PLOS Water

RESEARCH ARTICLE

Developing environmental flows and metrics to quantify river ecosystem needs for regional water planning in Georgia, USA

Laura E. Rack[1*], **Mary C. Freeman**[1], **Gail Cowie**[2], **Carol Yang**[1], **Steven Kyle McKay**[3], **Laura S. Craig**[4], **Seth J. Wenger**[1]

1 Odum School of Ecology, University of Georgia, Athens, Georgia, United States of America, **2** Georgia Water Planning and Policy Center, Albany State University, Albany, Georgia, United States of America, **3** Woolpert, New York, New York, United States of America, **4** AKRF, Asbury Park, New Jersey, United States of America

* laura.rack@uga.edu

Citation: Rack LE, Freeman MC, Cowie G, Yang C, McKay SK, Craig LS, et al. (2026) Developing environmental flows and metrics to quantify river ecosystem needs for regional water planning in Georgia, USA. PLOS Water 5(2): e0000445. https://doi.org/10.1371/journal.pwat.0000445

Editor: Pierre Horwitz, Edith Cowan University - Joondalup Campus: Edith Cowan University, AUSTRALIA

Received: March 18, 2025

Accepted: December 21, 2025

Published: February 9, 2026

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pwat.0000445

Abstract

Effective water management requires the capacity to make trade-offs among diverse uses of water such as municipal water supply, irrigation, and ecological outcomes. Environmental flow management seeks to understand the relationships between river flows and ecosystem processes to evaluate the relative change in ecological outcomes associated with different strategies for river management. However, operationalizing ecological flow thresholds remains technically and administratively challenging, particularly at large scales. Here, we present a case study identifying environmental flow targets using the functional flows framework in the Oconee River Basin, Georgia, USA. Quantitative discharge thresholds are developed for five ecologically relevant flows addressing channel maintenance, floodplain connectivity, springtime pulses, reproductive season baseflows, and dry season baseflows. We demonstrate how these targets integrate ecosystem water needs into a broader state-level water planning process. Four themes emerge from this case study that are applicable in other geographies and contexts. First, environmental flow targets cannot be abstracted from their physical, ecological, and political geography, and context-specificity is critical to developing management-relevant flow targets. Second, quantitative environmental flow thresholds help establish ecological outcomes on equal footing with socio-economic uses of water in planning processes. Third, environmental flow frameworks should align with the management scope so that metrics also align with established evaluation criteria. Finally, decision makers should be provided with information to evaluate and interpret different outcomes for environmental flow targets alongside other water management targets. Despite these complexities, environmental flow analyses remain an essential tool to address the threats to freshwater ecosystems and biodiversity driven by human alteration, water use, and global change.

Data availability statement: We cited publications and theses we extracted data from, included links for reports or public databases to access reports, and provided contact information for references that are not publicly available in the citation list. Data was extracted from the following citations for the section 'Developing Metrics for Water Planning' and Table 2: 49, 50, 51, 53, 54, 55, 56, 57, 58. The following citations require database searches or an agency contact: 31. Yoe C. Trade-off analysis planning and procedures guidebook. Alexandria, VA: U.S. Army Institute for Water Resources; 2002. Contract No.: IWR Report 02-R-2. [Available by search at: https://iwrlibrary.sec.usace.army.mil or direct link: https://publibrary.sec.usace.army.mil/resource?title=Trade-Off%20Analysis%20Planning%20and%20Procedures%20Guidebook&documentId=fbee8a0d-16e1-4dcc-a6f1-8c69c8859b2f]. 57. EA Engineering S, and Technology, Inc.,. Georgia Power Company Sinclair License Application, Accession No. 19950914-0187, FERC e-library, Docket P-1951; 1995.[Available from: https://elibrary.ferc.gov/eLibrary/filelist?accession_number=19950914-0187&optimized=false&sid=68099c01-8ef8-48f2-8de9-955cc8f8b60f]. 38. ARCADIS. Methods for flow regime evaluation, Ocmulgee River, Georgia. prepared for Georgia Environmental Protection Division; 2019.[Report available by request from water.planning@dnr.ga.gov].

Funding: This work was supported by the Georgia Environmental Protection Division (Regional Water Planning Seed Grant - 761-230117 to GC, with funding for LR) and the U.S. Army Engineer Research and Development Center (the Network for Engineering with Nature (https://n-ewn.org) supported SKM). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Societies depend on provisioning, regulating, cultural, and supporting services provided by freshwater ecosystems [1,2]. However, the maintenance of naturally functioning freshwater ecosystems often is omitted as an objective of water management, particularly for rivers [3]. Most riverine ecosystems have undergone significant changes through damming, water withdrawal, channelization, impacts from development, altered flows of water, and inputs of nutrients and sediment [4–7]. In addition, weather patterns are becoming more variable and extreme under climate change, leading to greater uncertainty around the quantity and timing of access to water resources [8]. There has been increased emphasis in the management realm on recognizing impacts to biodiversity and freshwater ecosystems through development and implementation of natural infrastructure and river restoration [9], but this necessitates foresight in both planning and management to address specific ecological outcomes.

A broadly accepted approach to preserving functioning river ecosystems is to maintain aspects of the natural flow regime through "environmental flows" (or "e-flows")—i.e., the quantity, timing, and volume of water needed to produce valued environmental services and outcomes, which may range from sustaining aquatic organisms to maintaining natural riverine geomorphic processes [10]. Prioritizing and implementing e-flow frameworks in practice often requires high-level coordination through policy or other mechanisms, as in the case of the Building Blocks Method, which was codified at the national level in South Africa [11]. In the USA, agencies charged with public water supply or regulating water resources often have a narrow scope of legal authority, complex institutional connections to other entities, or lack specific targets for environmental protection [12,13], defaulting to vague objectives concerning natural system sustainability. There are some regulatory circumstances, such as when river flow affects an endangered species or during dam relicensing (a federal process in the USA), in which e-flows may be used to support species-specific or environmental endpoints [14]. However, in the absence of explicit environmental protections, the language of instream flow laws and institutional biases tend to favor human uses [14].

The functional flows approach, as described in [15], has similarities to the Building Blocks Method and was developed for use by state agencies, non-governmental organizations (NGOs), watershed groups, and others to develop e-flow relationships and recommendations based on aspects of the flow regime that support generalized ecological and geomorphic processes of a river system [16]. The functional flows approach has the same underpinnings as many ecological-flow frameworks, namely that river ecosystems reflect adaptations to a flow regime [17–19] and humans have severely altered the flow regime through damming, diversions, alterations to channel structure, and landscape-level changes to hydrology [20–22]. The functional flows approach was developed for regulated systems where it is not feasible to emulate or maintain all aspects of the natural flow regime, and instead focuses on a few aspects of the natural flow regime that support physical and biological processes in rivers. By design, functional flows can be applied within a larger e-flow framework or can be used as a standalone approach and can include species–specific flow needs in addition to broader ecosystem functions [16].

Ecologists have developed numerous hydrologic indicators (e.g., the Indicators of Hydrologic Alteration [23] and more complex metrics (e.g., [24–26]) that could be used to assess potential loss of ecological functions because of flow alteration. Environmental flows based on measured hydrologic alteration have been successfully implemented, such as in the Murray-Darling Basin in Australia [27] and projects in the Klamath River in the USA [28]. However, in rivers that "have a high proportion of their total annual stream flow diverted and/or managed for social uses" [15], mechanisms sufficient to enable implementation of a full suite of environmental flows may not be in place [29]. The functional flows framework is intended to address the need to restore key ecological functions to such regulated rivers.

We contend that functional flows may also advance e-flow implementation in water planning, by providing a practicable number of metrics (i.e., five or fewer) that broadly represent ecosystem functions while acknowledging that a return to the natural flow regime may not be feasible given the current state of water allocation. Planners assess water availability to meet specific municipal and industrial targets; creating analogous targets to meet ecosystem needs is a better fit to the planning process than asking planners to assess degree of departure from a natural flow regime (e.g., [30]). Limiting the number of targets to five or fewer aligns with research on the cognitive limits on decision-making [31,32].

We present a case study on the applicability of a functional flow approach to develop ecological metrics for use in basin-wide water planning. Our work is relevant to the challenge of specifically assessing water availability for ecological values when environmental protection is vaguely defined in the regulatory and management context and is secondary to meeting other societal needs. Water planning provides a high-level process to flag concerns about environmental outcomes in rivers, while the functional flows approach provides a path for specifying a small set of e-flows to support ecological functions that are grounded in the natural flow regime. We illustrate how we used available data to develop functional flow targets for distinct portions of a river basin, with the recognition that these represent a first set of quantitative targets based on the data currently available and should be updated over the long-term as new information becomes available. We also show how we integrated ecosystem water needs into the planning process. We then discuss four themes that emerged from the work that may be broadly useful when addressing e-flows in water planning.

Case study: Developing functional flows for the Oconee River

Georgia's Comprehensive State Water Plan was adopted in 2008 by the Georgia General Assembly and was guided by state and federal statutes that protect environmental quality and support public health, and is intended to ensure water resource availability into the future [33]. The plan established 10 regions, each with its own council that develops a regional water plan that is updated every five years [34]. These regions are mostly drawn around river basins, though the boundaries follow county lines, such that each local government only belongs to a single region. The regional water plans assess surface water availability, ground water availability, and surface water quality (primarily through the lens of assimilative capacity). As of the 2023 planning cycle, the Surface Water Availability Resource Assessment (herein "Resource Assessment") conducted by the Georgia Environmental Protection Division uses a hydrologic model that can be applied to make comparisons of withdrawals, discharges and other water demands at a spatial resolution of the stream reach to provide quantitative information to guide water management decisions. Water plans summarize the current municipal, energy, agricultural, and industrial water demands within a region and develop a forecast of future water demand. Based on the results of the demand forecasts and Resource Assessments, the plans highlight expected challenges in meeting water needs, along with management practices to address those challenges [33,35]. However, regional water plans do not typically consider current or future gaps in surface water availability to meet environmental or recreational needs. The functional flow approach we describe below is not being applied at the state level but was developed for the Upper Oconee Regional Water Council (one of 10 councils in the state) as an instream flow approach that is compatible with the state level water planning framework.

In Georgia, water rights are governed by the riparian doctrine and "reasonable use" as determined by impacts to downstream neighbors or other riparian landowners [36]. As authorized by state and federal laws, the Georgia Environmental Protection Division implements permitting programs for wastewater discharge, drinking water, water withdrawals, stormwater, and erosion and sedimentation. The typical minimum flow defined in water withdrawal and wastewater discharge permits is the one-in-ten year, 7-day low-flow (7Q10), a level that was intended for the protection of water quality, not to maintain aquatic ecosystems [37]. The need for better information about environmental water needs has been expressed in reports produced for Georgia's regional water councils (e.g., [38]).

Our study specifically focused on the Oconee River Basin (Fig 1), which is almost entirely within the Upper Oconee Water Planning Region, located in east-central Georgia. This water planning region spans 13 counties and has a population of around 620,000 [35]. The watershed exhibits a suite of water management challenges common to the Piedmont region, namely a legacy of soil erosion from historic land uses [39] and modern water supply and stormwater issues associated with urban development [40]. Most urbanization is in the northern part of the region, with the remaining basin dominated by agriculture, silviculture and low-density residential development. The basin supports municipal, industrial, energy, and agricultural water uses, with surface water as the main water source for the region [35].

The Oconee River drains 8,578 km^2 on the Atlantic Slope of Georgia and is a major tributary of the Altamaha River (Fig 1). The Oconee Basin has 34 surface water withdrawal permits (with 17 in the mainstem river and reservoirs), 90 National Pollution Discharge Elimination System (NPDES) permitted discharges, and three licensed hydropower projects (data as of 2020, with permit lists available through GAEPD - https://epd.georgia.gov/watershed-protection-branch-lists). One hydropower project is a small run-of-river dam (Tallassee Dam) on the Middle Oconee River in the Piedmont portion of the basin. The other two, Wallace and Sinclair dams, are situated near the Fall Line (the physiographic divide between the Piedmont and Coastal Plain), and impound large reservoirs (Lake Oconee, about 8000 ha and Lake Sinclair, about 6200 ha) that are jointly operated for pumped storage hydropower. Recreation includes motorized boating in the reservoirs and larger river reaches and non-motorized (e.g., canoeing, kayaking) boating throughout the basin. People also use areas along the river for hunting, fishing, and outdoor recreation on public and private lands.

The headwaters of the Oconee basin are in the Piedmont physiographic province where larger streams have rocky shoal habitats that support distinct aquatic communities, along with deeper-water pools and runs. Bottomland hardwood is the most common floodplain system in the Piedmont [41]. As the river transitions into the Coastal Plain, river and floodplain habitats include oxbow lakes, sand and gravel bars, deeper pools, snags (i.e., accumulations of large wood), and seasonally inundated floodplains. Floodplain communities are dominated by hickory-gum bottomland hardwood and cypress-tupelo swamp forests [41,42]. The river basin is home to at least 60 native species of fishes, 16 native mussel species, and 11 native crayfish species [43].

Developing metrics for water planning

The functional flows approach explicitly accounted for the geomorphic and ecological processes supported by a river's flow regime [15]. Rivers in the Piedmont and Coastal Plain physiographic provinces of the southeastern US were classified as perennial runoff systems [44], in contrast with the snowmelt dominated systems for which the functional flows approach was initially developed. We modified the functional flows framework to reflect the seasonally higher flows in the winter and spring and lower flows in the summer and fall, and to accommodate the differences between the geologic context of the Piedmont and Coastal Plain. We developed five categories of functional flows (or functional flow components; [45]) for Georgia rivers (Table 1) to encompass a range of fundamental ecological processes driven by seasonal flow variation.

Our objective was to develop hydrologic environmental flow thresholds and metrics for the Upper Oconee Water Planning Region that could be evaluated with the Resource Assessment and could be used similarly to the metrics applied by planners to identify shortfalls in water availability for municipal supply and wastewater treatment. There was a range

Fig 1. The Oconee River Basin is outlined in blue, and the Upper Oconee Regional Water Planning Region is in yellow and drawn based on county lines. The Fall Line denotes the transition between the Piedmont physiographic province (north) and the Coastal Plain physiographic province

(south). The two largest hydropower dams are situated near the Fall Line. United State Geological Survey (USGS) gages are denoted with red points. Basemap is Esri World Ocean Base, available at https://services.arcgisonline.com/ArcGIS/rest/services/Ocean/World_Ocean_Base/MapServer.

https://doi.org/10.1371/journal.pwat.0000445.g001

Table 1. Five functional flow components developed for application in regional water planning.

Functional Flow	Description
1. Channel maintenance flows	Maintain the dynamic erosional and depositional forces that shape channel form and aquatic habitats
2. Floodplain connectivity flows	Inundate, connect and cue movements to diverse floodplain habitats, support riparian and wetland flora and fauna, and support sediment and nutrient exchange between river and floodplain
3. Springtime pulse flows	Provide spawning cues for fishes or other organisms and flushing flows during the spawning season
4. Reproductive season baseflows	Provide adequate water for successful reproduction (e.g., spawning behaviors, egg-laying, and larval rearing) including availability of and connectivity among diverse habitats
5. Dry season baseflows	Maintain habitat connectivity and conditions for the survival of aquatic organisms during seasonal low-flows

https://doi.org/10.1371/journal.pwat.0000445.t001

of approaches that could be used to develop environmental flow relationships or metrics for implementation, including desktop analysis, functional analysis, hydraulic habitat analysis and modeling, or some combination [46], and these varied in data requirements and statistical complexity, see [45,47,48]. Given our need to integrate directly into the existing water planning process and ground information locally, we used data and models from local studies to develop threshold flow levels (river discharges) that supported an ecological or geomorphic process, or below which an ecological function was expected to decline. The intent was that managers and stakeholders could evaluate location-specific hydrographs to estimate how long or how often (or both) flows would be above or below a threshold given future water demand.

Each of our thresholds was based on a specific research study and linked with the nearest USGS gage (with at least a 20-year record) to the study location (Table 2). These thresholds provided a starting point for management and were intended to be updated as new information became available. To provide context for the thresholds in the Oconee River Basin, we used historical gage data to calculate the flow percentile for each threshold based on the month or months that were specified in the metric for each functional flow component (Table 2). For example, the flow percentile for the floodplain connectivity component was the percentage of all daily flow values from November to March for the period of record that were less than the floodplain connectivity threshold. Because Piedmont and Coastal Plain regions experience very different physical, ecological, and social drivers, we developed separate flow recommendations for each region, described below.

Piedmont Region. The primary water use in the Piedmont portion of the study basin, which subsequently had the greatest effects on daily river discharge, was withdrawals for municipal or industrial use. The Piedmont region had one run-of-river dam in the mainstem Middle Oconee River with minimal upstream water storage. Power generation at this dam could alter sub-daily flows when the river was relatively low (i.e., $< 23\ m^3s^{-1}$) but otherwise did not modify hydrologic patterns for an extended distance downstream.

We identified eight local studies that reported information useful for identifying river discharges that supported four of the five functional flow components at sites in the Piedmont portion of the Oconee River basin. We did not find a study with sufficient information for a threshold for channel maintenance flow (functional flow category 1), so we could not evaluate this function at any Piedmont site. We estimated a floodplain connectivity threshold (functional flow category 2) for a site on the North Oconee River from observations of active dispersal by mayfly nymphs (*Leptophlebia* sp.) between the river channel and floodplain [49], as a starting point for a site-specific

Table 2. Functions associated with each functional flow component and a metric that could be evaluated with location-specific thresholds for the Piedmont and Coastal Plain portions of the Oconee River Basin, Georgia, USA. We reported thresholds for each physiographic province when data were available. We linked each threshold with a nearby USGS gage number with at least a 20-year flow record. We reported the discharge values and flow percentiles over the period of record, for the calendar months associated with the metric.

Functional Flow Component	*Function(s)*	*Metric*	*Location-specific thresholds*
Channel maintenance	Sediment transport and channel dynamics that maintain and create diversity of in-channel habitats	# years > *channel threshold level*	Piedmont: No data available for channel maintenance flow levels or frequencies Coastal Plain: flow levels that maintain channel migration and bank erosion processes. USGS gage: 02223000 340 m^3s^{-1}; 97%
Floodplain connectivity	Inundate and connect habitat for wetland dependent species (amphibians, aquatic insects, fishes, birds) Support seed dispersal and seasonal inundation for floodplain tree species, e.g., bald cypress and water tupelo Nutrient exchange between channel and floodplain	# days during November-March with flows > *floodplain threshold level*	Piedmont: flows that connect the river and floodplain, which supports connectivity and movement by organisms USGS gage: 02217770 30 m^3s^{-1}; 88% Coastal Plain: inundation of floodplain habitat and oxbow lakes; ranges from low elevation habitat inundation to full inundation of floodplain habitat USGS gage: 02223000 283 m^3s^{-1}; 93% USGS gage: 02223056 142 m^3s^{-1}; 80% USGS gage: 02223500 425 m^3s^{-1}; 93%
Springtime pulse flows	Flush fine sediment from fish spawning substrates (e.g., gravel, crevices, cavities)	# years with the maximum 10-day high flow in March-May > *spring pulse flow*	Piedmont: flushing flows maximize reproduction output for gravel-spawning fishes USGS gage: 02217500 34 m^3s^{-1}; 91% Coastal Plain: No data available for spring pulse flows
Reproductive season baseflows (spring and early summer)	Create and maintain conditions needed for animals to successfully reproduce, including habitat availability, preventing settling (broadcast- spawned) and siltation (gravel- and crevice-spawned) of eggs and larvae, providing oxygen to deposited eggs and larvae	# days during March-May with flow < *reproductive season threshold*	Piedmont: decline in availability of swift water habitats USGS gage: 02217500 14 m^3s^{-1}; 49% Coastal Plain: maintain spawning and rearing habitat for fishes USGS gage: 02223056 Oxbow habitat 85 m^3s^{-1}; 62% Robust redhorse *Consecutive days between* 28 – 57 m^3s^{-1}; 14% - 41%
Dry season baseflows (summer and fall)	Support growth and survival of aquatic organisms Sustain higher velocity habitats Maintain habitat connectivity	# days during June-October with flow < *dry season threshold*	Piedmont: severe reduction in deep swift water habitat; loss of aquatic organisms at severe low flows USGS gage: 02217500 7.5 m^3s^{-1}; 62% 2.8 m^3s^{-1}; 15% Coastal Plain: loss of connectivity between channel and oxbow and decline in area of submerged woody debris USGS gage: 02223056 21 m^3s^{-1}; 7% 14 m^3s^{-1}; 2.5%

https://doi.org/10.1371/journal.pwat.0000445.t002

flow that facilitates floodplain habitat connectivity for small organisms (Table 2). For spring pulse flows (functional flow category 3), which depended on rainfall rather than water releases in the Piedmont, we used a model of fish recruitment in relation to the springtime flow regime for a Middle Oconee River site [50]. This model combined the probability distribution for 10-d maximum flows during species-specific spawning seasons for five genera of Oconee River fishes (*Cyprinella, Notropis, Lepomis, Micropterus, Etheostoma*) with a generalized, trait-based model of flow effects on juvenile fish recruitment [51] to estimate "effective discharges" [52] for juvenile recruitment by each of the five fish genera. We selected a 10-d maximum springtime flow threshold that theoretically provided for recruitment by all five fish taxa. To estimate a threshold for reproductive season baseflow (functional flow category 4), we used a hydraulic model for the same Middle Oconee River shoal site as in the fish recruitment model [53] to estimate availability of relatively deep (>35 cm) and swift (>55 cm/s) shoal habitat used for spawning by fishes that deposit eggs in silt-free gravel and crevices (e.g., *Cyprinella* spp., *Percina* spp., *Etheostoma* spp.). The hydraulic model showed a sharp decline in availability of this spawning habitat at about 14.2 m^3s^{-1}, which we selected as a threshold for reproductive season baseflow (Table 2), noting that habitat for fishes that spawn in slower velocities would be available (e.g., along channel margins) at this threshold and higher discharges. Finally, we identified two thresholds for dry season baseflows (functional flow category 5). The first threshold was based on maintaining at least some relatively deep (≥ 35 cm) and swift velocity (>55 cm/s) habitat in Middle Oconee River shoals, as estimated by hydraulic modelling [53], as a low-flow refuge for a submerged aquatic macrophyte (*Podostemum ceratophyllum*) [53,54]. The second dry season threshold represented an extreme low flow associated with measured decline in *Podostemum* biomass and filter-feeding caddisfly (*Hydropsychidae*) abundance in Middle Oconee River shoals during drought conditions [55,56].

Coastal Plain Region. River discharges in the Coastal Plain portion of the basin were affected by water storage behind the two large, mainstem hydropower dams at the upstream boundary of the Coastal Plain. To estimate functional flow thresholds in this flow-regulated portion of the study basin, we relied on habitat simulation models constructed as part of the 1996 Federal Energy Regulatory Commission (FERC) relicensing process for the downstream-most Oconee River dam (Sinclair Dam, FERC relicensing project 1951; [57]). In addition to water withdrawals for municipal, agricultural, and industrial uses, operations at the hydropower dams potentially had large effects on seasonal water availability downstream.

We estimated high flows needed for channel maintenance (functional flow category 1; Table 2) from a study of the effects of Sinclair Dam on downstream channel planform [58] and the analysis in support of FERC relicensing [57], which estimated similar discharges for maintaining bank erosion and channel migration. We extracted thresholds for three other functional flows from physical habitat simulation models developed to support FERC relicensing [57] by identifying flows below which functionally-defined habitats were projected to decrease substantially in one or more modelled Coastal Plain reaches (Table 2). Specifically, we identified two thresholds for floodplain habitat connectivity (functional flow category 2), one in which low-lying floodplain and oxbow lakes were inundated and a higher flow level that inundated a substantial portion of the floodplain (Table 2). Inundated floodplain forests and oxbow lakes have been found to support reproduction by a diversity of Coastal Plain fishes in the southeastern US [59–61]. We did not have information available to develop a spring flow pulse (functional flow category 3) in the Coastal Plain. Reproductive season baseflow (functional flow category 4) thresholds were based on 1) flows that provided a variety of habitat conditions in channel-connected oxbow lakes to support fish spawning and rearing, and 2) a specific flow range that maintained spawning habitat (moderate to swift velocities over gravel shoals) availability for a state-protected fish species (Robust Redhorse, *Moxostoma robustum*; Table 2). Finally, for functional flow category 5, we identified summer and fall baseflows to support fish passage for small-bodied fishes between the river channel and oxbow lakes and a second, lower flow threshold estimated to inundate at least a third of in-channel woody debris, known to support insect production and to provide refugia for aquatic organisms during low-flows [62]. For more detailed information on the foundation for functional flows and the rationale for functional flow components for the Oconee Basin, see the project report "A review of flow related benefits and uses of the Oconee Basin" (https://h2opolicycenter.org/wp-content/uploads/2022/09/A-Review-of-Flow-Related-Benefits-and-Uses-of-the-Oconee-Basin_final.pdf).

Communication and contextualization of environmental flow thresholds

The information we developed on functional flows was included on a webpage, "Waters of the Oconee River Basin: Uses, Benefits, and Flow-Related Metrics for Water Planning" (https://h2opolicycenter.org/projects/waters-of-the-oconee-river-basin/) intended for use by regional planners, state water regulators, and other partners. Prior to webpage release, the material was revised based on review comments from members of the Upper Oconee Water Council.

As part of the project summary, we included hydrographs to provide planners and other partners visual representations of how the functional flows to support aquatic habitats and species related to long-term averages and other water uses at a select location. Hydrographs plotted the long-term daily median flow (50th percentile daily flow) in the Middle Oconee River, near Athens, GA (Fig 2, USGS gage 02217500; [63]) along with daily flows for a select year (e.g., 2020, a relatively wet year), simply to illustrate the flow variability within a year, not to identify it as a reference condition (Fig 2). Using this hydrologic context as the backdrop, we illustrated the relationship between functional flow thresholds and other socio-economic values in a reach of the Middle Oconee River with a municipal water supply withdrawal and a run-of-river dam upstream, but which otherwise was free-flowing. The purple dashed line (Fig 2) represented the minimum permitted withdrawal level; below that flow level the utility was not allowed to withdraw water from the river. Partner input [64–66] conveyed that this reach of the Oconee was also popular for canoeing and kayaking, and so we illustrated the range of flow conditions that supported relaxed paddling (orange box, Fig 2). We defined relaxed paddling as the flow range that was safe and navigable for a novice paddler. Above this level, higher river flows could be unsafe and below this level paddlers would have to drag their boat to pass through the shoals and shallow sections of the river. Thresholds for functional flow categories 4 and 5 (reproductive season baseflows and dry season baseflows) are shown in blue on Fig 2. The higher dry season baseflow (from June to October) was the point at which deep and swift water habitats were lost, and the lower threshold was the point at which drying in shoals occurred, leading to loss of aquatic plants and associated invertebrates. Visualizing the thresholds for multiple uses in the river helped to illustrate how river uses and functions overlap. We chose to display two of the three functional

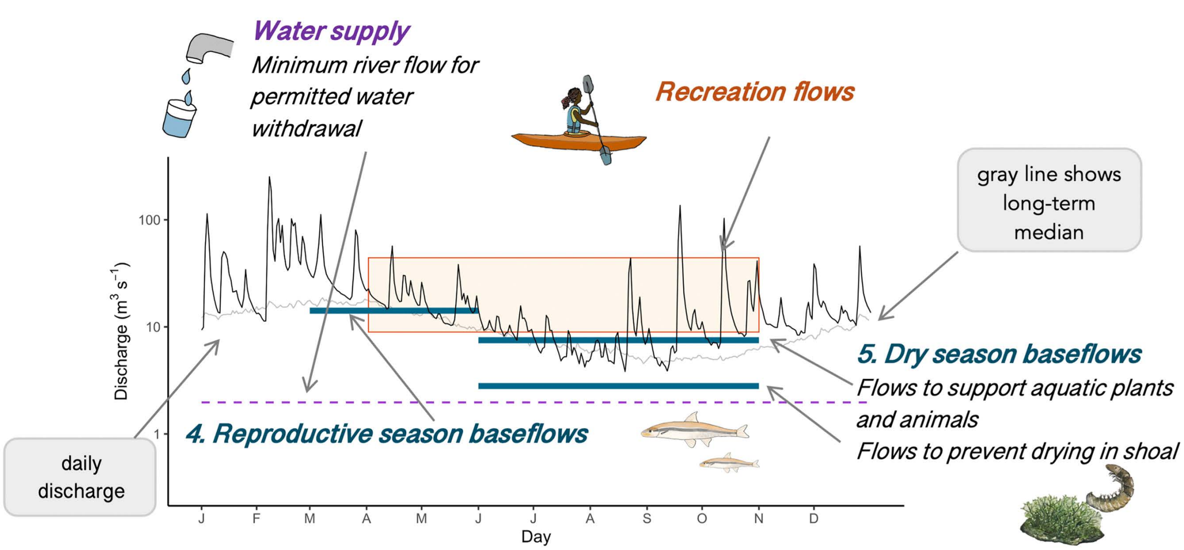


Fig 2. Multiple uses supported by the Middle Oconee River ecosystem in the Middle Oconee River, near Athens, GA (USGS gage 02217500; [63]). At this location, there is a run-of-river dam upstream and a water withdrawal point, but the river is not otherwise regulated. We display the two functional flows that have the greatest potential for management action at this reach alongside other uses, including water supply and flows that support paddling recreation. Visualizing thresholds for multiple uses demonstrates how meeting a flow need can support multiple uses. The daily flow hydrograph is for 2020.

https://doi.org/10.1371/journal.pwat.0000445.g002 flows developed for this site to show a straightforward graphic relating different water needs and uses and the functional flows that can be addressed through management action. While we use a specific location in the Middle Oconee River to illustrate this relationship, the concept holds across locations.

The Upper Oconee Regional Water Planning Council included the functional flow metrics (and also recreational boating flows) in an appendix to their 2023 regional water plan, recognizing that these metrics could be evaluated in future planning cycles [35]. While we plan to bring these conversations into the next planning cycle, our content and products represented an early step in formalizing conversations that consider ecological outcomes and recreation in the water planning process in Georgia.

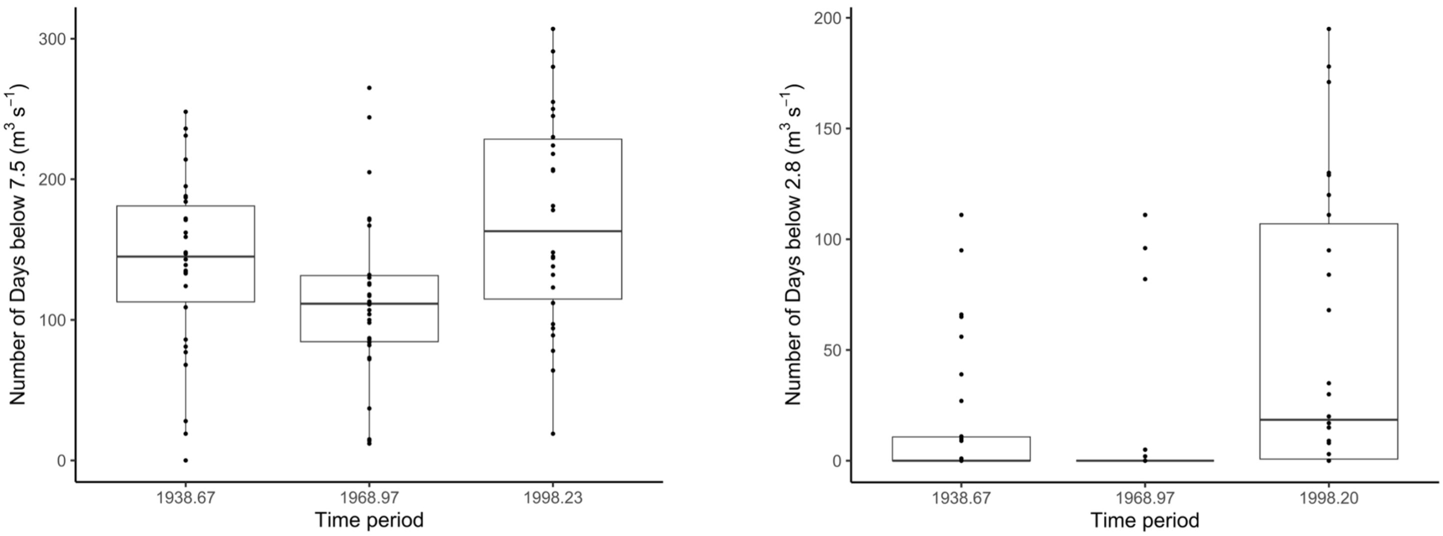
Evaluating metrics for water planning

The next update of the Upper Oconee Regional Water Plan is scheduled to begin in 2026 for a Plan revision in 2028. Incorporating functional flows to represent environmental water needs in this and future updates will require a shift in how council members evaluate water availability. The water planning process currently involves members of a regional water planning council evaluating metrics for water supply, wastewater assimilation, etc. under current and future conditions to assess potential challenges in meeting future water needs. The results reported for each metric (e.g., water supply, wastewater assimilation, etc.) are the proportion of time that flows are below a threshold (e.g., a minimum level for a water withdrawal) over an 80-year planning scenario. To apply the functional flows approach in water planning and meaningfully evaluate an ecological outcome, council members will need a more ecologically-relevant comparison of current and future water demands. One such comparison would evaluate changes in the annual duration or the total number of years that functional flow thresholds are not met. This approach would flag locations where the aquatic ecosystem is projected to experience more frequent periods of inadequate water availability.

To illustrate how planners could evaluate functional flow metrics using annual frequencies and durations of functional flows, we use the historical time series from the Middle Oconee River (USGS gage 02217500; [63]). We split the 86-year period of record into three sequential periods and evaluate temporal shifts in attainment of the two dry-season (summer and fall) baseflow thresholds (Fig 3). We recognize that human water demand and development on the landscape have increased over this time period; this example illustrates the types of patterns or trends that could trigger concerns during the planning process. We find an increase in frequency and duration of flows below the summer and fall baseflow thresholds in the most recent period, 1998–2023 (Fig 3). During those years, there are a similar number of low-rainfall years as in the previous 30-year period, but substantially higher failure to meet the summer and fall functional flows compared with both prior periods (Fig 3). The most recent period also corresponds with three multi-year droughts and increased water demand, including the 2002 completion of an off-channel, pump-storage reservoir that provides water to multiple counties upstream of the study site. Increases in the frequency and duration below the dry season baseflow (functional flow category 5) could trigger a planning need, which planners could address by developing management practices to reverse or offset the shift.

Applying a similar analysis for the Coastal Plain, we observe fewer annual days in the most recent period, 1998–2023, with river connectivity to the floodplain (USGS gage near Dublin GA 02223500; [63]). We also observe a decline through the three time periods in the 80th percentile number of days with flows that connect the river and floodplain (Fig 4). It is unclear the extent to which these shifts are driven by climate versus increased human water use.

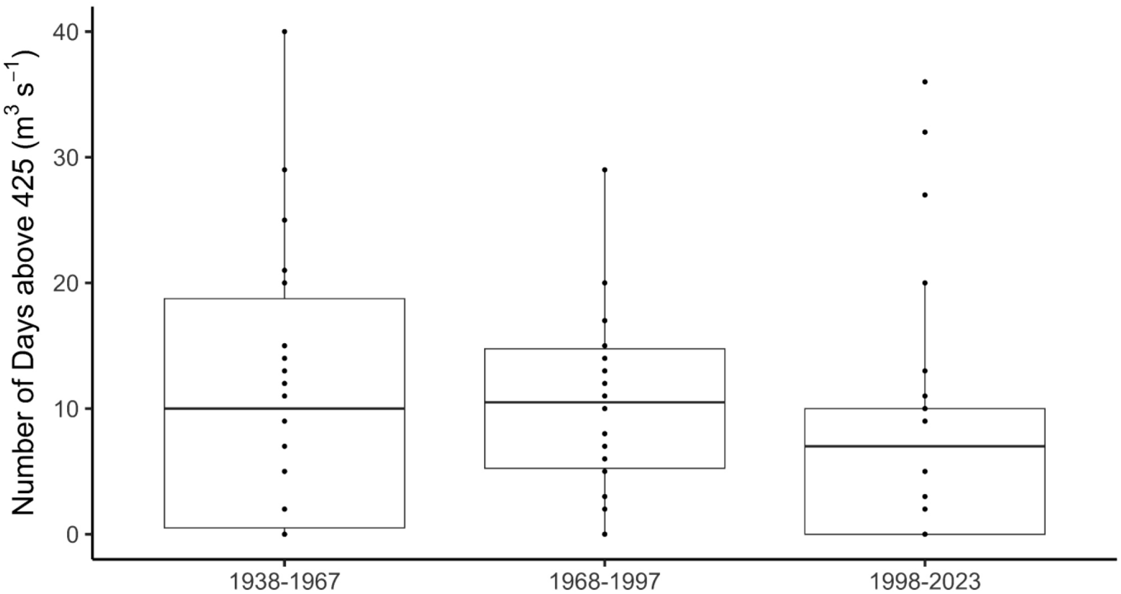
An important next step for water planning will entail agreeing to and establishing an ecological reference period to avoid a moving “goal post” for evaluating ecological outcomes. Although our examples (Figs 3, 4) implicitly use the earliest time period as a “reference”, we believe that it is important to engage with planners directly to establish a reference period in the context of a specific planning process. While ecologists can provide guidance for reference development, success will depend on group consensus.



	1938-1967	1968-1997	1998-2023
TOTAL # YEARS	30	30	26
MEAN ANNUAL FLOW (m^3s^{-1})	14.15	15.38	12.66
MEAN ANNUAL RAINFALL (cm)	127.88	122.89	121.28
# YEARS <100 cm OF RAINFALL	2	5	6
# YEARS WITHOUT OCCURRENCE OF FLOWS:			
<7.5 m^3s^{-1}	1	0	0
<2.8 m^3s^{-1}	18	23	7
TOTAL % OF TIME BELOW FLOW:			
<7.5 m^3s^{-1}	38%	32%	47%
<2.8 m^3s^{-1}	4.5%	3.8%	15.1%
MEDIAN # DAYS JUNE - OCTOBER WITH FLOWS:			
<7.5 m^3s^{-1}	104.5	98	110
<2.8 m^3s^{-1}	0	0	18.5

Fig 3. Comparison of failure to meet dry-season functional flow thresholds during three time periods in the Middle Oconee River, Georgia, spanning 1938 to 2023. At this location, there is a run-of-river dam upstream (constructed in 1902) and a newer water withdrawal (implemented in 2002) just upstream of this study area. The impact of these operations tends to be greater during low flow periods in the summer. The most recent interval (1998 - 2023) has more years of June to October flows with longer durations under the thresholds for maintaining swift-water habitat (7.5 m^3s^{-1}, left) and for drought survival (2.8 m^3s^{-1}, right). The majority of years during the two earlier periods (1938-1967, 1968-1997) do not experience June to October flows below the drought survival threshold, in contrast to an annual June to October median of 18.5 days below this threshold in the recent period, with durations extending three or more months in some years.

https://doi.org/10.1371/journal.pwat.0000445.g003



	1938-1967	1968-1997	1998-2023
TOTAL # YEARS	30	30	26
# YEARS NOVEMBER – MARCH > 425 m^3s^{-1}	22	26	19
MEAN ANNUAL FLOW (m^3s^{-1})	131.8	124.5	103.4
MEAN ANNUAL RAINFALL (cm)	117	120	118
MEDIAN # DAYS, NOVEMBER – MARCH > 425 m^3s^{-1}	10	10.5	7
80^{TH} PERCENTILE # DAYS, NOVEMBER – MARCH > 425 m^3s^{-1}	20.2	15.4	11

Fig 4. Comparison of attainment of floodplain habitat connectivity functional flow thresholds during three time periods in the Oconee River, Georgia. This site is located about 96 river kilometers downstream of the Sinclair and Wallace Dams, which were operational starting in 1953 and 1979 respectively, and is near a surface water intake (in place since the 1970s). The most recent interval (1998 - 2023) has fewer days above the threshold for connecting the river to the floodplain. We also observe a decline in the 80^{th} percentile number of days connecting the river and floodplain (> 425 m^3s^{-1}) over the three time-intervals, meaning that over time events connecting the river and floodplain become shorter.

https://doi.org/10.1371/journal.pwat.0000445.g004

Discussion

Decisions around water are socially complex due to multiple uses and varying values of stakeholders that rely on water. Despite this complexity, there is a pressing need to address the threats to freshwater ecosystems and biodiversity driven by human alteration, water use, and changing weather patterns [67]. We highlight four themes that we found important to integrating ecological outcomes into a water planning framework: 1) Identifying and understanding the context for water resource decision-making; 2) Developing quantitative ecological metrics and thresholds at the level of complexity that is relevant and relatable to decision makers; 3) Adapting and translating e-flow frameworks to function within existing management or planning structures, including established evaluation criteria; and 4) Providing the necessary information for decision-makers to evaluate and interpret ecological metrics alongside other water uses.

Vaguely defined laws and goals for environmental protection, and fragmentation of environmental responsibility among and within local, state, and national governments, make it challenging to manage directly for environmental outcomes [14,68]. Regulatory agencies responsible for biological or environmental protections often do not have direct authority to allocate instream flows for aquatic species and habitats [14,69]. Water utilities, or other entities responsible for municipal, industrial, or agricultural water supply, must prioritize meeting the needs of water users and complying with statutes for surface or groundwater management. However, we believe that the existing water planning framework in Georgia provides sufficient structure to allow incorporation of a functional flows approach to achieve ecological outcomes. The water planning process in the state of Georgia is well established, has relatively high spatial resolution information on the water resources for the state, and offers a formalized setting to discuss water resources across sectors. Working within the water planning space allows for discussion of opportunities to meet ecological objectives across sectors rather than asserting pressure on any one entity. Our pilot project has attempted to meet water planners at their level of interaction with the river, which is generally from the human use perspective. The next step is to engage with council members directly on evaluating functional flows during the water plan update, which occurs every 5-years and is scheduled for 2028. Though it takes time to build trust and shared definitions among participants, partnerships and collaborations are key to building a solid foundation and a shared vision for management that can be responsive to changes in research or policy [70–74].

In addition to understanding the context around water resource decisions, ecologists face the challenge of the typical sparsity of place-specific data to support environmental flow thresholds. Quantitative flow-ecology relationships are difficult to develop [75], and even when there is a signal of flow effects on aquatic communities, high variance [76] or context dependency [77] may complicate the identification of flow thresholds for community change. Nevertheless, defining a quantitative threshold, even if it is provisional, provides a tangible ecological outcome to discuss and compare alongside other water uses. It may not be feasible to develop flow-ecology relationships for all organisms of interest or make decisions about which organisms to manage for in highly biodiverse systems. Alternatively, leveraging locally available data to support hypothesized thresholds around broader ecological outcomes and river processes (e.g., Will fish be able to spawn? Will plants and animals survive the summer?) may be more meaningful for water resource partners. While there are many methods and modeling approaches to develop e-flows, we have found that describing river dynamics and grounding understanding in local knowledge is relevant for planners and other partners. There is uncertainty around the functional flow thresholds and magnitude of ecological response, and the field of ecology has grappled with methods to quantify or reduce uncertainty [78,79]. Uncertainty also looms large for applied sciences and policy [80], but we have observed that it is not often discussed directly in the planning space. It is important to communicate early with partners that these relationships should be revised as new data become available, ideally through strategic monitoring and model-updating [81,82].

Building on the ecological flow thresholds, it is important to identify and modify an e-flow framework or approach that is appropriate in scale and scope for the application. Strengths of the functional flows approach for water planning lie in the flexibility of application and in that it is developed in part for systems where water is already allocated for human uses [15]. The approach emphasizes a few high-level aspects of the natural flow regime, or functional flow components via [45], that support biological and geomorphic processes in river systems. Presenting the functional flows as thresholds to evaluate can open conversation for what actions, both short- and long-term, would be needed to move towards meeting an instream flow. Most e-flow frameworks build on the assumption that there is interest or engagement from some entity to manage for ecosystem outcomes, but that is not necessarily the case for water planning focused on municipal, agricultural and industrial uses. In our case, we have had to figure out how we could adapt functional flows to fit the current evaluation structure used for water planning, i.e., a hydrologic model that was developed around the permitted water withdrawals, discharges, and dam operation where relevant. The planning level is meant to be the high-level pass that can identify areas of concern in meeting surface water needs. Ecologically, the planning process is a first pass at flagging the types of events, conditions, or potential development that could impair ecosystem functions. The follow-up to identifying concerning shortfalls in water to support functional flows could be to engage in higher-resolution studies of management actions and ecological outcomes, both of which are time- and resource-intensive activities but may be justified if they are identified ahead of time in the planning phase.

Ecological metrics for water availability need to be comparable to the metrics for other water needs, such as water supply, wastewater discharge, hydropower, etc. [83,84], but also require guidance for interpretation because ecological outcomes can depend on the magnitude, duration, and frequency of flow events. Planners in Georgia assess water availability for municipal withdrawal as the proportion of all days under a future scenario when streamflow is projected to be insufficient to support permitted withdrawal rates [35]. Using the same approach for ecological metrics is less informative, however. For example, the final period (1998–2023) of our evaluation of temporal change in dry-season flows at the Middle Oconee River site could be interpreted as having 9% more days per year with flows less than $7.5 m^3 s^{-1}$ compared with first period (i.e., 47% compared with 38%; Fig 3 table). This could be the result of 33 more days each year below the $7.5\ m^3 s^{-1}$ threshold, or conversely, it could be 10.5 months longer below $7.5\ m^3 s^{-1}$ every 10 years, with different ecological consequences depending on the ecosystem's resistance and resilience to prolonged drying. Instead, specifically comparing shifts in the annual frequency and duration of low-flow events (as in Fig 3) could better reveal ecologically meaningful changes to flow conditions. Guidance from scientists for how to evaluate and interpret ecological metrics can support dialogue between planners, utilities, scientists and other interested parties [83]. Whether a given shift in an ecological flow metric (e.g., from <50% to >70% of years with extreme low-flow durations) is too much depends on social tolerance for risk, ecological understanding of aquatic community resilience to drying, and regulatory guidance (if available) for a given situation.

Conclusions

Integrating ecological information into water planning represents a first step in assessing ecological outcomes, however moving from information to action also requires prioritizing environmental outcomes alongside other uses. Often environmental flows are given the lowest priority when water becomes scarce and are viewed only as protecting non-human benefits, rather than supporting river ecosystems that provide valuable services [68]. In addition, private water interests are often over-emphasized by traditional optimization methods or decision support tools used in the water planning process [85,86], making it difficult to represent public interest. Increasing representation in the water planning space for cultural uses, recreation, and ecological outcomes involves changes to the structure of decision making around water. Evaluating ecological conditions in water planning can start a dialogue about managing for environmental outcomes. Often decisions to address environmental impacts are made reactively; however, developing, evaluating, and interpreting e-flow metrics that fit the management context highlight risks to traditionally under-valued resources, and encourage exploration of management approaches to minimize those losses. This may help shift away from the idea of water for either humans or nature and towards a system that values ecosystem services of natural river ecosystems alongside other social and economic water use.

Acknowledgments

Opinions expressed here are those of the authors and not necessarily those of the entities they represent.

Author contributions

Conceptualization: Gail Cowie.

Data curation: Laura E. Rack, Mary C. Freeman.

Formal analysis: Laura E. Rack, Mary C. Freeman.

Funding acquisition: Gail Cowie.

Investigation: Laura E. Rack, Mary C. Freeman, Gail Cowie.

Methodology: Laura E. Rack, Mary C. Freeman.

Project administration: Gail Cowie.

Resources: Gail Cowie, Seth J. Wenger.

Supervision: Gail Cowie, Seth J. Wenger.

Validation: Laura E. Rack.

Visualization: Laura E. Rack, Carol Yang.

Writing – original draft: Laura E. Rack.

Writing – review & editing: Mary C. Freeman, Gail Cowie, Carol Yang, S. Kyle McKay, Laura S. Craig, Seth J. Wenger.

References

1. Hanna DEL, Tomscha SA, Ouellet Dallaire C, Bennett EM, Hooftman D. A review of riverine ecosystem service quantification: Research gaps and recommendations. J Appl Ecol. 2017;55(3):1299–311. https://doi.org/10.1111/1365-2664.13045
2. Vári Á, Podschun SA, Erős T, Hein T, Pataki B, Iojă I-C, et al. Freshwater systems and ecosystem services: Challenges and chances for cross-fertilization of disciplines. Ambio. 2022;51(1):135–51. https://doi.org/10.1007/s13280-021-01556-4 PMID: 33983559
3. Richter BD, Davis MM, Apse C, Konrad C. A presumptive standard for environmental flow protection. River Res Apps. 2011;28(8):1312–21. https://doi.org/10.1002/rra.1511
4. A. Auerbach D, B. Deisenroth D, McShane RR, McCluney KE, LeRoy Poff N. Beyond the concrete: Accounting for ecosystem services from free-flowing rivers. Ecosyst Serv. 2014;10:1–5. https://doi.org/10.1016/j.ecoser.2014.07.005
5. Carlisle DM, Wolock DM, Meador MR. Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Front Ecol Environ. 2010;9(5):264–70. https://doi.org/10.1890/100053
6. Ferrazzi M, Botter G. Contrasting signatures of distinct human water uses in regulated flow regimes. Environ Res Commun. 2019;1(7):071003. https://doi.org/10.1088/2515-7620/ab3324
7. Fisher DS, Steiner JL, Endale DM, Stuedemann JA, Schomberg HH, Franzluebbers AJ, et al. The relationship of land use practices to surface water quality in the Upper Oconee Watershed of Georgia. Forest Ecol Manag. 2000;128(1–2):39–48. https://doi.org/10.1016/s0378-1127(99)00270-4
8. Palmer MA, Filoso S. Restoration of ecosystem services for environmental markets. Science. 2009;325(5940):575–6. https://doi.org/10.1126/science.1172976 PMID: 19644112
9. van Rees CB, Jumani S, Abera L, Rack L, McKay SK, Wenger SJ. The potential for nature-based solutions to combat the freshwater biodiversity crisis. PLOS Water. 2023;2(6):e0000126. https://doi.org/10.1371/journal.pwat.0000126
10. Arthington AH, Bhaduri A, Bunn SE, Jackson SE, Tharme RE, Tickner D. The Brisbane Declaration and Global Action Agenda on Environmental Flows. Front Environ Sci. 2018;6.
11. King JM, Tharme RE, de Villiers MS. Environmental Flow Assessments for Rivers: Manual for the Building Blocks Methodology. Pretoria, South Africa; 2000. Available from: https://www.wrc.org.za/wp-content/uploads/mdocs/tt%20354-conservation.pdf
12. Prosser T, Morison PJ, Coleman RA. Integrating stormwater management to restore a stream: perspectives from a waterway management authority. Freshwater Sci. 2015;34(3):1186–94. https://doi.org/10.1086/682566
13. Yaryan Hall HR, Bledsoe BP. Integrated Urban Riverscape Planning: Spatial Prioritization for Environmental Equity. ASCE OPEN: Multidiscip J Civ Eng. 2023;1. https://doi.org/10.1061/aomjah.aoeng-0001
14. Zellmer S. Legal tools for instream flow protection. Integrated approaches to riverine resource stewardship: Case studies, science, law, people, and policy. The Instream Flow Council; 2008. p. 285–327.
15. Yarnell SM, Petts GE, Schmidt JC, Whipple AA, Beller EE, Dahm CN, et al. Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. BioScience. 2015;65(10):963–72. https://doi.org/10.1093/biosci/biv102
16. Framework CEF. Fact Sheet and FAQs. University of California, Davis; 2024 . Available from: https://ceff.ucdavis.edu/fact-sheets-and-faqs
17. Power ME, Sun A, Parker G, Dietrich WE, Wootton JT. Hydraulic food-chain models. BioScience. 1995;45(3):159–67.
18. Poff NL, Allan DJ, Bain MB, Karr JR, Prestegaard KL, Richter BD, et al. The Natural Flow Regime: A Paradigm for River Conservation and Restoration. BioScience. 1997;47(11):769–84.
19. Petts GE. Water allocation to protect river ecosystems. Regul Rivers Res Mgmt. 1996;12(4–5):353–65. https://doi.org/10.1002/(sici)1099-1646(199607)12:4/5<353::aid-rrr425>3.0.co;2-6
20. Spinti RA, Condon LE, Zhang J. The evolution of dam induced river fragmentation in the United States. Nat Commun. 2023;14(1):3820. https://doi.org/10.1038/s41467-023-39194-x PMID: 37380647
21. Carpenter SR, Stanley EH, Vander Zanden MJ. State of the World's Freshwater Ecosystems: Physical, Chemical, and Biological Changes. Ann Rev Environ Res. 2011;36(1):75–99.

22. Craig LS, Olden JD, Arthington AH, Entrekin S, Hawkins CP, Kelly JJ, et al. Meeting the challenge of interacting threats in freshwater ecosystems: A call to scientists and managers. Elementa Sci Anthropocene. 2017;5:1–15. https://doi.org/10.1525/elementa.256
23. Mathews R, Richter BD. Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting. J American Water Resour Assoc. 2007;43(6):1400–13. https://doi.org/10.1111/j.1752-1688.2007.00099.x
24. Olden JD, Poff NL. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res Apps. 2003;19(2):101–21. https://doi.org/10.1002/rra.700
25. George R, McManamay R, Perry D, Sabo J, Ruddell BL. Indicators of hydro-ecological alteration for the rivers of the United States. Ecol Ind. 2021;120:106908. https://doi.org/10.1016/j.ecolind.2020.106908
26. Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, et al. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology. 2009;55(1):147–70. https://doi.org/10.1111/j.1365-2427.2009.02204.x
27. Stewardson MJ, Guarino F. Basin-scale environmental water delivery in the Murray–Darling, Australia: A hydrological perspective. Freshw Biol. 2018;63(8):969–85. https://doi.org/10.1111/fwb.13102
28. Chaffin BC, Gosnell H, Craig RK. The Emergence of Adaptive Governance in the Klamath River Basin. In: Cosens B, Gunderson L, editors. Practical Panarchy for Adaptive Water Governance. Cham: Springer; 2018. p. 83–97.
29. Arthington AH, Tickner D, McClain ME, Acreman MC, Anderson EP, Babu S, et al. Accelerating environmental flow implementation to bend the curve of global freshwater biodiversity loss. Environ Rev. 2024;32(3):387–413. https://doi.org/10.1139/er-2022-0126
30. McKay SK. Quantifying Tradeoffs Associated with Hydrologic Environmental Flow Methods. J American Water Resour Assoc. 2015;51(6):1508–18. https://doi.org/10.1111/1752-1688.12328
31. Yoe C. Trade-off analysis planning and procedures guidebook. Alexandria, VA: U.S. Army Institute for Water Resources; 2002. Contract No.: IWR Report 02-R-2. Available from: https://iwrlibrary.sec.usace.army.mil or direct link: https://publibrary.sec.usace.army.mil/resource?title=Trade-Off%20Analysis%20Planning%20and%20Procedures%20Guidebook&documentId=fbee8a0d-16e1-4dcc-a6f1-8c69c8859b2f
32. Retief F, Morrison-Saunders A, Geneletti D, Pope J. Exploring the psychology of trade-off decision-making in environmental impact assessment. Impact Assess Project App. 2013;31(1):13–23. https://doi.org/10.1080/14615517.2013.768007
33. State Water Council. Georgia Comprehensive State-wide Water Management Plan. 2008; Available from: https://waterplanning.georgia.gov/state-water-plan
34. Georgia Water Planning: State of Georgia; Available from: https://waterplanning.georgia.gov/water-planning
35. Council. Upper Oconee Regional Water Plan. In: Georgia Department of Natural Resources EPD, 2023; Available from: https://waterplanning.georgia.gov/water-planning-regions/upper-oconee-water-planning-region/upper-oconee-regional-water-plan
36. Bowen BL, Georgia Riparianism and Irrigation. Hatcher K, editor. Proceedings of the 2001 Georgia Water Resources Conference; 2001; University of Georgia: Institute of Ecology. Available from: https://repository.gatech.edu/server/api/core/bitstreams/81472a8f-cfb7-4ea7-8980-0be72da7e183/content
37. Board of Natural Resources. Water Issues White Paper. Georgia Department of Natural Resources 2001.Available from: https://epd.georgia.gov/search/results?query=water%20issues%20white%20paper
38. ARCADIS. Methods for flow regime evaluation, Ocmulgee River, Georgia. prepared for Georgia Environmental Protection Division; 2019 [Report available by request from water.planning@dnr.ga.gov].
39. Jackson CR, Martin JK, Leigh DS, West LT. A southeastern piedmont watershed sediment budget: Evidence for a multi-millennial agricultural legacy. J Soil Water Conserv. 2005;60(6):298–310. https://doi.org/10.1080/00224561.2005.12435820
40. Jackson CR, Wenger SJ, Bledsoe BP, Shepherd JM, Capps KA, Rosemond AD, et al. Water supply, waste assimilation, and low-flow issues facing the Southeast Piedmont Interstate-85 urban archipelago. J American Water Resour Assoc. 2023;59(5):1146–61. https://doi.org/10.1111/1752-1688.13130
41. Wharton CH. The Natural Environments of Georgia. Geologic and Water Resources Division and Resource Planning Section, Office of Planning and Research Georgia Department of Natural Resources, 1978. Available from: https://epd.georgia.gov/sites/epd.georgia.gov/files/related_files/site_page/B-114.pdf
42. Evans JW. A Fisheries Survey of the Oconee River Between Sinclair Dam and Dublin, Georgia. Social Circle, Georgia: Georgia Department of Natural Resources; 1994. Available from: https://robustredhorse.com/wp-content/uploads/2025/06/Fisheries-Survey-of-the-Oconee-River-James-Evans-1994-report.pdf
43. Water Resources Division. Georgia Rare Species & Natural Community Data: Georgia Department of Natural Resources; 2021. Available from: https://georgiawildlife.com/conservation/species-of-concern
44. McManamay RA, DeRolph CR. A stream classification system for the conterminous United States. Sci Data. 2019;6:190017. https://doi.org/10.1038/sdata.2019.17 PMID: 30747915
45. Yarnell SM, Stein ED, Webb JA, Grantham T, Lusardi RA, Zimmerman J, et al. A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. River Res Apps. 2020;36(2):318–24. https://doi.org/10.1002/rra.3575
46. Acreman MC, Dunbar MJ. Defining environmental river flow requirements – a review. Hydrol Earth Syst Sci. 2004;8(5):861–76. https://doi.org/10.5194/hess-8-861-2004

47. Webb JA, Arthington AH, Olden JD. Models of ecological responses to flow regime change to inform environmental flows assessments. In: Horne A, Webb JA, Stewardson MJ, Richter BD, Acreman M, editors. Water for the environment: From policy and science to implementation and management. Elsevier Academic Press; 2017. p. 287–316.
48. Grantham TE, Carlisle DM, Howard J, Lane B, Lusardi R, Obester A, et al. Modeling Functional Flows in California's Rivers. Front Environ Sci. 2022;10.
49. Galatowitsch ML, Batzer DP. Benefits and costs ofLeptophlebia(Ephemeroptera) mayfly movements between river channels and floodplain wetlands. Can J Zool. 2011;89(8):714–23. https://doi.org/10.1139/z11-044
50. McKay SK, Freeman MC, Covich AP. Application of Effective Discharge Analysis to Environmental Flow Decision-Making. Environ Manage. 2016;57(6):1153–65. https://doi.org/10.1007/s00267-016-0684-4 PMID: 26961419
51. Craven SW, Peterson JT, Freeman MC, Kwak TJ, Irwin E. Modeling the relations between flow regime components, species traits, and spawning success of fishes in warmwater streams. Environ Manage. 2010;46(2):181–94. https://doi.org/10.1007/s00267-010-9511-5 PMID: 20559635
52. Doyle MW, Shields CA. An alternative measure of discharge effectiveness. Earth Surf Processes Landf. 2007;33(2):308–16. https://doi.org/10.1002/esp.1543
53. Bhattacharjee N, Willis JR, Tollner EW, McKay SK. Habitat Provision Associated with Environmental Flows. EMRRP Technical Notes Collection. ERDC/TN EMRRP-SR-85. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center; 2019. Available from: https://apps.dtic.mil/sti/pdfs/AD1069271.pdf
54. Wood JL, Skaggs JW, Conn C, Freeman MC. Water velocity regulates macro-consumer herbivory on the benthic macrophyte Podostemum ceratophyllum Michx. Freshw Biol. 2019;64(11):2037–45. https://doi.org/10.1111/fwb.13393
55. Katz RA. Abundance And Survival Of Common Benthic Biota In A River Affected By Water Diversion During An Historic Drought [MS]: University of Georgia; 2009. Available from: https://openscholar.uga.edu/record/9042?v=pdf
56. Pahl J. Effects Of Flow Alteration On The Aquatic Macrophyte Podostemum Ceratophyllum (Riverweed); Local Recovery Potential And Regional Monitoring Strategy. [MS]: University of Georgia; 2009. Available from: https://openscholar.uga.edu/record/17775?ln=en&v=pdf
57. EA Engineering S, and Technology, Inc,. Georgia Power Company Sinclair License Application, Accession No. 19950914-0187, FERC e-library, Docket P-1951; 1995. Available from: https://elibrary.ferc.gov/eLibrary/filelist?accession_number=19950914-0187&optimized=false&sid=68099c01-8ef8-48f2-8de9-955cc8f8b60f
58. Yearwood KI. River Planform Change Downstream Of The Sinclair Dam, Oconee River, Georgia. Gainesville, FL: University of Florida; 2010. Available from: https://ufdc.ufl.edu/UFE0041429/00001/citation
59. Light HM, Darst MR, Grubbs JW. Aquatic habitats in relation to river flow in the Apalachicola River floodplain, Florida. US Geological Survey; 1998. Report No.: 1594. Available from: https://pubs.usgs.gov/publication/pp1594
60. Zeug SC, Winemiller KO. Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. River Research & Apps. 2007;24(1):90–102. https://doi.org/10.1002/rra.1061
61. Burgess OT, Pine WE III, Walsh SJ. Importance of floodplain connectivity to fish populations in the Apalachicola River, Florida. River Res Apps. 2012;29(6):718–33. https://doi.org/10.1002/rra.2567
62. Benke AC, Van Arsdall TC Jr, Gillespie DM, Parrish FK. Invertebrate Productivity in a Subtropical Blackwater River: The Importance of Habitat and Life History. Ecol Monogr. 1984;54(1):25–63. https://doi.org/10.2307/1942455
63. U.S. Geological Survey. *National Water Information System: U.S. Geological Survey (USGS)*. Web Interface; 2024. Available from: https://nwis.waterdata.usgs.gov/nwis
64. Georgia River Network. Oconee River undated. Available from: https://garivers.org/oconee-river/
65. Cook J. Oconee River User's Guide. Athens, GA: University of Georgia Press; 2019.
66. American Whitewater. Georgia River List; 2025. Available from: https://www.americanwhitewater.org/content/River/view/river-index/state/USA-GEO
67. Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, et al. Bending the curve of global freshwater biodiversity loss: An emergency recovery plan. BioScience. 2020;70(4):330–42.
68. Richter BD. Re-thinking environmental flows: from allocations and reserves to sustainability boundaries. River Res Apps. 2009;26(8):1052–63. https://doi.org/10.1002/rra.1320
69. Wineland SM, Başağaoğlu H, Fleming J, Friedman J, Garza-Diaz L, Kellogg W, et al. The environmental flows implementation challenge: Insights and recommendations across water-limited systems. WIREs Water. 2021;9(1). https://doi.org/10.1002/wat2.1565
70. Barbour EJ, Holz L, Kuczera G, Pollino CA, Jakeman AJ, Loucks DP. Optimisation as a process for understanding and managing river ecosystems. Environ Model Softw. 2016;83:167–78. https://doi.org/10.1016/j.envsoft.2016.04.029
71. Anderson EP, Jackson S, Tharme RE, Douglas M, Flotemersch JE, Zwarteveen M, et al. Understanding rivers and their social relations: A critical step to advance environmental water management. WIREs Water. 2019;6(6):10.1002/wat2.1381. https://doi.org/10.1002/wat2.1381 PMID: 31827789
72. Iwanaga T, Wang H-H, Hamilton SH, Grimm V, Koralewski TE, Salado A, et al. Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach. Environ Model Softw. 2021;135:104885. https://doi.org/10.1016/j.envsoft.2020.104885 PMID: 33041631

73. Golladay SW, Craig LS, DePalma-Dow AD, Emanuel BN, Rogers SG. Building resilience into water management through public engagement. Freshw Sci. 2021;40(1):238–44. https://doi.org/10.1086/712514
74. Rack LE, Freeman MC, Emanuel BN, Craig LS, Golladay SW, Yang C, et al. How low is too low? Partnering with stakeholders and managers to define ecologically based low-flow thresholds in a perennial temperate river. River Res Apps. 2024;40(7):1393–416. https://doi.org/10.1002/rra.4301
75. Poff NL, Zimmerman JKH. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw Biol. 2010;55(1):194–205.
76. Knight RR, Murphy JC, Wolfe WJ, Saylor CF, Wales AK. Ecological limit functions relating fish community response to hydrologic departures of the ecological flow regime in the Tennessee River basin, United States. Ecohydrology. 2013;7(5):1262–80. https://doi.org/10.1002/eco.1460
77. Walters AW. The importance of context dependence for understanding the effects of low-flow events on fish. Freshw Sci. 2016;35(1):216–28. https://doi.org/10.1086/683831
78. Hobbs BF. Bayesian Methods for Analysing Climate Change and Water Resource Uncertainties. J Environ Manag. 1997;49(1):53–72. https://doi.org/10.1006/jema.1996.0116
79. Milner-Gulland EJ, Shea K. Embracing uncertainty in applied ecology. J Appl Ecol. 2017;54(6):2063–8. https://doi.org/10.1111/1365-2664.12887 PMID: 29225369
80. Dewulf A, Biesbroek R. Nine lives of uncertainty in decision-making: strategies for dealing with uncertainty in environmental governance. Policy Soc. 2018;37(4):441–58. https://doi.org/10.1080/14494035.2018.1504484
81. Peterson JT, Freeman MC. Integrating modeling, monitoring, and management to reduce critical uncertainties in water resource decision making. J Environ Manage. 2016;183(Pt 2):361–70. https://doi.org/10.1016/j.jenvman.2016.03.015 PMID: 27012362
82. Souchon Y, Sabaton C, Deibel R, Reiser D, Kershner J, Gard M, et al. Detecting biological responses to flow management: missed opportunities; future directions. River Res Apps. 2008;24(5):506–18. https://doi.org/10.1002/rra.1134
83. Enquist CAF, Jackson ST, Garfin GM, Davis FW, Gerber LR, Littell JA, et al. Foundations of translational ecology. Front Ecol Environ. 2017;15(10):541–50.
84. Vogel RM, Lall U, Cai X, Rajagopalan B, Weiskel PK, Hooper RP, et al. Hydrology: The interdisciplinary science of water. Water Res Res. 2015;51(6):4409–30. https://doi.org/10.1002/2015wr017049
85. Yang G, Giuliani M, Castelletti A. Operationalizing equity in multipurpose water systems. Hydrol Earth Syst Sci. 2023;27(1):69–81. https://doi.org/10.5194/hess-27-69-2023
86. Fletcher S, Hadjimichael A, Quinn J, Osman K, Giuliani M, Gold D, et al. Equity in Water Resources Planning: A Path Forward for Decision Support Modelers. J Water Resour Plann Manage. 2022;148(7). https://doi.org/10.1061/(asce)wr.1943-5452.0001573