination, initial testing, and outreach that may be instructive for other large-scale programs. We also outline ongoing challenges for successful long-term implementation, foremost of which is ensuring the technical and policy infrastructure to support CEFF is established in a manner that accomplishes the overall goals of resource protection and sustainable water use with opportunities for adaptive management and refinement over time.

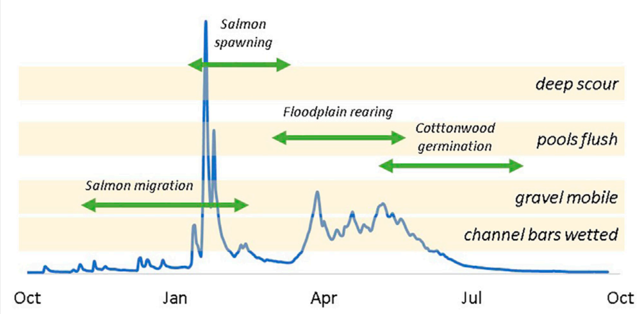

FIGURE 1 | Schematic representation of an idealized annual hydrograph associated with key physical processes (yellow bars) and species needs (green arrows) that are supported by functional flows. Modified from Yarnell et al., 2010.

GUIDING PRINCIPLES FOR DEVELOPING THE CALIFORNIA ENVIRONMENTAL FLOWS FRAMEWORK

Key objectives of CEFF are to provide a consistent approach and set of tools for developing environmental flow recommendations across California's diverse landscape; incorporate a more holistic understanding of flow and the physical, biological, and chemical functions it sustains in a way that is accessible to managers; standardize, streamline, and improve transparency of environmental flow assessments; provide flexibility to accommodate diverse management goals and priorities; and improve coordination and data sharing among management agencies and other stakeholders. To realize these objectives, CEFF development was guided by the following key principles.

Functional Flows Approach

Functional flows are distinct aspects of a natural flow regime that sustain the ecological, geomorphic, and biogeochemical functions upon which native aquatic communities depend (Escobar-Arias and Pasternack 2010; Yarnell et al., 2015). By focusing on the functions provided by flow variability within and among seasons, functional flows offer a more effective means of improving river ecosystem health than conventional approaches (Grantham et al., 2020). Conventional environmental flow approaches often focus on species-specific or life-stage specific flow requirements (e.g., Bovee 1982) or seek to explicitly link individual flow metrics to specific ecological response metrics (e.g., Poff et al., 2010). By omitting consideration of other aquatic species, community interactions, the physical landscape, and physical or chemical processes, these traditional approaches are typically not protective of the broader river ecosystem over large spatial or temporal scales. In contrast, a functional flows approach characterizes key flow components, via a suite of flow metrics, that are ecologically protective across rivers and species (Yarnell et al., 2020), and thus provides a mechanism to address a diversity of stream types and management needs within a large-scale environmental flow program.

A functional flows approach supports overall ecological function by identifying the components of the annual hydrograph necessary to support geomorphic and biological processes. This approach recognizes that all components of the natural flow regime are necessary to support freshwater biodiversity (Bower et al., 2021) and that different elements of the flow regime work together to support diverse species assemblages (**Figure 1**; Yarnell et al., 2015, 2020). The approach emphasizes both intra- and inter-annual flow variability and spatial heterogeneity of flow needs; for example, flows necessary to support floodplain inundation in low gradient systems may be different from flows necessary to support sediment movement in higher gradient systems. Similarly, higher spring flows in wet years may better support native fish communities, while lower spring flows in dry years may be more advantageous to native amphibians. A function-based approach is also critical for accommodating non-stationarity in environmental conditions associated with shifting climatic patterns. Poff (2017) emphasizes that to provide for long-term resiliency, environmental flows must evolve from state-based to process-based approaches that are both temporally and spatially variable and account for "non-flow" factors such as temperature and sediment.

The focus on function also provides more flexibility as managers work to balance ecological and non-ecological needs. Rather than prescribing specific daily or monthly flows, the approach provides seasonal ranges and prioritizes flows to support ecological functions. For example, managers could evaluate a range of scenarios with variable flow timing and magnitude to achieve the function of providing migration cues for anadromous species, rather than attempting to implement a single static value. The focus on function allows environmental water to be targeted to specific times of the year where flows will have the greatest environmental benefit. It also recognizes that most native aquatic species are adapted to the natural flow variability that maintains physical processes supportive of key life history needs (e.g., periodic overbank flooding that fills breeding pools on the floodplain) and reduces suitability for invasive species. Moreover, functional flows can be managed over multiple years, providing the flexibility to emphasize ecological uses in some years while allocating more water for other uses in other years, thereby limiting impacts to long-term stream health.

Consistent Statewide Approach

A consistent statewide approach lowers the barriers to implementation of more holistic environmental flows and promotes consistency and transfer of knowledge across individual applications. Providing readily accessible tools (and models) allows for evaluation of ecological flow needs in any watershed or region of the state regardless of the level of available data or local expertise (Grantham et al., 2021). Previously, most commonly used tools for rapidly determining ecological flow needs in California were based on a percentage of unimpaired flow (Tessman, 1980). Although easy to apply, these approaches often fail to support a broad suite of ecological functions and can result in inefficiencies in water allocation that foster conflicts between competing water demands. CEFF can be used to determine function-based ecological flows in watersheds across the state and be adapted to a variety of management contexts.

These statewide tools make it possible for state, regional, or watershed agencies and programs to rapidly develop environmental flow recommendations that support a broad suite of ecological and geomorphic functions for their location of interest. Consistent assessment approaches can also be helpful in illustrating the connections between hydrology and ecology in a manner that is accessible to local managers and stakeholders and can encourage deeper investigation based on local priorities and resources. When implemented, innovations and expansions developed to support local uses can be incorporated back into the statewide framework, allowing it to continue to evolve and improve.

Tiered Structure

A tiered approach provides a consistent foundation that is broadly applicable as well as mechanisms for expansion and intensification to meet local and regional needs. Many programs aim to establish environmental flow recommendations to balance water needs associated with agricultural production, urban water demands, groundwater management, energy production, or other uses. Availability of data and tools, as well the level of detail necessary to conduct tradeoff analysis, may vary across programs (or regions). Opperman et al. (2018) developed a tiered approach to developing environmental flow recommendations by beginning with desktop analyses and incorporating additional data and resources as needed. We have expanded on the concept by providing the predicted natural range of functional flow values as a starting point for ecological flow needs that can be readily applied across an entire region or state. The tiered approach also provides transparency around management objectives at each tier of the framework, by providing an "ecological-only" management scenario based on natural functional flow components in the first tier, the ability to account for local circumstances (e.g., altered sediment regimes, channel incision, invasive species, water quality) in the second tier if needed, and specific management objectives for balancing ecological outcomes and human water needs in the third tier.

CEFF is structured so that managers can choose to develop environmental flows using a readily available statewide functional flows dataset (Grantham et al., 2021), or can draw extensively on site-specific information, depending on need and data availability. The first tier allows for rapid determination of ecological flow needs for all stream reaches in the state through the application of statewide models that provide estimates of natural flow ranges. This consistent process lowers barriers to initial development of environmental flow programs associated with insufficiency of local data. In areas where potential for conflict with other water uses is low, the first tier products based on natural flows may be sufficient and/or may provide interim flow recommendations until additional data or models can be developed. The second tier allows for consideration of local physical or biological conditions that require additional analysis to increase certainty in ecological flow needs; this may be particularly important in areas where the potential for conflict with other uses is high. The third tier guides managers through a process to develop final environmental flows that evaluates trade-offs between human and ecological needs, when necessary. Human water needs only inform the third tier, so the tiered structure also clearly distinguishes the scientific process of determining ecological flow needs from the sociopolitical process of balancing ecological and non-ecological water demands.

Broad Applicability Across Programs

California has a diverse set of local agencies, water users, stakeholders, and other parties that are involved with and affected by environmental flow decisions. An environmental flows framework must be robust enough to apply across numerous programs with different mandates and objectives. Existing laws, policies, and processes focused on water quality, water supply, and habitat often also relate to environmental flows resulting in piecemeal and uncoordinated approaches. Furthermore, state and local ordinances may have competing objectives that can constrain environmental flow implementation (e.g., stormwater management, wastewater discharge requirements, water recycling policies). California's "first in time, first in right" system of water rights, combined with overallocation of many river systems, has led to conflict among water users that does not fully integrate ecosystem needs (Grantham and Viers, 2014). For an environmental flows framework to be successful over the long-term, it must be flexible enough to be applied to address a broad range of management needs, such as stream restoration, dam releases, fisheries management, water recycling, and groundwater recharge. Broad applicability helps ensure that the framework is not "owned" by any one agency or program, but is a product of the collective, allowing a consistent set of tools and approaches to be more uniformly applied.

Stakeholder-Driven Process

Early, ongoing, and transparent interaction with stakeholders improves trust and helps to build agreement on key management objectives and approaches to meet them. Past studies have shown that analytical results alone cannot produce decisions (Failing et al., 2013); decisions are the product of stakeholder values. Stakeholder factions often have different values based on both cognitive and emotional perspectives. Successful development and implementation of an environmental flows program requires mechanisms for coordination among agency programs to achieve consensus on a technical approach and for providing maximum transparency and opportunity for engagement by the larger stakeholder community.

Hall et al. (2021) lay out a process for meaningful public engagement in the scientific process. They argue that useful public participation in science is not a function of simply asking for assistance, but a function of relationships of trust and respect earned over time. Researchers must commit themselves to cultivating on-going relationships with a broad array of community members (Burdett et al., 2021; Golladay et al., 2021), and these relationships cannot solely be based on researchers' needs. Instead, relationships should be built on mutual understanding that emerges when research design and execution are informed by community members' place-based experiences. An example of broad stakeholder coordination is development of the Nile Basin Initiative (NBI 2017), arguably, one of the most ambitious environmental flows efforts globally. The Nile Basin Initiative produced a 10-year strategy among ten member states to achieve sustainable water use through equitable utilization of water resources. Development of the NBI was a broadly inclusive process that resulted in six goals that address agricultural, ecological, hydropower, and socioeconomic interests.

Stakeholders may not always come to consensus on the trade-offs inherent in choosing a set of environmental flow recommendations for implementation, but clarity around management objectives and trade-offs provides transparency for how decisions are made and a framework for adaptive management if management objectives are not fully achieved.

CALIFORNIA ENVIRONMENTAL FLOWS FRAMEWORK DEVELOPMENT PROCESS

CEFF was developed through multiple layers of collaboration and coordination with technical experts, key agencies, and potentially affected stakeholders based on the guiding principles discussed above. Technical development was led by a cross-disciplinary team of scientists and engineers working collaboratively with environmental flow practitioners from state agencies. The team drew from environmental flow experiences around the world to develop an approach that is both rigorous and practical. The broad technical expertise and experiences of the development team included hydrology, geomorphology, ecology, modeling, and statistical analysis. Proposed technical approaches were vetted through agency experts to ensure that the ultimate framework and products were compatible with agency mandates and implementation capability. The key elements of success of this group were the close working relationship between agency and outside technical experts, including shared workloads, consistent sharing of data and technical outputs, and routine communication. This produced a level of understanding and trust among the technical workgroup and fostered broader outreach to other technical experts around the state. Ultimately, this led to CEFF being a product of the collective and not a product of any single agency or program.

Agencies with traditionally different objectives were involved throughout the development of CEFF, including the State Water Resources Control Board, which is responsible for balancing human and ecological water needs, and the California Department of Fish and Wildlife, which determines flow needs in streams and rivers for fish and wildlife. Because CEFF was not developed to support any one regulatory program and is not a regulatory tool, agencies had the opportunity to co-develop CEFF so that it could be applied across a variety of contexts and augmented to meet their program-specific needs. For example, the California Department of Fish and Wildlife is using CEFF products to inform the development of ecological flow criteria for priority watersheds when site-specific data are unavailable, or site access is limited; they have also used CEFF tools to complement some of their site-specific technical studies. The State Water Board is using CEFF to inform allowable water withdrawals associated with cannabis cultivation and diversions of treated wastewater associated with the State's Recycled Water Policy. Involvement of multiple agencies throughout the process ensured that the final products would be useful in addressing a broad range of mandates and helped spread funding and program management costs and responsibilities among programs.

Technical development of CEFF was coupled with a broad stakeholder engagement process centered around a statewide environmental flows workgroup. This workgroup was established by the State's Environmental Protection and Natural Resources agencies as a forum for discussion of assumptions and approaches used during CEFF development. This workgroup includes federal, state, and local agency representatives, watershed groups, and other entities involved in developing and implementing environmental flow programs at the watershed or regional level, and it was co-chaired by the State Water Resources Control Board and the California Department of Fish and Wildlife. The workgroup provided a mechanism for feedback from a variety of stakeholders and instream flow practitioners during the formative stages of CEFF development. The technical development team presented draft technical products and discussed alternative approaches at each step. Iterative adjustments were made to address stakeholder questions and concerns throughout the development process.

As part of stakeholder coordination, several watershed groups partnered with the development team to conduct "proof of concept" investigations. These initial applications were critical in helping to refine the approach in a way that could be implemented across the diverse climatic and physical landscape of California. For example, several watershed groups used CEFF to determine ecological flow needs for the Cosumnes River in the Central Valley agricultural region to be used in future flow negotiations and paired this work with other efforts to address groundwater sustainability in the watershed. In southern California, CEFF was used in the urbanized San Juan Creek watershed management area to prioritize streams for restoration based on locations where restoring functional flows would result in greatest ecological gain (Irving et al., 2021) and to develop refined ecological flow needs that consider altered physical habitat (Taniguchi et al., 2021). Partnering with local workgroups provided a mechanism to determine the ability for CEFF to accommodate the vast array of local circumstances and provide feedback to the overall statewide approach to facilitate maximum applicability. At the same time these local groups help build a broad constituency for CEFF and a level of trust in the underlying technical foundation. Ultimately, the aim is to have this network provide "bottom-up" support for ongoing implementation of CEFF in concert with the relatively "top-down" approach used during the development phase. This hybrid approach has proven to be successful over the long term by reducing resistance to pure command-and-control approaches and ensuring that specific social, cultural, and economic considerations are accounted for

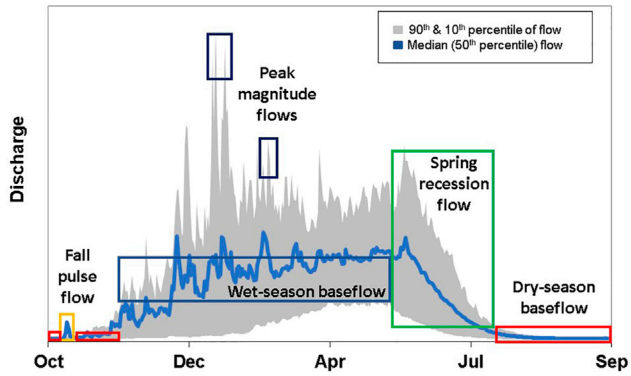

FIGURE 2 | Functional flow components for California depicted on a representative hydrograph. Blue line represents median (50th percentile) daily discharge. Gray shading represents 90th to 10th percentiles of daily discharge over the period of record (Yarnell et al., 2020).

in program implementation (Yohannes 2001; Chiranjeewee and Vacik 2012).

OVERVIEW OF THE CALIFORNIA ENVIRONMENTAL FLOWS FRAMEWORK

The technical approach of CEFF is based on functional flows–i.e., distinct aspects of a natural flow regime that sustain ecological, geomorphic, or biogeochemical functions, and that support the specific life history and habitat needs of native aquatic species (Yarnell et al., 2015). Most California streams have five functional flow components that support several critical physical, biogeochemical, and biological functions that maintain river ecosystem's health and satisfy life history requirements of native species (**Figure 2**; Yarnell et al., 2020):

- *Fall pulse flow*: Following first major storm event at the end of dry season
- *Wet-season peak flow*: Coincides with the largest storms in winter
- *Wet-season baseflow*: Sustained by overland and shallow subsurface flows in the periods between winter storms
- *Spring recession flow*: Represents the transition from the wet to dry season and is characterized by a steady decline of flows over a period of weeks to months
- *Dry-season baseflow*: Sustained by groundwater inputs to rivers

Managing for these five functional flow components preserves essential patterns of flow variability within and among seasons, but it does not mandate either the restoration of full natural flows or maintenance of historical ecosystem conditions. Although the five natural functional components of flows are recognized in all of California's rivers, their flow characteristics–magnitude, timing, frequency, duration, and rate of change–vary regionally. For example, the spring recession flow component will have a larger magnitude and longer duration for snowmelt-dominated rivers in the Sierra Nevada than for the flashy, ephemeral rivers in the South Coast. Characteristics of the functional flow components also vary by water year type (e.g., wet, moderate, dry). These functional flow components can be quantified by a suite of *functional flow metrics*—quantitative measures of the flow characteristics of each of the five functional flow components—that reflect the natural diversity in flow characteristics throughout the state.

CEFF uses a tiered approach that begins with general statewide environmental flow recommendations based on natural hydrology, progresses through site-specific adjustments, and finally reconciles with non-ecological flow needs (**Figure 3**). The first two sections focus on development of consistent, scientifically-supported estimates of *ecological flow needs*, expressed as quantifiable metrics that describe ranges of flows that must be maintained within a stream and its margins to support the natural functions of healthy ecosystems. The final section provides a process whereby non-ecological management objectives, including water needs for people, are evaluated and a final set of *environmental flow recommendations* are produced. An example output of CEFF is shown in **Table 1**. The final framework does not prescribe flows that must be implemented, but instead outlines a method for quantifying flows that support ecological function and assessing trade-offs among multiple competing objectives to meet the needs of different stakeholder groups.

CEFF Section A-Identify Ecological Flow Needs Based on Natural Functional Flows

Section A of CEFF provides guidance for evaluating ecological flow needs based on natural functional flow metrics. Natural functional flow metrics have been quantified for all stream reaches in California (Patterson et al., 2020; Grantham et al., 2021). Reference expectations are generated by a statewide model of reference hydrology that is based on physical and climatic watershed characteristics and provide a consistent starting point for all environmental flow assessments. The flow metrics

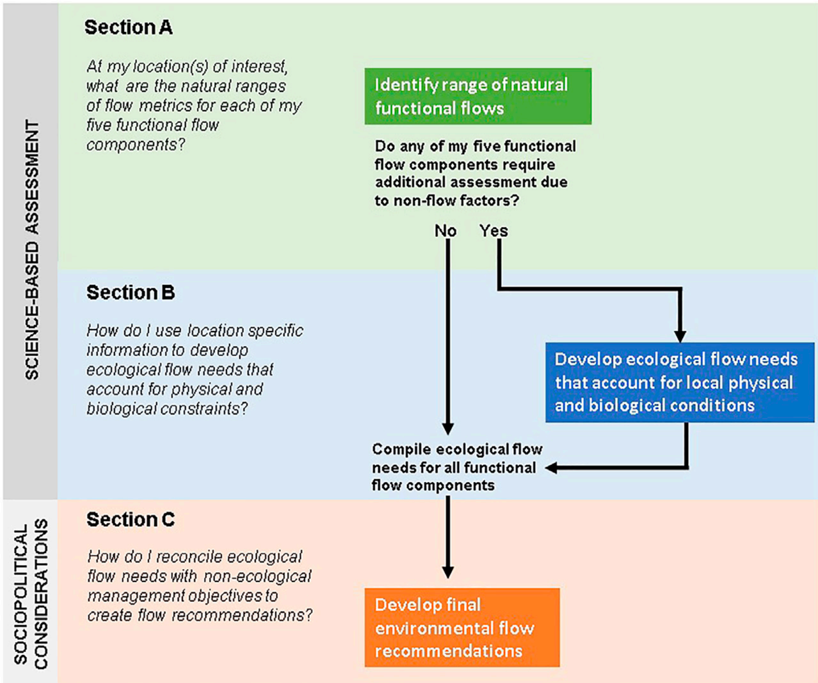

FIGURE 3 | An overview of three sections of the California Environmental Flows Framework, with the key questions addressed in each section.

produced by the statewide model account for streams in different climatic or physiographic settings that will have inherently different natural flow regimes, such as the relative contribution and timing of rainstorms, snowmelt runoff, and groundwater discharge, all of which affect biological community composition (Lane et al., 2018).

The outcome of Section A is a set of values for natural functional flow metrics that characterize the natural variability in flow that supports essential ecosystem functions. The user will also have evaluated whether there are non-flow mediating factors, such as altered physical habitat or water quality impairments, that could limit the effectiveness of the natural range of functional flow metrics in supporting ecosystem functions. If limiting factors are identified for one or more flow components, the user should proceed to Section B to refine ecological flow needs for the subset of functional flow components for which natural flows are

TABLE 1 | Example output from CEFF process showing environmental flow recommendations for a subset of functional flow metrics. Ranges of flow recommendations shown in parentheses allow for accommodation of natural variability and different water year types.

Functional flow component	Flow metric	Environmental flow recommendations
Fall pulse flow	Fall pulse magnitude Fall pulse timing Fall pulse duration	62 (30–180) cfs Oct 20 (Oct 7–Oct 28) 3 (2–7) days
Wet-season baseflows	Wet-season baseflow magnitude Wet-season start timing Wet-season duration	324 (260–410) cfs Nov 13 (Nov 3–Nov 30) 168 (145–184) days
Peak flow	5-year peak flow magnitude 5-year peak flow duration 5-year peak flow frequency	3,790 (3,000–4,800) cfs 3 (1–6) days 1 (1–3) event(s)
Spring recession flows	Spring recession magnitude Spring start timing Spring duration Spring rate of change	520 (300–980) cfs Apr 28 (Apr 6–May 14) 50 (36–66) days 6 (3–10) % decline per day
Dry-season base flows	Dry-season baseflow Dry-season start timing Dry-season duration	22–23 cfs June 20 (June 5–July 7) 151 (121–183) days

unlikely to support ecosystem functions. If no additional limiting factors are identified, the user can proceed to Section C to develop final environmental flow recommendations.

CEFF Section B-Refine Ecological Flow Needs for Components Requiring Additional Consideration

Section B of CEFF provides guidance for determining if non-flow impairments–such as altered physical habitat, poor water quality, or invasive species–require further consideration because the natural range of functional flow metrics may fail to support desired functions. Section B allows users to account for site-specific non-flow impairments that may change the relationship between reference-based flow metrics and ecological outcomes. This involves developing conceptual models, compiling data and information, and performing quantitative analyses to assess the relationship between functional flow components and ecosystem responses relevant to ecological management goals (**Figure 4**). The user performs a detailed analysis of the linkages between flow, physical habitat, water quality, and biological interactions to refine ecological flow needs for the functional flow components requiring additional consideration. For example, consideration of floodplain inundation during peak flood flows in an incised channel may require site-specific data and detailed flow-ecology relationships to refine the initial set of ecological flow needs to support ecological functions either combined with channel restoration or without it. At the end of Section B, these refined needs are combined with those developed in Section A to define a full set of ecological flow needs associated with all functional flow components.

CEFF Section C-Developing Environmental Flow Recommendations

Section C outlines a process for developing environmental flow recommendations that balance ecological management goals with other non-ecological water management objectives, such as human uses. This section represents a transition from a scientific process, in which ecological flow needs are developed (Sections A and B), to a process that incorporates social values and other management needs, including human uses of water, public health and safety needs, and legal and regulatory requirements. For example, application of CEFF in the Little Shasta Watershed involved considering how to balance ecological needs with the need for groundwater withdrawals and spring diversions to support agricultural priorities (Yarnell et al., 2021). In Section C, the user continues to engage stakeholders (including traditionally underrepresented groups) to guide the development of a final set of environmental flow recommendations and an implementation plan for their study area.

Because users must take into account numerous sociopolitical considerations that are often site-specific and non-scientific, Section C provides less prescriptive guidance than Sections A and B. Instead, Section C offers a conceptual framework, including suggested tools, to help the user appropriately balance ecological and non-ecological management objectives to develop a set of environmental flow recommendations. The end of Section C provides guidance for the development of an implementation plan and monitoring strategy that incorporates adaptive management principles to increase the likelihood that environmental flow recommendations will achieve desired management objectives.

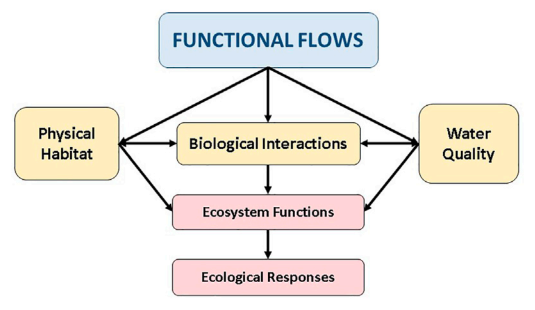

FIGURE 4 | Generic conceptual model demonstrating relationships between a functional flow component, ecosystem functions, and ecological response as mediated by factors such as physical habitat, water quality, and biological interactions.

LOOKING FORWARD TOWARD IMPLEMENTATION

Completing an accepted and agreed upon framework for developing ecological flow needs is only a starting point. Developing, implementing, and sustaining environmental flow programs in a manner that protects and restores ecological functions requires long-term commitment from numerous entities, a process for continually adapting and improving the approach, mechanisms for communication and data sharing, and sustained funding. CEFF, like many environmental flows approaches, is complex and initial applications will inevitably reveal challenges not contemplated during the development process. Ongoing technical assistance and a forum for addressing implementation challenges is critical for early successes. Moreover, there needs to be a mechanism for sharing positive and negative experiences from initial projects to support and encourage continued use of the framework. To help achieve these goals, the California Environmental Flows Workgroup has developed an implementation workplan to support application of CEFF. Key elements of this workplan include:

- Maintaining the statewide workgroup as a forum for receiving, addressing, and disseminating frequently asked questions and answers regarding CEFF application. This will help build a consistent and engaged community of practitioners that can ultimately support each other and contribute to future improvements and refinements of the approach.
- Continued development of technical tools and models for estimating flows in ungaged streams, calculating functional flow metrics, and predicting biological consequences of flow

modification. These tools will be documented and made widely available through the state's environmental flows website.

- Expansion of technical tools to improve the ability to consider groundwater interactions, effects of geomorphic alteration (either impacts or restoration), and relationship of flow alteration with other stressors, such as temperature and water quality. These tools will support the ability to refine ecological flow needs to accommodate local circumstances (as outlined in CEFF Section B). Future efforts will include evaluation of effects of climate change on natural flows to support development of "climate resilient" ecological flow needs.
- Process for documenting case studies and the associated lessons learned (both positive and negative). A variety of case studies are being implemented across the state. A metadata and case study documentation template has been developed to help users document, catalogue, and track these case studies and associated data, products, and reports in a clear and consistent manner. A web portal is planned to provide ready access to these case studies to help inform future applications of CEFF.
- Development of a monitoring and adaptive management strategy to track and improve CEFF effectiveness. This effort will include 1) developing consistent methods, protocols, and data structures and 2) developing consistent performance standards that support a process to track and assess outcomes of flow management actions across projects. Part of the strategy involves developing relationships with existing monitoring programs and identifying opportunities to partner/leverage efforts across programs.
- Development of data management infrastructure to allow compilation of development and monitoring data. As implementation proceeds, this structure will provide standard data templates that will facilitate compilation of monitoring data in a consistent manner. This will facilitate ongoing improvement of CEFF by providing a way to use data to improve statewide and regional models. This will also provide the ability to track the effectiveness of CEFF flow recommendations in supporting ecological functions.

CONCLUSION

Environmental flow programs are inherently complicated and often contentious. Successful implementation requires a commitment to maintain technical rigor and a willingness to recognize and remedy weaknesses as they are identified. Given the multitude of entities that must cooperate to implement environmental flow programs, shared commitment and responsibility and ongoing open and cordial dialogue are critical. Only through such cooperation will there be sufficient knowledge, resources, time, and funding to realize the ecological and social benefits of managing environmental flows. The California Environmental Flows Framework provides an example of one approach that hopes to accomplish these goals over time.

Although the concept of functional flows has been broadly understood for some time (Beechie et al., 2010; Yarnell et al., 2015), managers have lacked a mechanism for translating these concepts to a decision-making process that could be readily implemented at broad spatial scales. Through CEFF, managers can easily access information about functional flows in varying watersheds and regions and incorporate these concepts into water management decisions. The tiered framework allows for full consideration of ecological flow needs (Sections A and B) before trade-offs between competing management objectives are considered and final environmental flow recommendations are developed (Section C).

CEFF is in early phases of implementation, so the ultimate outcomes are still uncertain. However, the time and effort dedicated to an inclusive and transparent development process establishes a clear roadmap and expectations that should reduce conflicts during implementation. CEFF implementation is envisioned as an incremental process, where early stages will produce successes, failures, and lessons that can be used to expand and improve the Framework over time. Therefore, the interagency workgroup is committed to supporting pilot application case studies that can be used to test CEFF and learn which concepts apply well on the ground and which require refinement. The myriad of potential applications can never be fully anticipated, so the commitment of the statewide team to continue to receive feedback from early adopters is key to ensuring long-term success and acceptance of CEFF.

Providing water for the environment requires compromises to support both ecological and non-ecological uses. This balance can be achieved by adopting strategies that focus on maintaining ecosystem functions over long time periods and across watersheds as opposed to goals based on specific species or habitats in specific locations. The functional flows approach accounts for different needs of different stream types in different seasons and the natural variability of flows between wet and dry years, and it ensures available environmental water is allocated in a way that delivers the maximum potential benefit. This ultimately demonstrates the value of environmental flows and provides more certainty about the amount, timing, and persistence of available water for all uses. The functional flows approach also offers the opportunity to adapt water allocation programs over time in response to both short-term droughts and long-term changes in precipitation and runoff patterns associated with long-term climate change.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://sccwrp.hub.arcgis.com/.

AUTHOR CONTRIBUTIONS

Conceptualization and development of evaluation framework (ES, JZ, SY, BS, BL, KT, AO, RL, SS and TG) principle authorship (ES) contribution to manuscript, editing and review (JZ, SY, BS, BL, KT, AO, SS and TG).

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