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A Three-Level Framework for Assessing and Implementing Environmental Flows

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In the decade since the Brisbane Declaration (2007) called upon governments and other decision makers to integrate environmental flows into water management, practitioners have continued to seek ways to expand implementation of flow restoration or protection. The science and practice of environmental flow assessment have evolved accordingly, generating diverse methods of differing complexity from which water managers or regulators need to select an approach best fitting their context. Uncertainty over method choice remains one of several of the more readily overcome barriers that have contributed to slowing the implementation of environmental flows. In this paper, we introduce a three-level framework intended to help overcome such barriers by intertwining holistic environmental flow assessment with implementation. The three levels differ based on the availability of resources and level of resolution required in the flow recommendations, with the framework designed to guide the user toward implementation at any level as soon as possible, based on at least some of the recommendations. Level 1 is a desktop analysis based on existing data, typically conducted by one or a few scientists. Level 2 is similarly mostly reliant on existing information, but brings together a multidisciplinary set of experts within a facilitated workshop setting to use both this knowledge and professional judgment to develop flow recommendations and fill data gaps. The most comprehensive assessment level, Level 3, guides the collection of new data and/or construction of models to test hypotheses developed by the expert team. Key characteristics of this framework include: (1) methods are matched to the levels of resources available and certainty required; funds for research are invested strategically to address critical knowledge gaps and thereby reduce uncertainty; (2) the framework is iterative and information generated at one level provides the foundation for, and identifies the need for, higher levels and; and (3) processes for flow assessment and implementation are intertwined, meaning they move forward in coordinated fashion, with each process informing the other. Using practical cases from North America, we illustrate how environmental flow assessment at each level has led to implementation, with changes in policy or management.

Keywords: hydrology, river restoration, water management, freshwater ecosystems, environmental flows

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INTRODUCTION

Hydrological alteration—defined as changes in the magnitude and temporal pattern of a water flow regime caused by the storage, regulation, diversion and/or extraction of water by dams and other infrastructure—is one of the primary contributors to the decline of freshwater habitats and species (Postel and Richter, 2003). Recognizing these threats, biologists and managers in the 1970s began to advocate for maintaining river flows, with an initial emphasis on identifying and protecting a "minimum flow" to remain in rivers and streams. However, as scientific understanding of river function has matured, so too have the expectations for water resource management. The terms used to describe flow protection have evolved to keep pace: from minimum flows to "instream flows" and, today, "environmental flows." The term "environmental flows" reflects current understanding that river ecosystems and processes are maintained by a diverse range of flow levels and events—commonly referred to as a "flow regime"—including high flows that extend beyond the river channel (Poff et al., 1997).

The science and practice of environmental flows have also evolved; a review by Tharme (2003) described more than 200 environmental flow assessment methods in use, with the types and application contexts ever advancing (Arthington, 2012; Poff et al., 2017) and Konrad et al. (2011) evaluated more than 100 monitored environmental flow experiments. Following this maturation of the science and technical sophistication of environmental flow assessment, water managers and regulators are now confronted with a multitude of assessment options. Hirji and Davis (2009) report that uncertainty over methods has contributed to slow implementation of environmental flows. Further, it has become recognized that the specific method selected to define environmental flows is an important factor determining whether or not environmental flows are subsequently implemented (Warner et al., 2014).

In this paper, we introduce a framework for environmental flow assessment and implementation intended to reduce uncertainty over methods and help address several other constraints to implementation. Rather than prescriptively answer which flow assessment methods are "best," we describe a flexible and iterative framework through which methods are selected based on the specific context, resource and data availability, and the level of certainty required. Throughout the framework, processes for flow assessment and implementation are explicitly linked. The framework is intended to match methods to resources and to develop flow recommendations that are appropriate for the management context, increasing the likelihood of implementation.

In recent years, environmental flow practitioners have advocated system-scale holistic assessments to dramatically increase the number of rivers which have flow recommendations in place (Poff et al., 2010; Kendy et al., 2012) and to catalyze greater implementation (Poff et al., 2017; Opperman et al., in review). The framework described here can be applied at both site-specific and regional scales.

Environmental Flows: Evolution of Assessment and Challenges to Implementation

Environmental flow management requires the application of methods to define environmental flow requirements and for these requirements to be integrated within water resources management (LeQuesne et al., 2010). The four main categories of methods that were evident early on, namely hydrologic (predominantly desktop), hydraulic, habitat simulation, and holistic methods (Tharme, 2003; Annear et al., 2004) remain in use today (Poff et al., 2017). A common limitation associated with many of the most widely used hydrologic, hydraulic and habitat simulation methods, typically inherent in their design or the nature of their implementation, is that they tend to produce a single flow level or a narrow set of flow levels (Hatfield and Paul, 2015; Poff et al., 2017).

In part because of the narrow representation of flow variability in many common environmental flow methods, "holistic" approaches emerged in the 1990s (Tharme, 2003). Examples include Downstream Response to Imposed Flow Transformations (DRIFT; Arthington et al., 2003) and Building Block Methodology (BBM; King and Louw, 1998; King et al., 2008). Holistic approaches seek to protect or restore a diverse set of socially and ecologically important river resources and processes across the full spectrum of low flows to flood events characterizing a river's flow regime within and between years. Holistic methods were originally developed to be deployed in river basins for which data were limited and were intended to produce more scientifically credible results than simple hydrologic desktop approaches.

In 2007, the Brisbane Declaration called on governments and other decision makers to support widespread assessment of flow needs and to integrate environmental flows into water management (Brisbane Declaration, 2007). Ten years later, practitioners are still seeking to apply flow assessment and flow restoration or protection more broadly (Acreman et al., 2014; Harwood et al., 2017). Reviews of environmental flow implementation (Hirji and Davis, 2009; Horne et al., 2017) have found several consistent obstacles that constrain implementation, including: (1) maintaining political and stakeholder support for implementation; (2) institutional inertia within agencies that manage water; (3) matching flow assessment methods to the regulatory and social context; (4) cost; and (5) marshaling capacity and expertise.

The three-level framework, described in the following section, is specifically intended to address some of the obstacles that have slowed application of both assessment and implementation. It was developed based on experience with a set of processes (featured in this paper as case studies) in which flow assessment has led to implementation of flow recommendations through changes in management and/or policy.

THREE-LEVEL FRAMEWORK FOR ENVIRONMENTAL FLOW ASSESSMENT AND IMPLEMENTATION

To be effective, an environmental flow assessment must address three primary challenges. First, rivers are extremely complex ecosystems and a broad range of climate-driven flow levels and events is necessary to maintain the river ecosystem's diverse components, including fish, birds, invertebrates, channel morphology, riparian vegetation, and river-floodplain connectivity. Human dependencies on the river ecosystem—ranging from fishing and flood-dependent agriculture to spiritual activities—are coupled with these ecosystem components. The second challenge is that, to effect any change, environmental flow recommendations must actually be implemented within complex and often contentious river management contexts (Horne et al., 2017). Finally, the level of complexity of the environmental flow assessment must be tailored to the financial resources available.

The first challenge suggests that environmental flow methods must be sufficiently comprehensive and holistic (Poff et al., 1997; Richter et al., 1997)—that is, the methods must address a range of flow levels and events and consider diverse resources and processes that are characteristic of, and important to, that river system. Methods focused on single species or minimum flow levels fail to capture the complexity of relationships between flow and the processes through which rivers produce a range of ecosystem services. The other two challenges suggest that environmental flow assessment methods must be tailored to the specific management context and must produce recommendations that can be understood, appreciated, and implemented by water managers, and supported by the public. Taken together, all three challenges emphasize that there is no single method that will work best in all situations and that methods must be selected and implemented based on a range of factors, including the specific geographic context (e.g., spatial scope, type of resources at stake), the availability of data and funding, and the level of certainty required.

Here we describe a three-level framework for developing and implementing environmental flows in the pursuit of ecologically sustainable water management (*sensu* Richter et al., 2003). Tharme (1996), Arthington et al. (2003), and Poff et al. (2017), among others, recommend that practitioners apply a hierarchical approach to environmental flow assessment. This framework builds on that recommendation, with steps to promote implementation embedded throughout the hierarchy.

While the three levels vary in their intensity and complexity (**Table 1** and **Figure 1**), each can be considered holistic because each level explicitly addresses a range of flow levels and events and encompasses diverse value sets, riverine resources/assets, and processes. The framework can be used for environmental flow assessment and implementation in diverse settings, from rivers or regions with relatively few data to those with extensive data. The specific assessment methods used within this framework systematically progress in complexity, from relatively simple desktop methods to resource-intensive approaches that require significant modeling capacity and the collection of new data.

The key characteristics of this framework include:

- The framework is iterative such that higher levels are deployed only to the extent they are necessary, and information generated at one level identifies the need, and provides the foundation and priorities, for higher levels. Funds for data collection and/or research and modeling are invested strategically to address the most important issues and reduce the most important uncertainties first.
- Processes for flow assessment and flow implementation are coupled. Many of the key characteristics of the assessment process are used to design and initiate flow implementation—through mechanisms such as caps on withdrawals or experimental flow releases from a dam (Horne et al., 2017)—as soon as possible. This early implementation is critical for generating both learning opportunities and support for further investment, if needed. To facilitate this linkage between assessment and implementation, scientists should work with water managers to the greatest extent possible throughout the process, in settings that encourage collaboration, knowledge sharing, and problem solving (e.g., see Acreman, 2005).

The three levels can be viewed as sequential steps but, in some cases, a lower level may address a management need and lead toward implementation without requiring a higher level (**Figure 1**). In many cases, opportunities exist to implement one or more flow recommendations immediately, while various constraints and/or uncertainties prevent other recommendations from being implemented without further analysis and refinement. Thus, flow assessments at each level of the hierarchy can potentially generate one or more recommendations that can be implemented (and monitored) quickly while also focusing subsequent, higher-level assessment on resolving the constraints and/or uncertainties that impede implementation of the remaining flow recommendations.

In the following sections, we describe each of the three levels and, to illustrate that the framework can be applied at a range of scales, provide examples of both river-specific and regional-scale applications. For regional applications, such as water resource planning, water withdrawal permitting, and basin-wide dam operations, we draw on the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al., 2010; Arthington, 2012; Kendy et al., 2012) which can be used within widely differing governance and management systems (Pahl-Wostl et al., 2013). The ELOHA is a flexible framework for determining and implementing environmental flows for all the rivers within a region using existing hydrologic, geomorphological, biological, and social information (Jackson et al., 2014; Poff et al., 2017). Its premise is that although every river is unique, many exhibit similar morphological and ecological (or social) responses to flow alteration. By assessing existing information for groups of similar rivers with varying degrees of hydrologic alteration, scientists can quantify relationships between flow and resources for different river *types*, which inform the environmental flows needed to meet objectives for river conditions.

TABLE 1 | Characteristics of the three levels of flow assessment and implementation.

Level of environmental flow assessment and implementation	Degree of confidence required	Cost	Appropriate application
Level 1—holistic (eco)hydrologic desktop	Low	Low (e.g., <USD 10,000)	Precautionary, first-cut flow recommendations for planning
Level 2—holistic expert panel	Moderate	Moderate (<USD100,000)	Opportunities exist to protect or experiment with flow regime (i.e., some degree of operational or management flexibility)
Level 3—holistic research-driven	High	High (e.g., >USD 100,000)	High degree of certainty is required before changes in flow management or policy can be considered
Implementation and adaptive management		Budget is variable; sustainable budget needed for monitoring	All situations should result in implementation, monitoring, and adaptive management.

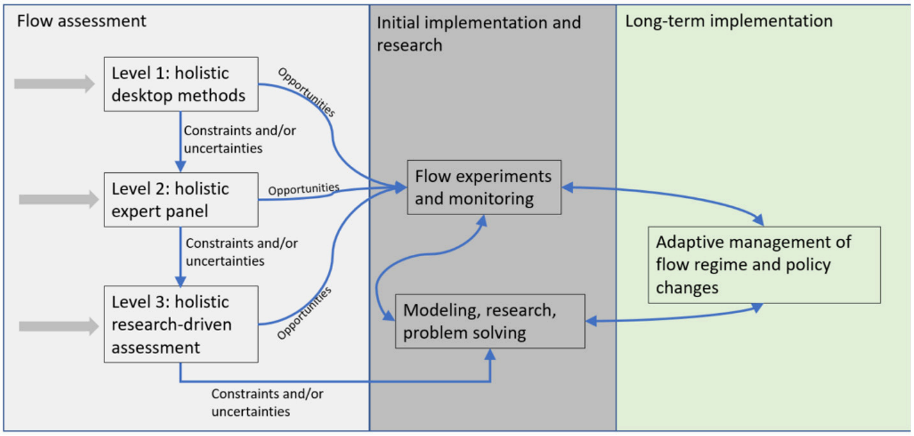

FIGURE 1 | Three-level framework for environmental flow assessment and implementation. Levels are selected based on the specific geograhpic context (e.g., spatial scope, type of resources at stake), the availability of data and funding, and the level of confidence required of the flow recommendations. The levels can stand alone (thick gray arrows indicate alternative entry points) or levels can be sequential (vertical sequence from Level 1 to 3). All levels have the potential to produce flow recommendations that can be implemented through collaboration with water managers (arrow marked "opportunities" leading to "flow experiments").

Level 1: Holistic Hydrologic Desktop Methods

A Level 1 approach is appropriate for developing initial flow recommendations for a river or for regional planning and preliminary standard setting. This level also serves to provide the information foundation for higher level approaches. In this framework, a Level 1 application can be considered a "desktop" method, in that new data are not collected and it can be conducted by a small team. However, it strives to be far more holistic than common hydrologic desktop methods, many of which feature "look-up tables" to define a flow level (e.g., a percent of mean annual flow). While these "look-up" desktop methods are quick and inexpensive, they generally provide overly simplistic flow levels that do not fully account for river functions and processes. Below we describe how a Level 1 (desktop) approach can incorporate elements of holistic methods.

A holistic hydrologic desktop approach synthesizes two primary sources of information: (1) hydrologic data—typically measured or modeled daily or monthly streamflow; and (2) basic principles of biophysical processes of rivers, augmented with the known linkages between the flow regime and key riverine resources. In the absence of specific information on a focal river, practitioners can draw on broader literature with an emphasis on information relevant to similar river types (e.g., in terms of geomorphology, drainage area, valley characteristics) and ecosystems. What advances a holistic desktop approach beyond simple "rules of thumb" is the application of this review to the hydrological analyses to develop recommendations quantified across the full flow regime, often using ecologically relevant low flow and high flow indices, in contrast to a single, or seasonally variable, minimum flow. In at least one case, a holistic desktop method directly incorporates geomorphic and ecological sub-models (Hughes et al., 2014).

An example of a hydrological analysis tool that can support a comprehensive hydrologic desktop approach is the Indicators of Hydrologic Alteration (IHA; Richter et al., 1996; The Nature Conservancy, 2009). The IHA calculates 67 ecologically relevant flow statistics from a hydrologic record of daily flow values

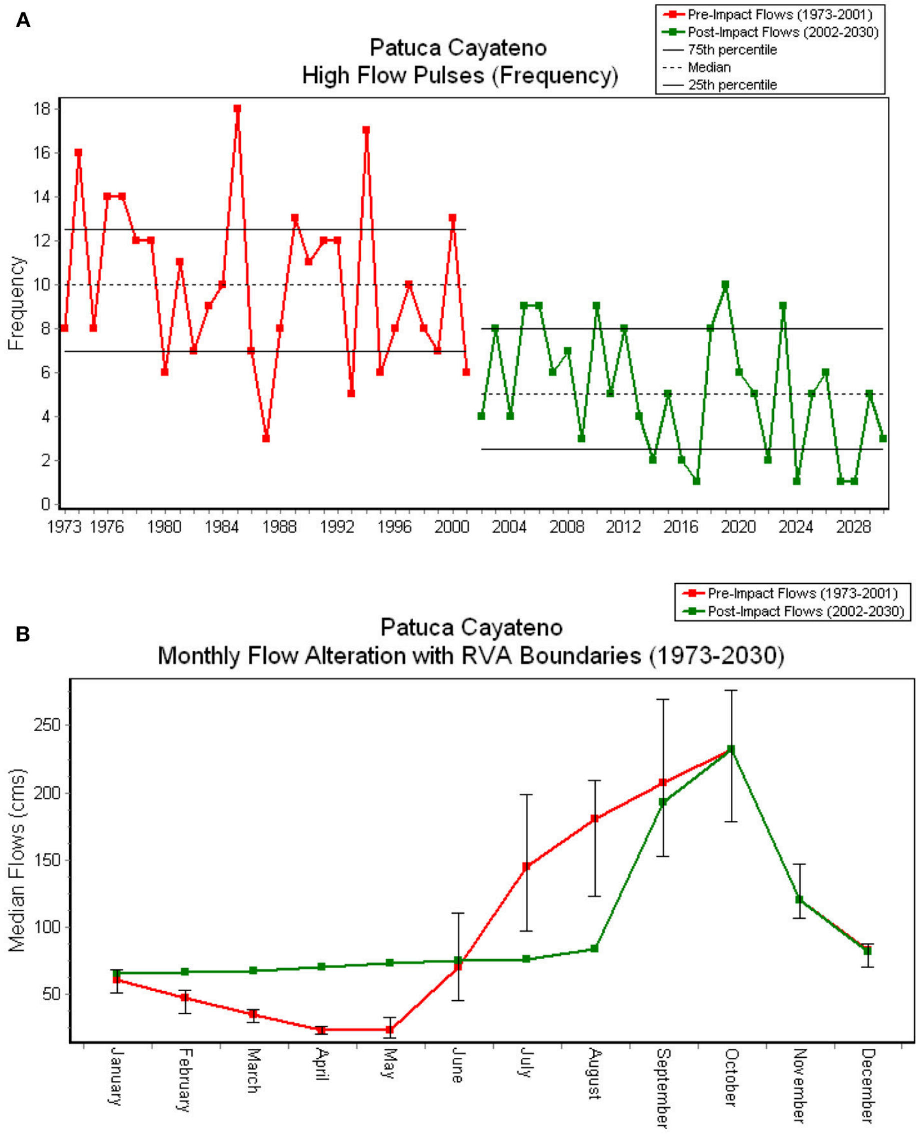

FIGURE 2 | Output from the software Indicators of Hydrologic Alteration (IHA) for the Patuca River, Honduras. The red lines show natural ("pre-impact") flows from 1973 to 2001 while the green lines show the "post-impact" flows. Note that in this case the dam on the Patuca River has not been built yet and the "post-impact" flows are actually the same flow data set (1973–2001) run through a model simulating flows with dam operations. Thus, the years 2002–2030 do not actually represent future years but are given those dates because of how IHA processes data. Panel **(A)** shows that the dam will reduce the frequency of high-flow pulses from ~10 per year to 5 per year because the reservoir will be refilling during the initial onset of the rainy season (June through August), as shown in **(B)**, when high-flow pulses tend to occur. Flow recommendations were developed based on these hydrological analyses combined with a literature review on tropical lowland rivers and an expert panel workshop (Esselman and Opperman, 2010).

(**Figure 2**) (Richter et al., 1996, 1997). IHA can categorize flow levels into "environmental flow components" (EFCs), which include large floods, small floods, high-flow pulses or freshets, low flows, and extreme low flows (Mathews and Richter, 2007). The U.S. Geological Survey (USGS) has developed similar hydrologic analysis software called Hydrological Assessment Tool (HAT; Cade, 2006). Although HAT and IHA do not directly generate environmental flow recommendations, their calculation of flow metrics, informed by a literature review of the linkages between the flow regime and river processes, can form the basis of a Level 1 environmental flow assessment (Richter et al., 1997).

In Texas, the EFC algorithm of IHA was used to develop the Hydrology-based Environmental Flow Regime (HEFR) method for establishing first-approximation environmental flow recommendations. The recommendations are expressed in terms of the magnitude, frequency, duration, timing, and rate of change of subsistence flows, high flow pulses, base flows, and overbank flows (Texas SB3 Science Advisory Committee, 2011). In South Africa, the Revised Desktop Reserve model is a desktop approach that moves beyond hydrology to also include linked sub-models for hydraulics and ecology to produce low flow recommendations (with a simpler approach for high flow recommendations) (Hughes et al., 2014). An ELOHA study (described below) can provide relevant information on linkages between flow and resources for rivers in the focal region. Thus, the ELOHA results can inform a Level 1 process for a river within that region and could potentially provide precautionary flow recommendations.

Hydrologic desktop methods are equally amenable to site-specific and regional applications, because the same simple, robust algorithms can be used for both. For example, a major advantage of HFER for regulatory use is its consistent application across all rivers in Texas (Texas SB3 Science Advisory Committee, 2011). Richter et al. (2011) suggested a precautionery and regime-based desktop calculation of initial flow recommendations, expressed as the allowable degree of alteration in daily flow magnitude. With minimal computational effort, this "presumptive standard" approach maintains natural flow variability within a "sustainability boundary." Richter et al. (2011) note that, in the absence of a more rigorous flow assessment, this boundary can serve as a precautionary preliminary flow recommendation and, because of its simplicity, can be applied at regional scales.

In situations with low risk or controversy and/or immediate need for guidance, a Level 1 assessment could produce flow recommendations that lead to preliminary withdrawal limits or to experimental flow releases from reservoirs (see Green River case study below). An important role of a Level 1 assessment could be to spur dialogue between river scientists and water managers, providing a foundation for generating further interest and funding for higher level assessments, if needed.

A Level 1 Flow Assessment and Subsequent Implementation at the Green River

The Green River, a tributary to the Ohio River in Kentucky (USA), supports high levels of freshwater species richness including 151 fish species (12 endemic) and 71 mussel species. The Nature Conservancy and the US Army Corps of Engineers ("the Corps") began collaborating in 1998 to determine strategies for restoring the flow regime below Green River Dam, a multipurpose dam operated primarily for flood control (this collaboration led to the Sustainable Rivers Program, described below). Work on the Green River began as a Level 1 effort, with initial flow recommendations developed through a hydrological analysis using IHA combined with insights on the relationships between flows and river processes gleaned through discussions with a small group of biologists familiar with the river. The biologists were specifically asked to articulate important life stages and the associated seasons—with as much temporal specificity as possible—and habitat requirements for a diversity of species native to the Green River system. Through this process, the team generated a set of flow recommendations to present to reservoir operators.

Water managers within the Corps analyzed their operational flexibility and found that, by adjusting the timing and rate of filling and drawdown, they could meet important components of the environmental flow recommendation. Note that although the flow recommendations were developed through a Level 1 process, the evaluation of how to integrate those recommendations into water management required modeling of reservoir operations. The Corps began to implement new operations that achieved environmental flow objectives in 2002 and this new operation scheme was formalized with a revision to the dam's Water Control Manual in 2006 (**Figure 3**; Konrad et al., 2012; Warner et al., 2014).

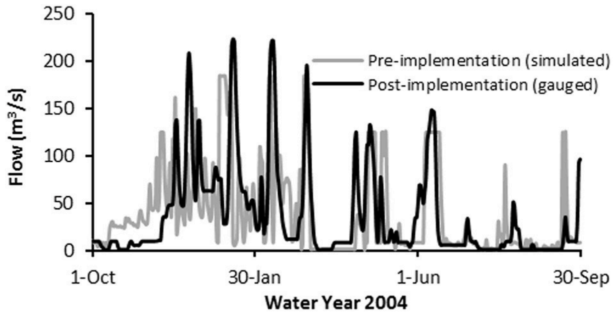

FIGURE 3 | Flow regime on the Green River below the Green River Dam following implementation of environmental flows ("Post-implementation") compared to the flow regime produced by previous operations ("Pre-implementation"). The post-implementation hydrograph comes from gauged data whereas the pre-implementation hydrograph was modeled by applying the previous operation scheme to the same gauged flow data. From Warner et al. (2014).

Level 2: Holistic Expert Panel Environmental Flow Assessment

A Level 2 process is centered around an expert panel assessment. This level still does not require new data collection to generate flow recommendations, but can draw on considerably more information than does a Level 1 process. Using expert panels, flow recommendations are developed through professional judgment supported by literature review and quantitative analysis of existing data, including the types of analyses conducted during a Level 1 process.

Numerous flow methods feature expert panels, including the Building Block Methodology (King and Louw, 1998; King et al., 2008), Downstream Response to Imposed Flow Transformations (DRIFT) (Arthington et al., 2003; King et al., 2003), and the Savannah Process, so called because it was first used on the Savannah River (Georgia and South Carolina, USA) (Richter et al., 2006). A Level 2 process can be conducted in places with very limited existing data (e.g., see Esselman and Opperman, 2010) to places with extensive existing data (e.g., on flows, water quality and fisheries).

While results from a process relying on expert judgment are not as replicable as those from a quantitative model, such as PHABSIM, Kondolf et al. (2000) suggest that such models "only give the illusion of objectivity because [they] always involve simplifying assumptions" and that model output should be combined with professional judgment. Similarly, Castleberry et al. (1996) suggest that quantitative models should not "substitute for common sense, critical thinking about stream ecology, or careful evaluation of the consequences of flow modification." Most importantly, expert panels expediently fill knowledge gaps for ecosystem components for which sufficient data to rigorously quantify flow relationships are lacking. For example, whereas comprehensive data on fish populations exist in many places, flow-related data for aquatic vegetation are rare. The credibility and replicability of expert panels can be increased through structured processes with diverse participants representing the range of stakeholders, as opposed to *ad hoc* contributions (Dyson et al., 2003; Acreman, 2005), and through structured pre-workshop literature review using a weight-of-evidence approach to assess the strength of hypothesized flow-resource relationships (Taylor et al., 2013). Cottingham et al. (2002) recommend a set of "best practices" for ensuring the defensibility of expert panel approaches.

The primary steps of a Level 2 process are summarized in **Table 2**. While these steps correspond most closely to processes focused on implementing flow changes in one to a few rivers, the process for a regional-scale Level 2 process can be quite similar. After discussing the steps of a river-focused process, we then describe some of the distinct steps for a regional Level 2 process intended to inform policy, such as setting standards for a state's water withdrawal permitting process.

Participants for the expert panel flow workshop should be drawn from a broad range of disciplines, encompassing biophysical sciences as well as those who understand the linkages between flows and the cultural, economic and recreational values of the system. Within a workshop (step 3), participants are tasked with developing a set of flow recommendations. Importantly, each recommendation is framed as a hypothesis or set of hypotheses that describe the resources or processes supported by each flow component, including the relationship between flow and cultural or recreational resources (**Tables 3**, **4**). Throughout the workshop, participants identify uncertainties and, during the final discussion, develop a set of research priorities. The uncertainties, research priorities and flow-ecosystem hypotheses inform subsequent research, modeling and analysis. For example, a recommendation for a small flood may be hypothesized to provide fish access to and use of floodplain habitats for spawning. The flow recommendation should include various hydrological parameters (e.g., 300 – 400 cms for a duration of >3 weeks during April–May) that are hypothesized to provide the appropriate conditions for this process to occur, and participants should identify their confidence in these parameters. If a better understanding of this linkage is identified as a research priority, subsequent research and modeling can then focus on these processes and refine the estimates of the flow parameters that support them. Of critical importance is how data gaps and uncertainty are managed during the workshop. Specifically, gaps in knowledge are recognized and captured, but do not prevent a quantified flow recommendation from being developed (Warner et al., 2014).

The steps provided in **Table 2** are primarily based on environmental flow assessment and implementation projects conducted under a partnership, the Sustainable Rivers Program (SRP), between TNC and the U.S. Army Corps of Engineers following the "Savannah Process" (Postel and Richter, 2003; Richter et al., 2006). The Corps is the largest dam owner and

TABLE 2 | Steps in a level 2 process.

Step	Description
1. Orientation workshop	A workshop for stakeholders and potential contributors; the organizers describe the forthcoming process and primary objectives, and ask stakeholders to suggest additional participants and sources of data and information. This meeting also initiates the dialogue on specific objectives.
2. Build the information base	This second step encompasses the key components of a Level 1 process—the hydrological analysis and literature review, generating a summary report with information on hydrological patterns, including hydrological alteration, and a review of research and data available for the river basin with an emphasis on the linkages between the flow regime and important biophysical processes. Distributed in advance of the expert panel flow workshop.
3. Expert panel flow workshop	The flow workshop includes participants from a broad range of disciplines (e.g., river and riparian ecologists, hydrologists, geomorphologists, fisheries and wildlife biologists, and social scientists who understand cultural, economic and recreational values of the system) drawn from a spectrum of organizations—academia, private sector, non-governmental organizations, and resource agencies representing Federal, Tribal, state and local governments. The objective of the workshop is to recommend a comprehensive environmental flow regime.
4. Dialogue with managers	Scientists and practitioners begin a dialogue with water managers and users about the feasibility of implementing the various initial flow recommendations. Through this dialogue, scientists and water managers identify opportunities for initial changes to operations that can serve as experimental releases and flow recommendations that cannot be implemented without further study or due to various constraints (**Figure 1**).
5. Initial operational changes and flow experiments	Relatively rapid implementation of at least a sub-set of recommended flow components that are clearly feasible within current operational requirements.
6. Targeted research and modeling	To resolve uncertainties or to find solutions to implementation constraints, participants can develop a research and modeling program. Developing this program will generally require additional funding and moves the process toward Level 3.
7. Long-term implementation, monitoring and adaptive management	To be durable, an environmental flow program must move beyond initial recommendations and experimental implementation and toward long-term implementation. This will generally require that the new flow regime be articulated within the policies that govern water management for that river. Sustainable funding will likely be required to ensure ongoing monitoring and adaptive management.

TABLE 3 | A sample of the initial flow recommendations from a Level 2 process for the Middle Fork of the Willamette River (Warner et al., 2014).

Environmental Flow Component (EFC)	Hydrological characteristics	Related ecosystem functions
Low flow levels for Chinook spawning	*Magnitude*: 1800–2500 cfs *Frequency:* every year *Duration:* Following spawning, flows must remain at level that occurred during spawning, or somewhat higher, until eggs have hatched and juvenile fish have left the spawning gravels *Season:* September and October	• Provide sufficient flows to support incubation of eggs • Avoid stranding of redds (locations of deposited eggs within gravel)
Spring flow pulses	*Magnitude:* 4,000–15,000 cfs *Frequency:* 1–5 per year, based on precipitation events *Duration:* Mimic duration of unregulated events *Season:* March 1–July 1	• Provide flows for downstream migration of juvenile salmon and smolts • Create lateral habitats on floodplain margin • Disperse seeds and establish cottonwood seedlings • Smooth transitions after winter high flows are required for aquatic species to move between lateral refuges
Floods	*Magnitude:* 25,000–40,000 cfs *Frequency:* Once every two years *Duration:* Approximately two weeks *Season:* November 15–March 15	• Transport sediment and create new pools and riffles • Create new floodplain surfaces through overbank erosion and deposition • Create new floodplain surfaces through bar development • Create surfaces for regeneration of cottonwood and other riparian trees

Note that each recommended environmental flow component (EFC) is expressed in terms of magnitude, frequency, duration and season. Also, each EFC is associated with a set of 'related ecosystem functions' that the particular EFC is hypothesized to support.

operator in the USA, and more than 60 of the agency's 700 dams are now included in the SRP. The implementation occurring at several SRP sites demonstrates the value of involving water managers—those who manage the dams whose operations would need to change to implement environmental flows—in key points in the assessment process to facilitate subsequent implementation (Warner et al., 2014; Harwood et al., 2017).

Water managers, such as dam operators, are generally involved in the first three steps, but the integration of flow science and assessment with water management is most pronounced in the subsequent steps. Following the expert panel workshop, the flow recommendations are discussed by a group of scientists and water managers (step 4). Water managers can generally place the flow recommendations into three categories: (1) those that can be implemented feasibly within current authorities and obligations ("opportunities"); (2) those that may require additional research and modeling prior to implementation (e.g., flood routing analysis to determine what levels of high flows can be released without causing flood damages); and (3) those that would require major changes—in physical conditions or authorities, policies, water rights or contracts—to overcome constraints (Bach et al., 2007). For example, a dam may not be able to release a recommended high-flow pulse without engineering changes or an agency may not be able to restrict water withdrawals during non-drought periods without regulatory changes.

Flow recommendations identified as "opportunities" can potentially be implemented relatively quickly (step 5). The rapid implementation of a portion of the recommended flow regime provides dam operators with experience making operational changes to implement flows and can generate important publicity and awareness for the environmental flow process. Further, if coupled with a monitoring program, these actions provide scientists with an opportunity to study how processes and ecosystems respond to management changes. Most of the SRP sites have initiated early implementation of some components of the recommended flows, as illustrated for the Bill Williams River case below.

Additional research and/or modeling are generally required to resolve uncertainties or find solutions to overcome the constraints that prevent implementation of other components of the flow recommendation (step 6), another step where scientists and water managers should collaborate effectively. While this step likely requires securing additional budget, note that it does not necessarily require establishment of a distinct research program, as in a new entity within a single institution. Rather, the research program can instead be advanced through improved coordination of efforts and resource allocation across institutions involved in the environmental flow project (Warner et al., 2014). For example, a number of sites with the SRP—such as the Bill Williams (Arizona) and Big Cypress/Caddo Lake system (Texas/Louisiana)—have established technical working groups that meet 2–4 times per year to coordinate upcoming environmental flow implementation, monitoring and research priorities, and associated resource commitments.

To be durable, an environmental flow program must move beyond initial recommendations and experimental implementation, and the new flow regime must be articulated within the policies that govern water management for that river. For example, the operations of each Corps dam are guided by a Water Control Manual. Until the Water Control Manual has been revised to incorporate environmental flows and associated adaptive management activities, the new flow regime is essentially experimental and temporary. The Green River case

TABLE 4 | A sample of the flow recommendations from a Level 2 process for all small rivers (drainage areas of 130 – 500 square kilometers) in the Great Lakes catchments of New York and Pennsylvania, USA.

Environmental Flow Component (EFC)	Hydrological characteristics				Related ecosystem functions
	Summer	**Fall**	**Winter**	**Spring**	
High flows *Annual/Interannual (≥bankfull)* *High flow pulses (<bankfull)*	**All seasons** • Maintain magnitude and frequency of 5-year (small) flood • Maintain magnitude, duration of channel forming (1 to 2-year) events **All seasons** • <10% change to the magnitude of high flow pulses (monthly Q_{10}) • No change to the frequency and duration of high flow pulses (monthly Q_{10})				• Recruit woody debris • Maintain ice scour for dynamic floodplain vegetation • Cue reproduction for riffle-associate fishes • Maintain channel morphology
Seasonal flows	**All seasons** • <10% change to upper seasonal flow range (between the monthly Q_{10} and Q_{50}) • <10% change to monthly Q_{50} **Summer and Fall (July–Oct)** • <10% change to lower seasonal flow range (between monthly Q_{50} and Q_{70})		**Winter and Spring (Nov–Jun)** • <10% change to seasonal flow range between monthly Q_{50} and monthly Q_{80}		• Sustain fluvial fish abundance in the summer • Prevent fish assemblage summer • Prevent fish assemblage shift from fluvial specialists to habitat • Sustain benthic insectivore populations in the summer • Stimulate movement and maintain access to upstream spawning habitats for migratory salmonids in the fall the fall • Maintain extent of available spawning habitat for riffle associates in the spring
Low flows	**Summer and Fall (July–Oct)** No change to low flow range (between monthly Q_{70} and Q_{99})		**Winter and Spring (Nov–Jun)** • No change to low flow range (between monthly Q_{80} and Q_{99})		• Avoid dewatering channel margins and exposing mussel habitat • Maintain extent of riffle habitat

Note that each recommended environmental flow component (EFC) is expressed in terms of magnitude, frequency, duration and season. Also, each EFC is associated with a set of 'related ecosystem functions' that the particular EFC is hypothesized to support. Hydrologic characteristics are expressed as relative, rather than absolute, values so they can be applied to any river. Adapted from Taylor et al. (2013).

study, above, provides an example of how a new flow regime was formalized through changes to a dam's Water Control Manual.

Richter et al. (2006) offers an extended case study of a Level 2 process for the Savannah River (Georgia, USA), including the structure of the expert panel workshop and the process of initial implementation. Esselman and Opperman (2010) provide an example of how this process was adapted to a river—the Patuca, in Honduras—with extremely limited existing data or information, combining a study of Traditional Ecological Knowledge with an expert panel workshop to develop flow recommendations. Warner et al. (2014) provide an overview of the SRP and a series of Level 2 processes that linked flow assessment with implementation.

Level 2 for Regional Standards to Inform Policy

A Level 2 process at the regional scale, intended to inform policies such as water withdrawal permitting, can follow much of the sequence for river-specific processes described above and in **Table 2**. Importantly, an expert panel process, augmented by literature review and analyses of existing data, can provide a mechanism to synthesize diverse information to guide a set of recommendations, corresponding to steps 1–3 above. Instead of developing flow recommendations for a single river, the panel recommends environmental flow criteria for different *types* of rivers within a basin or region. Discussions then could be held with operators of dams across the region, to explore opportunities for implementation, although more likely the dialogue with managers (step 4) will be conducted with those who will implement or regulate the policy at a regional scale. Similar to a river-specific process, it may be possible to implement some recommendations—such as protection of high flows—immediately (corresponding to step 5), while further research or problem solving (step 6) may be required before other recommendations can be integrated into policy or management, thus elevating the assessment to Level 3. For example, studies on how low-flow protections might impact water users (e.g., Buchanan et al., 2016) may be required before low-flow protections are integrated into policy. The case study below for the Susquehanna River basin (USA) illustrates how a Level 2 process can lead to the adoption in policy of some flow protection standards.

A Level 2 Process to Set Basin-Scale Flow Policy for the Susquehanna River Basin

A Level 2 approach was used to develop environmental flow recommendations simultaneously for all rivers and streams within the 72,000-square-kilometer interstate Susquehanna River catchment, USA. Through consultations with experts, a technical team assembled a broad list of ecological indicators, including flow-sensitive taxa groups, vegetation community types, and physical processes. A basic habitat classification based on watershed size, temperature, and flow stability was developed for organizing and synthesizing information. Based on hydrologic desktop analysis, the technical team defined monthly high, seasonal, and low flow components for each major habitat type. The technical team then surveyed scientific literature to find dependencies between these indicators and specific flow components and, where possible, to extract relationships between flow alteration and ecological response. Using species distribution data and expert consultations, they associated species groups with major habitat types and described common traits and microhabitat preferences for each species group.

The vast array of ecosystem flow needs convinced the project team that it needed to develop environmental flow recommendations for many different taxa for each major habitat type—even those that lack large databases. Rather than assume that a single species or group of species can represent all ecosystem needs, the team based its flow recommendations on (a) existing literature and studies that described and/or quantified relationships between flow alteration and ecological response, (b) expert input, (c) the analysis of long-term flow variability at minimally-altered gages, and (d) results of water withdrawal scenarios that tested the sensitivity of various flow statistics (DePhilip and Moberg, 2010).

The resulting low flow policy, adopted by the Susquehanna River Basin Commission (http://www.srbc.net/policies/lowflowpolicy.htm), avoids the use of a single annual minimum flow value for low flow protection and, instead, uses a series of seasonal or monthly values that more accurately reflect the seasonal variability of streamflow and associated ecosystem needs. However, additional rulemaking is needed to meet the high-flow recommendations that resulted from this Level 2 process.

Level 3: Holistic Research-Driven Flow Assessment

The descriptions of Levels 1 and 2, and corresponding case studies, indicate that a Level 3 research program will often be necessary to resolve uncertainties and overcome constraints to implementation. Thus, Level 3 will often be required for processes initiated at lower levels. As Level 3 will often require a significant budget, this framework suggests that lower levels can be carried out first because they may lead to some changes to operations or policies relatively quickly and these changes can initiate ecosystem restoration, provide an opportunity for learning and potentially increase the profile and support for the assessment and implementation process—thus helping to secure resources for Level 3.

In some situations, however, it will be most effective to begin the process at Level 3 (**Figure 1**), such as those that require a high degree of certainty before any operational changes can made. Such situations may include those where water is over-allocated and heavily contested, the presence of endangered species limits operational flexibility, defined policies dictate management, or binding (or nearly binding) long-term decisions are being made. In these situations, decision makers will require a higher degree of analytical rigor before initiating an environmental flow program. Thus, a Level 3 process is characterized by greater up-front investment in more sophisticated methods for examining tradeoffs and predicting results from operational changes or flow allocation rules.

We recommend that a Level 3 process retain many of the features of Level 2 that are intended to develop collaborative relationships—facilitating subsequent implementation—and target research funds to the most important issues. Thus, a Level 3 process can share many steps with a Level 2 process. For example, a Level 3 process can include workshops to identify key questions, priorities, and sources of existing information and expertise, so that the subsequent research program does not duplicate previous efforts. Similar to a Level 2 process, these steps focus on identifying which environmental flow, research and modeling methods are most appropriate for the specific situation.

A Level 3 research program focuses on resolving uncertainties and undertaking the research priorities identified in expert workshops (whether that was a workshop initiated under the Level 3 process or under a lower-level process). Further, a Level 3 process should also provide opportunities for dialogue between researchers and managers to understand potential constraints so that the research program can also pursue alternative solutions. The technical methods employed during a Level 3 research program may include methods specifically designed to determine environmental flow needs (e.g., those reviewed by Tharme, 2003) but usually encompass a much broader range of analytical methods that are not typically considered "environmental flow" methods. These may include, for example, hydraulic models to study thresholds for floodplain inundation; models for water temperature, sediment transport, meander migration, or riparian recruitment; or monitoring of fish population movements. An environmental flow process on the Roanoke River (Virginia and North Carolina, USA) used a range of research tools and methods over a period of 20 years, including hydrologic and hydraulic models of floodplain inundation and an adaptive management program studying floodplain tree regeneration in response to changed flow regimes (Pearsall et al., 2005). The research program provided the basis for two agreements in 2016 that will formalize environmental flows on the Roanoke: a settlement agreement that will govern flows from a privately managed hydropower dam and a revision to a Water Control Manual for a dam managed by the Corps (Opperman et al., 2017).

Level 3 Research Program on the Bill Williams River (AZ)

The Bill Williams River, in western Arizona, is a tributary to the Colorado River. Alamo Dam was constructed on the river in 1968, primarily for flood control, and flow regulation from the dam dramatically decreased the frequency and magnitude of floods. The river's riparian corridor supports some of the last and largest remaining stands of willow-cottonwood forest in the lower Colorado basin, providing habitat for 350 bird species. To restore river and riparian habitats, TNC and the

Corps began to explore alternative flow regimes as part of the Sustainable Rivers Program and, in March 2005, the Bill Williams River Corridor Steering Committee sponsored an expert-panel workshop to develop environmental flow recommendations. Participants included 50 scientists and resource managers and were divided into three groups: (1) aquatics, with a focus on fishes and aquatic macroinvertebrates; (2) riparian system - birds; and (3) riparian system—terrestrial fauna (other than birds). Each group developed flow recommendations for floods and base flows, defined in terms of magnitude, timing, duration, frequency and rate of change, necessary to maintain the processes and biota in its respective system (e.g., aquatics). The three groups then reconvened and reached agreement on a unified set of flow recommendations (Shafroth and Beauchamp, 2006).

Following the workshop, the Corps released experimental floods in 2005, 2006, and 2007 (Hautzinger, 2007; Shafroth et al., 2010; Konrad et al., 2011, 2012). on the Bill Williams under the SRP began as a Level 2 effort, with environmental flows defined and select components (controlled floods) implemented within a matter of months. Building upon the initial few years of experimental releases and monitoring, work expanded into a Level 3 effort with agency and academic scientists organizing a multi-institutional research program coordinated through the Bill Williams River Technical Steering Committee and designed to model flow recommendations and study the experimental floods, using a variety of models and field research techniques. Modeling capabilities of the system now encompass a reservoir operations model, one- and two-dimensional river hydraulics models to estimate stage–discharge relationships, a groundwater model to estimate surface- and groundwater interactions in a large, alluvial valley where surface flow is frequently absent and a coupled hydrology-ecology model (the Ecosystems Function Model), used to link a one-dimensional hydraulic model with riparian tree seedling establishment requirements in order to produce spatially explicit predictions of seedling recruitment locations (Shafroth et al., 2010).

As hypothesized during the environmental flow workshop, preliminary results have found that experimental floods were able to breach beaver dams, shifting the ratio of lotic to lentic habitat on the river closer to pre-dam conditions (Andersen et al., 2011). The floods also have resulted in proportionately much higher mortality among invasive *Tamarix* seedlings than native *Salix* saplings (Shafroth et al., 2010). Documenting these and other responses to controlled floods helps scientists and water managers refine the environmental recommendations for the Bill Williams River and inform its adaptive management, illustrating the value of a monitoring program.

DISCUSSION

Here we have proposed a flexible and iterative three-level framework for selecting appropriate holistic methods for assessing environmental flow needs within a process designed to simultaneously advance environmental flow implementation. This framework builds on earlier hierarchical methods and frameworks for participatory and collaborative environmental flow assessment.

The framework is intended to match the specific technical methods (and thus the cost and complexity of the assessment) with the highest priority research needs, the level of certainty required, and the level of resources available—and to move toward implementation as soon as possible. For example, if a dam that controls a river flow has considerable operational flexibility, then a Level 2 approach can relatively quickly produce flow recommendations that initiate experimental releases. These changes in the dam operations provide excellent opportunities for learning from real-world flow experiments as well as giving the dam operators experience with adjusting flows to support river ecosystem health, and giving scientists experience with monitoring to learn from flow implementation (Olden et al., 2014). In some cases, such as when releasing a prescribed flood, publicity generated around the flood release can raise awareness about the environmental flow program (e.g., Kendy et al., 2017).

The integration of environmental flow protection into water management in Mexico illustrates how a hierarchical approach to setting environmental flows can promote early implementation. The Mexican environmental flow standard was published in 2012 (Secretaría de Economía., 2012) and ratified in 2017. The standard includes a three-level hierarchical approach for environmental flow assessments: hydrological methods for the planning level, holistic methods for river basins where potential social or ecological conflicts are present, and methods that incorporate new data collection and hydrological and ecological modeling to inform decision making in basins where new infrastructure is proposed and thus greater certainty is required. Based on desktop analyses, Environmental Water Reserves (EWR) were proposed for 189 basins, covering 40% of national territory, with high conservation value and low potential for conflict over water (Barrios et al., 2015; Opperman et al., in review). In contrast, detailed studies of hydrology, sediment transport, and economics were conducted to explore potential conflicts between an EWR and a proposed hydropower dam on the San Pedro River. These studies demonstrated that operation of the dam would not be consistent with the EWR and the dam was canceled (Harwood et al., 2017).

In addition to being scientific processes, Levels 2 and 3 have important social dynamics that are intertwined with the scientific components. The workshops for these levels are intended to encompass a broad range of expertise and stakeholders. By doing so, the assessment process captures previous knowledge and experience for the focal river or region, reducing the likelihood of redundant efforts. Assembling diverse experiences and judgments also can sharpen the critiques of flow recommendations and research plans, improving their clarity and credibility. The shared sense of ownership for the flow recommendations among multiple stakeholders can increase their credibility, likelihood of implementation, and durability.

The interactions between scientists, practitioners, and water managers occur throughout the process. This allows water managers to understand the objectives and rationale for an environmental flow program to a much greater extent than if they are simply presented with a set of flow recommendations at the completion of a scientific assessment process. These exchanges among scientists and water managers also promote an appropriate balance between modeling/research and applied learning through operational changes and empirical results. If the managers are able to suggest operational changes that can be accomplished relatively quickly, then scientists can move beyond modeling and begin learning from real-world flow experiments. Conversely, if the managers anticipate specific issues or concerns that may arise, then scientists can focus their analyses on resolving those uncertainties.

Most of the locations where this framework has been developed and applied are currently in various stages of environmental flow implementation or protection—ranging from experimental flow releases to long-term formalization of specific flow levels within policy (Konrad et al., 2011, 2012; Kendy et al., 2012). Warner et al. (2014) provided a summary of several of these locations and offered the following observations about characteristics of the processes that have followed this framework and implemented changes to flow management:

- The process to define environmental flows is fully and explicitly embedded within the broader process of water management decision making
- Water managers/engineers are integrated from the beginning into the process to define environmental flows
- Environmental flow recommendations are articulated in terms that are readily usable by water managers
- The process for defining environmental flows manages uncertainty and knowledge gaps, turning them from potential roadblocks into catalysts for implementation;
- The process of defining environmental flows is used to strengthen both the professional relationships and subsequent coordination between scientists and water managers/engineers, which contributes to improved scientific knowledge and is foundational to long-term implementation and adaptive management.

Implementation of environmental flows has yet to reach the levels that environmental advocates and water practitioners have strived to achieve (LeQuesne et al., 2010; Harwood et al., 2017; Horne et al., 2017). The framework introduced here is intended to address several of the challenges to implementation, including uncertainty about which methods are most appropriate, the cost of flow assessment, and a disconnect between flow recommendations and management realities. The flexible, hierarchical approach and the social features of this framework are intended to help overcome those challenges.

AUTHOR CONTRIBUTIONS

JO, EK, RT, AW, EB, and BR worked on projects that contributed to the development of the framework described in this paper. JO and EK wrote the first draft. RT, AW, EB, and BR provided edits and writing contributions.

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The remaining authors declare that the research was conducted in the the absence of any commercial or financial relationships that could be as a potential conflict of interest.