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Putting Flow–Ecology Relationships into Practice: A Decision-Support System to Assess Fish Community Response to Water-Management Scenarios

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Abstract: This paper presents a conceptual framework to operationalize flow–ecology relationships into decision-support systems of practical use to water-resource managers, who are commonly tasked with balancing multiple competing socioeconomic and environmental priorities. We illustrate this framework with a case study, whereby fish community responses to various water-management scenarios were predicted in a partially regulated river system at a local watershed scale. This case study simulates management scenarios based on interactive effects of dam operation protocols, withdrawals for municipal water supply, effluent discharges from wastewater treatment, and inter-basin water transfers. Modeled streamflow was integrated with flow–ecology relationships relating hydrologic departure from reference conditions to fish species richness, stratified by trophic, reproductive, and habitat characteristics. Adding a hypothetical new water-withdrawal site was predicted to increase the frequency of low-flow conditions with adverse effects for several fish groups. Imposition of new reservoir release requirements was predicted to enhance flow and fish species richness immediately downstream of the reservoir, but these effects were dissipated further downstream. The framework presented here can be used to translate flow–ecology relationships into evidence-based management by developing decision-support systems for conservation of riverine biodiversity while optimizing water availability for human use.

Keywords: water management; environmental flows; decision-support system; streamflow alteration; scenario analysis; fish species richness; ecohydrology

1. Introduction

Water-resource managers are increasingly tasked with incorporating ecological considerations into water-management decisions, even as demands on water resources intensify for purposes ranging from irrigation to energy production [1–3]. Human modifications to streamflow regimes—such as from impoundments, diversions, and water withdrawals—are globally widespread and escalating, especially in areas that experience highly variable natural flow regimes [4–7]. Because streamflow is a master variable in stream ecology, influencing physical habitat characteristics, water quality, biotic interactions, and energy inputs [8–10], flow alteration is a serious threat to riverine biodiversity [11,12]. Literature reviews and regional assessments (e.g., [6,13–16]) indicate a variety of ecological responses by aquatic biota to streamflow alteration, including changes in reproductive behavior, community shifts based on trophic strategy, reduced species richness, and in particular the loss of native and sensitive species.

1.1. Needs and Challenges of Decision-Support Systems for Water-Resource Managers

In response to these challenges, decision-support systems (DSS) informed by environmental flows science offer a range of potential benefits to water-resource management—such as by improving the transparency, objectivity, and efficiency of the decision-making process—but are currently not widely applied [17–20]. In practice, many water-resource decisions are made in an ad hoc fashion, using experience-based rather than evidence-based approaches [21,22]. In some cases, overly simplistic "rules of thumb" have been adopted to define allowable degrees of hydrologic modification [2]. For example, minimum flow standards in the United States are commonly set at the annual 7Q10 (lowest flow over a seven-day period occurring on average once per decade), despite the fact that this statistic was developed for water quality purposes and is not suitable for ecosystem protection based on current environmental flows science [22,23]. Standards based on fixed percentages of mean annual flow (MAF) (e.g., [24,25]) have been criticized for failure to protect the components of natural flow regimes that are of primary ecological importance [2,5,22], yet are still widely employed globally [22,26]. The tendency for water-management decisions to be inadequately informed by environmental flows research is an example of the larger disconnect between conservation science and practice [17,27,28].

A key reason for the lack of widespread adoption of evidence-based DSS by water managers likely stems from mismatches between the practical contexts in which management decisions are made and the kinds of information typically provided by environmental flows studies [27–29]. Although region-wide planning and consensus building to achieve a comprehensive set of hydrologic and ecological targets is a laudable goal [30,31], many water-resource decisions are made in contentious contexts constrained by political, legal, social, and economic realities [32]. In a regulatory context, decisions are made in response to proposals (e.g., permit applications) representing specific, localized flow alterations. In some cases, proposals may represent profound and obvious alterations affecting entire basins, such as large impoundments or channelization of large rivers. More commonly, proposed alterations are highly localized withdrawals or return flows which, considered in isolation, may produce hydrologic effects that are too subtle to be readily apparent. However, the cumulative effects on aquatic communities of many such incremental alterations may become substantial when multiplied over entire river basins [1,33–35]. Similarly, reservoir release management typically involves a series of many short-term decisions (e.g., release of a flood pulse for a given duration on a given day), the cumulative effects of which may produce long-term ecological consequences [17]. The Ecological Limits of Hydrologic Alteration (ELOHA) [31] is commonly cited as a general framework for discerning flow–ecology relationships, but it provides little guidance on how these relationships can be operationalized to support specific and localized water-management decisions. For example, recent applications of the ELOHA framework have either produced flow–ecology relationships [36–39] or have prescribed general flow standards for particular river systems [40,41] but have not provided objective, quantitative frameworks for translating particular water-management decisions (e.g., withdrawal permits, and dam releases) into predicted hydrologic or ecological outcomes. Although substantial science exists on ecological effects of flow alteration [16,42], this understanding is often not specific enough to be readily translated into usable DSS [17], such that the "implementation" phase of ELOHA (lower left corner of figure 1 in [31]) remains a challenge. Thus, an important link to connect environmental flows science to real-world decision-making requires the application of generalized flow–ecology relationships to site-specific predictions of ecological response to particular proposed flow alterations.

One class of environmental flows studies that is explicitly geared toward decision-support involves optimization, by which pre-defined mathematical rules are applied to identify an "optimal" solution to meet an ecological objective [17,43]. Unfortunately, optimization approaches commonly fall short of evaluating ecological responses to hydrologic alteration (e.g., [44,45]) and instead present results only in terms of flow indices, which are implicitly assumed to be acceptable surrogates for ecological outcomes [17]. This approach requires multiple untested assumptions about the relationships between flow and ecological outcomes (e.g., that more flow necessarily implies improved ecological function) and fails to make use of the existing science that numerically characterizes these relationships. Those DSS that do incorporate ecological responses to flow regimes may consider a limited number of streamflow characteristics (e.g., [20]) or present "optimal" flow regimes without clear strategies for achieving them (e.g., [46]). Moreover, because optimization strategies are constrained by mathematical rules to identify singular "optimal" solutions, multiple (often competing) objectives are commonly combined into a single objective, e.g., by various weighting schemes [17]. This conflation of divergent sets of objectives may obscure important details relevant to water management and aquatic conservation. For example, a proposed flow alteration might enhance some components of the flow regime while degrading others, and it might benefit some taxonomic groups at the expense of others [47–50]. These limitations may help explain why the growing research on optimization modeling has generally failed to inform actual water-management decision-making [17].

1.2. Toward a Useful and Ecologically Relevant Decision-Support System for Water-Resource Managers

For a DSS to be useful to water-resource managers, it must perform a number of key functions (Box 1). Of primary importance is the need to link predicted effects of proposed alterations into the larger context of river basins as "hierarchical dynamic networks" [17] in which many incremental flow alterations are spatially and temporally integrated [33,35]. Consistent and transparent methods are vital so that, for example, all parties in a contentious permit evaluation process receive the same results and are able to see exactly how results were generated [19]. Flexibility and adaptability allow a decision-support system to remain relevant by allowing future incorporation of new water-management assets, scenarios, and locations for ecological assessment [51]. Translation of water-management decisions into ecological predictions is critical because, as described above, flow predictions alone are insufficient to evaluate water-management impacts on aquatic biodiversity. Ideally, ecological predictions should be stratified into ecologically meaningful groupings (e.g., taxonomic, functional, or habitat-based) to allow managers to evaluate multiple, and possibly competing, conservation priorities. Aggregated metrics of "ecosystem health" are somewhat vague and subjective [43], but may be useful in some cases to summarize complex ecological information for decision makers. Finally, end-users of the decision-support system must be engaged as primary stakeholders, rather than simply as recipients of the final model, and should be able to implement the DSS without complicated or expensive software development [19,29,51].

Box 1. Key functions of a useful and ecologically relevant DSS.

1. Integrates the hydro-ecologic effects of multiple water-management decisions that are spatially and temporally distributed
2. Uses a consistent and transparent methodology
3. Is flexible and adaptable, allowing for updates to water-management assets, scenarios, and locations for ecological assessment
4. Translates water-management decisions into explicit ecological predictions
5. Stratifies ecological predictions into ecologically meaningful categories
6. Engages end-users at key stages of model development
7. Can be applied by end-users in an efficient and cost-effective manner

We propose a four-step design process (Figure 1) by which existing flow–ecology relationships can be leveraged into a DSS that performs the functions listed in Box 1.

First, one or more proposed or hypothetical flow alterations must be defined. This should be a collaborative process involving stakeholders tasked with water-resource management and aquatic biodiversity conservation. Second, these flow alterations must be translated into predicted streamflow characteristics (e.g., components of flow regime representing the magnitude, frequency, timing, duration, rate of change, and predictability of high- and low-flow events). Hydrologic accounting methods can achieve this translation by adding and subtracting spatially distributed flow components across a basin on a user-defined time step [20,44]. These typically include inflows (obtained from stream-gauge data when available and otherwise from hydrologic models), and may also include reservoir releases, evaporative losses, water withdrawals, effluent discharges, and inter-basin water transfers. Third, the predicted streamflow characteristics under the influence of the proposed alteration(s) must be formatted for use as independent variables in the existing flow–ecology relationships. Finally, the flow–ecology relationships are applied to the independent variables to predict ecological response to the proposed alteration(s). Ideally, these predictions are subdivided into ecologically meaningful categories.

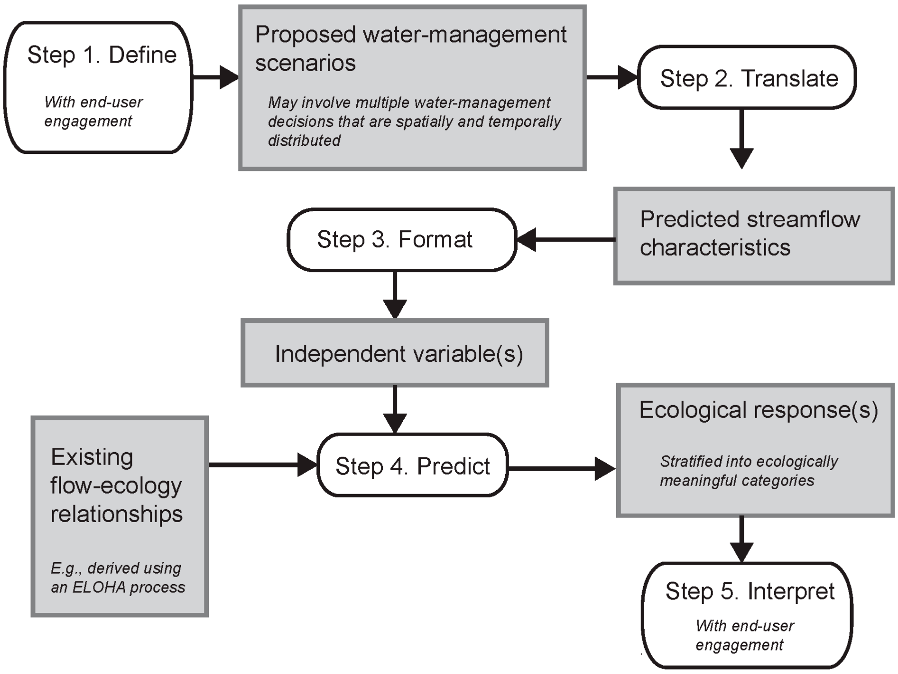

Figure 1. A conceptual model to operationalize flow–ecology relationships into decision-support systems for water-resource managers.

To illustrate this four-step process, we present a case study in the Cumberland Plateau of Tennessee and Kentucky, USA, in which existing flow–ecology relationships were operationalized into a DSS for prediction of fish community response to hypothetical water-management scenarios. Specifically, ecological-limit functions from [52] predict the upper bounds on fish species richness in response to cumulative hydrologic departure from reference conditions. Thus, for a given magnitude of cumulative hydrologic departure (as defined and quantified in [52]), ecological-limit functions predict the maximum fish species richness if other factors (e.g., water quality, habitat condition) are non-limiting. Thus, the DSS described here translates alternative water-management scenarios into predicted hydrologic response and predicted upper bounds on fish species richness.

This DSS directly addresses priorities of the National Park Service [53] and was developed in the prevailing management context (a partially regulated river system) and scale (local watershed) at which water-allocation decisions are commonly made [38]. The DSS allows simultaneous evaluation of multiple components of the hydrologic and water-infrastructure system, including withdrawals for municipal water supply, effluent discharges from wastewater treatment, inter-basin water transfer, and dam operation protocols, representing some of the many socio-economic, regulatory, and technical considerations that must be weighed by water-resource managers [54,55].

In developing this case study, our goal was to operationalize existing flow–ecology relationships into a DSS that will be of practical benefit to local water-resource managers. To achieve this, our primary objectives were to:

1. Model the effects of hypothetical flow alterations on streamflow characteristics known to be ecologically relevant to fish communities in this region.
2. Apply existing flow–ecology relationships relating fish community response to streamflow alteration to predict fish species richness under the influence of the hypothetical alterations, subdivided by fish category based on trophic and habitat characteristics.
3. Demonstrate a workflow to allow simultaneous evaluation of multiple alternative water-management scenarios in terms of their predicted effects on fish communities.

2. Materials and Methods

2.1. Case Study

This case study was conducted in the northern part of the Cumberland Plateau section of the Appalachian Plateaus Physiographic Province of Tennessee and Kentucky, USA (Figure 2A). This region is rich in biodiversity and supports a number of federally listed endangered species, including freshwater mussels and riparian plants [56]. The Big South Fork National River and Recreation Area (BISO) and Obed Wild and Scenic River (OBRI), Figure 2B, are managed by the National Park Service to conserve nationally important riverine biological communities and the flow regimes and water quality needed to sustain them. Within OBRI, the Obed River is listed under Tier III Outstanding Natural Resource Waters (ONRW) [57].

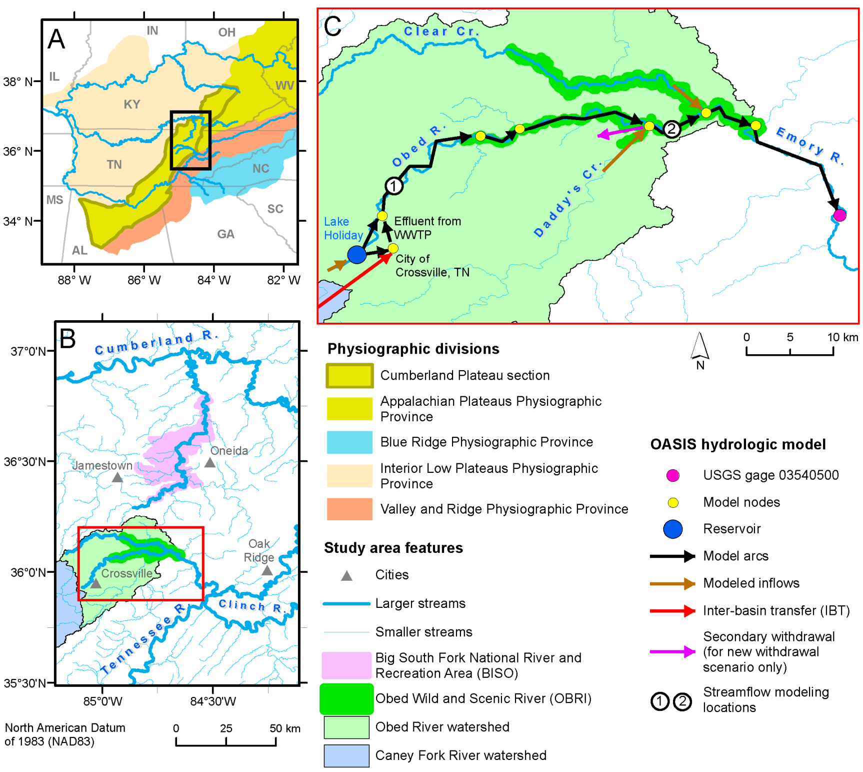

Figure 2. Map location of the case study depicting: (**A**) geographic context of the northern Cumberland Plateau; (**B**) locations of major rivers, protected areas, and cities; and (**C**) components of the OASIS hydrologic model for the Obed River. AL = Alabama, GA = Georgia, IL = Illinois, IN = Indiana, KY = Kentucky, MS = Mississippi, NC = North Carolina, OH = Ohio, SC = South Carolina, TN = Tennessee, WV = West Virginia, Cr = Creek, R = River.

The Obed River Basin includes several infrastructure features that influence stream hydrology (Figure 2C). Lake Holiday is a reservoir on the Obed River that supplies municipal water to the City of Crossville, Tennessee (0.059 m^3/s average withdrawal in 2014). Downstream, the Crossville wastewater treatment plant (WWTP) releases treated effluent (0.096 m^3/s annual average) into the Obed River [58,59]. In this system, effluent discharge exceeds upstream withdrawal because of an inter-basin transfer (IBT) from the Caney Fork River Basin into the Obed River Basin. Immediately below Lake Holiday, the Obed River is listed as impaired for fish and aquatic life because of streamflow and habitat alteration. Immediately downstream of the Crossville WWTP, the river is impaired because of nutrient concentrations [60].

2.2. Development of a Decision-Support System

2.2.1. Step 1: Define Flow Alterations

Hypothetical flow-alteration scenarios were defined for the case study in consultation with natural-resource managers at the National Park Service. It should be noted that these scenarios represent hypothetical possibilities rather than planned or proposed policies. A baseline scenario and four water-management scenarios representing hypothetical flow alterations were developed using current and hypothetical rates of water withdrawal and effluent discharge (Table 1).

- Baseline: The baseline scenario represents the current operational environment in the modeled system, including existing facilities and their current operating rules.
- Decreased IBT: The decreased inter-basin transfer (IBT) scenario represents a hypothetical reduction in IBT from the Caney Fork River Basin to the Obed River Basin. The rate of municipal water withdrawal from the reservoir is increased while the rate of effluent discharge is maintained the same as baseline.
- Increased demand: The increased demand scenario simulates future urban growth resulting in increased demand on municipal water supplies. Rates of reservoir withdrawal and effluent discharge are both increased by 50 percent. Because this scenario maintains the baseline IBT arrangement, the rate of IBT from the Caney Fork River Basin to the Obed River Basin is also effectively increased by 50 percent.
- New withdrawal: The new withdrawal scenario adds a hypothetical secondary instream withdrawal site on the Obed River immediately upstream of the confluence with Daddy's Creek (Figure 2C), at a rate of 0.087 m^3/s, while maintaining other operations the same as baseline.
- Minimum release: The minimum release scenario aims to balance reservoir storage with downstream flow by imposing hypothetical minimum release protocols that determine the percent of reservoir inflow that must be released as outflow to the Obed River as a function of reservoir storage conditions. Municipal water withdrawals and effluent discharges are maintained the same as baseline.

Table 1. Descriptions of water-management scenarios for defining flow alterations in the case study. (m^3/s, cubic meters per second; IBT, inter-basin transfer).

Scenario [1]	Minimum Release Protocol for Dam Operation	Withdrawal from Reservoir	Effluent Discharge	Secondary Withdrawal [2]
Baseline: represents the current operational environment	None [3]	0.059 m^3/s [4]	0.096 m^3/s [5]	None
Decreased IBT: reduces IBT from the Caney Fork River Basin to the Obed River Basin	None	0.175 m^3/s	0.096 m^3/s	None
Increased demand: withdrawal from reservoir and wastewater return increased 50 percent over baseline	None	0.089 m^3/s	0.144 m^3/s	None

Table 1. *Cont.*

Scenario [1]	Minimum Release Protocol for Dam Operation	Withdrawal from Reservoir	Effluent Discharge	Secondary Withdrawal [2]
New withdrawal: adds a hypothetical second water withdrawal site; see Figure 2C	None	0.059 m^3/s	0.096 m^3/s	0.087 m^3/s
Minimum release: imposes a minimum release protocol on dam operation [6]	If $x \leq 30$, y = 25; if $30 < x \leq 50$, y = 40; if $50 < x \leq 75$, y = 50; if $x > 75$; y = 75	0.059 m^3/s	0.096 m^3/s	None

Notes: [1] All scenarios were modeled over the hydrologic period of record (water years 1927 to 2014) for USGS stream gauge 03540500, Emory River at Oakdale, Tennessee; [2] Located on the Obed River immediately upstream of the confluence with Daddy's Creek; see Figure 2C; [3] The reservoir in this system (Lake Holiday) currently does not provide a guaranteed minimum outflow to the Obed River [59]; [4] Water withdrawal from Lake Holiday for the City of Crossville, Tennessee, modeled over the period of record at the 2014 average annual rate [58]; [5] Effluent discharged from the Crossville wastewater treatment plant into the Obed River downstream of Lake Holiday, modeled over the period of record using the average annual rate reported by [59]; [6] x is reservoir storage for Lake Holiday in percent; y is percent of inflow to Lake Holiday released as outflow to the Obed River.

2.2.2. Step 2: Translate Flow Alterations into Predicted Streamflow Characteristics

These hypothetical flow alterations were translated into predicted streamflow characteristics (SFCs) representing the magnitude, duration, frequency, timing, and rate of change of the annual hydrograph (Table S1); see table I of [61] for SFC definitions. To achieve this translation, the OASIS hydrologic accounting framework (HydroLogics, Chapel Hill, NC, USA) was applied to the Obed River and its tributaries (Figure 2C). OASIS is a spatially explicit mass-balance model operating on a daily time step, such that streamflow at each point in the model (node) is calculated by adding inflows (e.g., upstream flow, effluent discharge) and subtracting outflows (e.g., water withdrawals, reservoir evaporation). Mean daily streamflow data were retrieved from the U.S. Geological Survey (USGS) National Water Information System for the Emory River at Oakdale (Tennessee, USA, USGS gauge 03540500, located at 35°58′59″ N, 84°33′29″ W, drainage area: 1979 km^2), of which the Obed River is a tributary, for water years 1927–2014 [62]. A water year is defined as 1 October of the previous year to 30 September of a given year. For simplicity in this proof-of-concept study, inflows upstream of this gauge were modeled using drainage-area adjustments on daily streamflow values [63]. For each scenario, the OASIS model simulated a streamflow time series on a daily time step for water years 1927 to 2014 at two locations: (1) immediately downstream of the Crossville WWTP and (2) immediately downstream of the Daddy's Creek confluence, within OBRI (Figure 2C). Reservoir storage was also modeled on a daily time step for the same period. At these locations, SFCs for the OASIS-simulated streamflow time series were calculated using the USGS EflowStats package for the R software environment [64].

2.2.3. Step 3: Format Independent Variables for Flow–Ecology Relationships

The flow–ecology relationships used in this case study consist of a set of equations signifying statistically discernible upper bounds on fish species richness as functions of cumulative hydrologic departure from reference conditions [52]. Detailed descriptions of data and methods that produced these flow–ecology relationships are presented in [52,65] and are summarized as an annotated workflow in Figure S1. This case study required that the SFCs obtained in step 2 be formatted in terms of cumulative hydrologic departure from reference conditions [52,61] for use as independent variables in flow–ecology relationships for the Cumberland Plateau (Figure S2, Table S2).

2.2.4. Step 4: Predict Ecological Responses

Using the existing flow–ecology relationships for the Cumberland Plateau and the cumulative hydrologic departure values from Step 3, upper limits of fish-species richness were predicted for each modeling location and scenario. In a few cases, predicted fish-species richness was negative because of high levels of hydrologic alteration and negative slope of flow–ecology relationships; these values were set to zero. Fish-species richness predictions were stratified according to ecologically meaningful categories based on trophic, habitat, and reproductive characteristics; see table I in [52] for fish category definitions. Because flow–ecology relationships were developed independently for each fish category (Figure S2 and Table S2), predicted fish-species richness could not be compared directly from one fish category to another. However, within each fish category, predicted fish-species richness can be compared across water-management scenarios and between streamflow modeling locations.

3. Results

3.1. Streamflow Responses to Water-Management Scenarios

Flow-duration curves based on modeled streamflow indicated noticeable differences, primarily at low-to-moderate flows, across the 5 water-management scenarios (Figure 3). The nature of these differences varied depending on model location and MAF of the water year. For the driest year in the period of record (lowest MAF), differences across scenarios were generally greater than for the wettest year (highest MAF). This was the case both for Location 1 (downstream of the Crossville WWTP; Figure 3A,C, respectively) and for Location 2 (downstream of the Daddy's Creek confluence, Figure 3B,D, respectively).

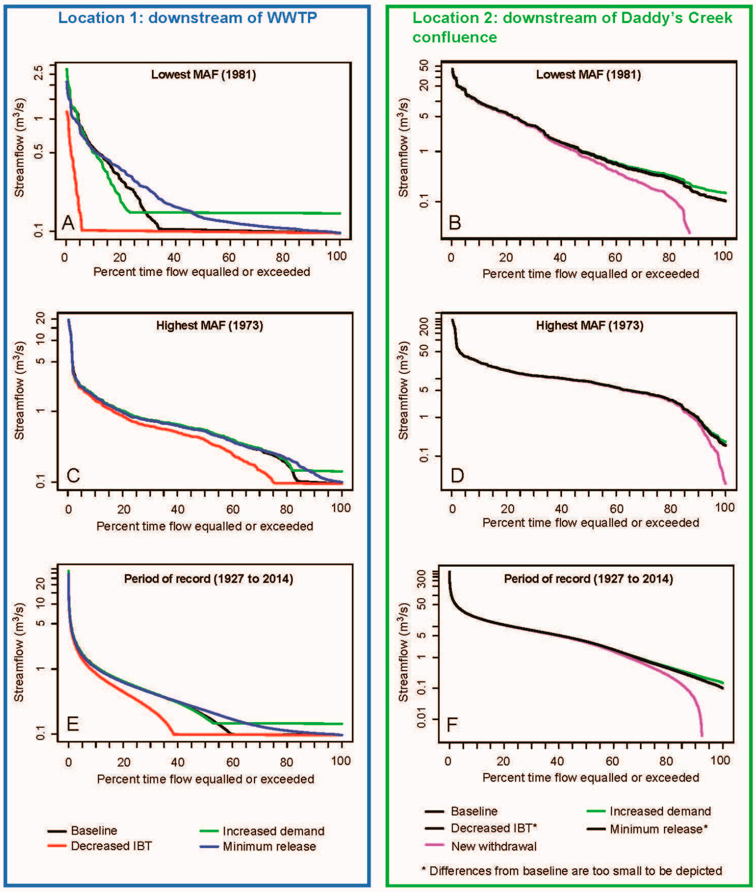

Figure 3. Flow-duration curves for modeled streamflow based on water-use scenarios for model Locations 1 (left) and 2 (right); see Figure 2C for model locations. Curves are presented for: (**A**,**B**) the year with the lowest MAF; (**C**,**D**) highest MAF; and (**E**,**F**) the entire period of record. The new withdrawal scenario does not apply to Location 1 because the secondary withdrawal site is downstream (see Figure 2C). At Location 2, differences from baseline are too small to be depicted for the decreased IBT and minimum release scenarios. IBT = inter-basin transfer, MAF = mean annual flow, Q = streamflow, WWTP = wastewater treatment plant, m^3/s = cubic meters per second.

Differences were considerable at Location 1 across scenarios, for the driest year, wettest year, and for the entire period of record (Figure 3A,C,E, respectively). At this location, which is immediately downstream of where scenarios were applied, thresholds on low flow were apparent for several scenarios and resulted from modeled wastewater returns from the Crossville WWTP (0.096 m^3/s for the baseline and decreased IBT scenarios; 0.144 m^3/s for the increased demand scenario). These wastewater returns provided a minimum threshold on streamflow about 40 percent of the time in the baseline scenario over the period of record (Figure 3E) and about 65 percent of the time in the driest year (Figure 3A).

In contrast to flows at Location 1, differences in modeled streamflow were largely dissipated downstream at Location 2 (Figure 3B,D,F), because of the inflow from Daddy's Creek that was unaffected by scenarios. At this location, differences from baseline for the decreased IBT and minimum release scenarios were negligible. Thresholds on low flow resulting from modeled wastewater returns were not apparent at Location 2.

The decreased IBT scenario noticeably reduced streamflow at Location 1 (Figure 3A,C,E) especially in the driest year (Figure 3A), indicating the importance to streamflow at this location of water delivered to the Obed River from the Caney Fork River Basin. By contrast, the minimum release scenario—which imposed rules on reservoir release as a function of reservoir storage—provided increased streamflow relative to baseline at Location 1. The effects on streamflow of both these scenarios were almost entirely dissipated downstream at Location 2 because of inflow from Daddy's Creek (Figure 3B,D,F).

Adding a hypothetical secondary withdrawal site immediately upstream of the Daddy's Creek confluence (the new withdrawal scenario; see Figure 2C) appreciably reduced flow at Location 2. According to this scenario, streamflow in the Obed River would be reduced to zero approximately eight percent of the time on average over the period of record (Figure 3F) and approximately 13 percent of the time during the driest year (Figure 3A).

3.2. Fish Community Responses to Water-Management Scenarios

Differences in modeled streamflow based on water-management scenarios affected predictions of fish species richness for several fish categories based on trophic, habitat, and reproductive characteristics (Figure 4); for fish category definitions see [52,66]. Scenario differences from baseline in terms of predicted species richness varied depending on model location and fish category. For the category encompassing all fish species (Figure 4A), predicted richness at Location 1 was somewhat lower than baseline for the decreased IBT scenario and considerably higher for the minimum release scenario. For the intolerants category—which includes species that are particularly sensitive to physical and chemical disturbances [66]—species richness at Location 1 was decreased relative to baseline under the decreased IBT and increased demand scenarios, and increased under the minimum release scenario (Figure 4B). Downstream at Location 2, predicted richness for all species and for intolerants was at the level expected under reference hydrologic conditions, regardless of scenario.

When fish species were categorized based on habitat characteristics, pool dwellers (Figure 4C) showed somewhat different responses to water-management scenarios than did riffle dwellers (Figure 4D). At Location 1, the decreased IBT and increased demand scenarios both reduced predicted species richness for pool dwellers relative to baseline, whereas only the decreased IBT scenario produced this effect for riffle dwellers. At this location, the minimum release scenario increased predicted richness relative to baseline for both pool and riffle dwellers. Downstream at Location 2, the new withdrawal scenario reduced predicted richness for pool dwellers but not for riffle dwellers, while all other scenarios were no different from baseline and were at levels expected under reference hydrologic conditions.

Fish categories based on reproductive and trophic characteristics also showed varying patterns of response to water-management scenarios. For lithophilic spawners (Figure 4E) and specialized insectivores (Figure 4F) at Location 1, predicted richness was reduced relative to baseline under the decreased IBT and increased demand scenarios and was increased relative to baseline for the minimum release scenario. For these fish categories at Location 2, predicted richness was reduced relative to baseline for the new withdrawal scenario, but was equivalent to baseline and at levels expected under reference hydrologic conditions for all other scenarios.

Notwithstanding differences across fish categories, certain general trends in predicted species richness were apparent. Across all fish categories and scenarios, predicted richness at Location 2 equaled or exceeded richness upstream at Location 1, reflecting generally reduced hydrologic departure from reference conditions at the downstream model location. Indeed, predicted richness at Location 2 was generally at levels expected under reference hydrologic conditions, except under the new withdrawal scenario for three fish groups. Moreover, differences in predicted richness across scenarios were generally less pronounced at Location 2 than at Location 1, indicating that downstream effects of water-management influences applied at upstream locations in the model (i.e., the decreased IBT, increased demand, and minimum release scenarios) were moderated by tributary inflows that were unaffected by these scenarios. In particular, for all fish categories, the minimum release scenario was associated with increased predicted richness relative to baseline at Location 1 but not Location 2. This suggests that imposing new reservoir release requirements could potentially increase fish species richness immediately downstream of reservoir operations, but that these gains would likely not be realized further downstream.

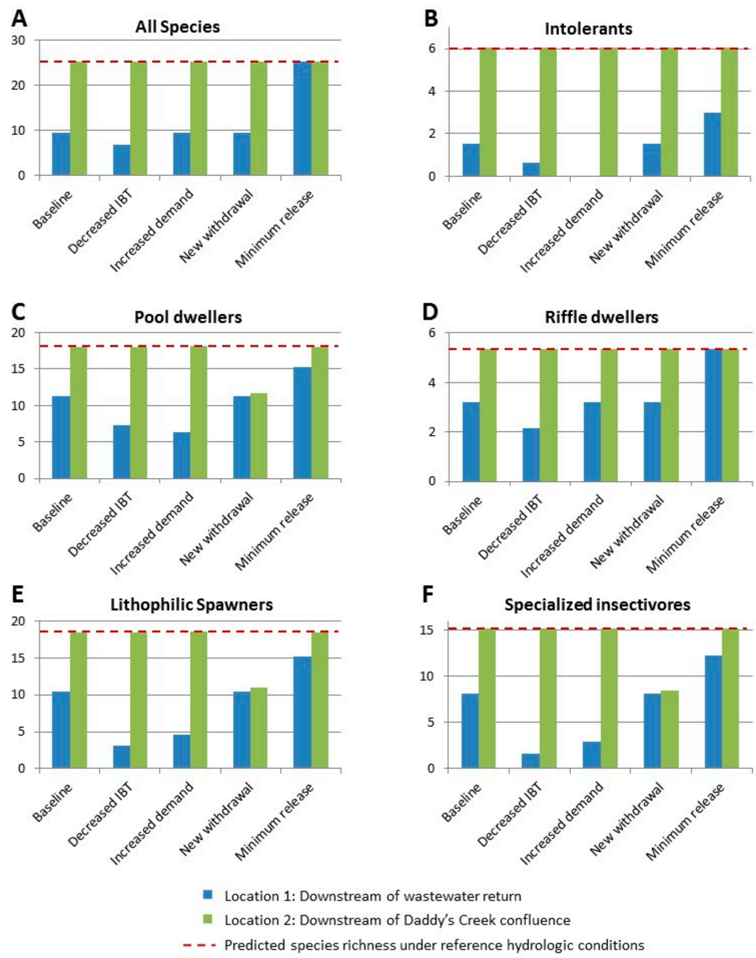

Figure 4. Predicted fish species richness for model Locations 1 and 2 based on water-use scenarios for: (**A**) all species; (**B**) intolerants; (**C**) pool dwellers; (**D**) riffle dwellers; (**E**) lithophilic spawners; and (**F**) specialized insectivores; see Table I in [52] for fish category definitions; dashed black lines indicate predicted species richness under reference hydrologic conditions (i.e., intercept values from flow–ecology relationships, see Figure S2 and Table S2).

4. Discussion

Water-resource managers are commonly tasked with balancing competing priorities, e.g., maintaining aquatic ecosystem health while also providing adequate water for municipal, agricultural, and industrial uses. Thus, for a DSS to be useful and relevant to water managers, it needs to effectively translate alternative water-management scenarios into spatially explicit predictions of ecological response. This paper presented a general workflow for DSS development and, through a case study, an example DSS that meets this need. This approach could be adapted to other river systems or ecological targets (e.g., macroinvertebrate communities, and riparian vegetation) where appropriate flow–ecology relationships have been developed, using the general process outlined in Figure 1.

4.1. A DSS for Real-World Decision-Making

For a DSS to bridge the gap between science and management practice, it must extend beyond generalized prescriptions for optimal flow regimes across a region to instead support the types of decisions that are actually faced by water-resource managers, either in a regulatory context (e.g., should a given withdrawal permit request be approved) or an infrastructure-management context (e.g., should outflow from a given reservoir be increased). To be useful to managers, a DSS needs to provide information at the required scale (typically local) and level of biological specificity (typically high). It must also integrate the effects of multiple spatially and temporally distributed hydrologic alterations, both existing and proposed, using flexible and transparent methods to produce ecologically meaningful predictions (Box 1).

The case study presented here demonstrates proof-of-concept for a DSS that meets these demands by enabling evaluation of various proposed or hypothetical flow alterations based on spatially explicit predictions of fish community response. It supports simultaneous analysis of multiple (possibly competing) components of the ecohydrologic and water-infrastructure system, including flow needs for fish species, withdrawals for municipal water supply, effluent discharges from wastewater treatment, inter-basin water transfers, and reservoir storage needs [1]. In doing so, it highlights a key capability of hydrologic accounting models: to predict the synoptic hydrologic effects of multiple flow alterations that are dynamic across time and space. In complex hydrologic systems, this capability is necessary to translate proposed changes in human water use into robust predictions of ecological response. While we found the OASIS model to be a useful accounting model for this purpose, other options are available including rainfall–runoff approaches (e.g., [67]).

4.2. Meeting the Information Needs of Water-Resource Managers

This case study yielded several findings that illustrate the types of temporally, spatially, and ecologically explicit information that can be provided to water-resource managers when flow–ecology relationships are effectively operationalized into a DSS. For example, differences in modeled streamflow across water-management scenarios were most apparent under low-flow conditions (Figure 3), suggesting that seasonal low flows in summer and early autumn represent a critically important context for evaluating ecological effects of water-management decisions [6,10]. In addition, pronounced spatial differences were apparent in response to water-management scenarios. Modeled streamflow and predicted fish species richness both showed considerable sensitivity to water-management scenarios at the upstream location (Location 1, immediately downstream of dam operations and effluent release), but these effects were largely dissipated downstream at Location 2, moderated by tributary inflow that was unaffected by the modeled scenarios. In addition, differences in ecological response to water-management scenarios were apparent when fish species were categorized based on habitat, trophic, and reproductive characteristics. These differences highlight the importance of stratifying predictions into ecologically meaningful categories, rather than assuming generalized flow–ecology relationships and applying them to entire communities. This level of biological detail is particularly important in contexts where natural-resource managers are tasked with conserving habitat for specific species or groups of species, e.g., rare, native, and/or environmentally sensitive [20,53,68,69]. In such cases, single-species flow–ecology relationships might be useful (e.g., to predict abundance or probability of occurrence of individual species of conservation concern), and could be incorporated into the DSS framework in Figure 1.

Predictions for several of the water-management scenarios evaluated in the case study are directly relevant to tradeoffs between human water needs and ecosystem function, which may intensify as demands on water resources increase within the study area [70] and in many other watersheds globally [1,4,22,71]. For example, incorporating a hypothetical secondary water withdrawal site within the Obed River Basin resulted in greater frequency of low-flow conditions and reduced predicted fish species richness for pool dwellers, lithophilic spawners, and specialized insectivores immediately downstream at Location 2. In practice, such decisions would necessarily require that these predicted consequences be weighed against any economic or social benefits of additional water withdrawals. Similarly, priorities such as maintaining adequate reservoir storage to buffer against possible droughts must be balanced against ecological flow needs downstream [55]. Predictions generated by the DSS in this case study—namely, that imposing new minimum release requirements on dam operations would enhance low flows and fish species richness relative to baseline conditions at Location 1—illustrate the types of information needed to support decision-making in the context of multiple competing priorities.

4.3. Transparency and Adaptability

The tradeoffs described above illustrate the importance of transparency and consistency in order for a DSS to provide concrete benefits in cases of conflict over water resources [1,17,29]. The DSS presented in the case study has a number of important advantages over informal, ad hoc, or experience-based approaches to water allocation. In particular, transparency is maintained by input data sources that are peer-reviewed, published, and freely available and by the use of rule-based hydrologic accounting algorithms that produce consistent numeric predictions of streamflow and fish response. Engagement of stakeholders and end-users in model development is also important for a DSS to be trusted as a source of impartial information.

Adaptability is another key feature of any useful DSS, because conditions, needs, and priorities commonly evolve over time and because, ideally, water-management actions are part of a larger adaptive management cycle allowing for iterative adjustments [28,29]. Flexibility and modularity are key advantages of the DSS developed in the case study, allowing future model refinements to take advantage of additional data and opportunities for prediction. It should be noted that the case study presented here represents a proof-of-concept approach rather than a fully developed predictive model. Thus, the results it generated are not intended to be definitive predictions of hydrologic or fish community outcomes for the Obed River. Specifically, the case study DSS involves several simplifications and limitations (i.e., input streamflow data derived from a single gauge, a limited number of streamflow modeling locations, and temporally static rates of water withdrawal, effluent discharge, and IBT) that could be refined in future model applications to produce a more sophisticated and realistic analysis. Because the hydrologic accounting model used in this DSS is modular, additional scenarios, streamflow modeling locations, dam operational protocols, modeled inflows, or water-management sites can be incorporated efficiently.

4.4. Challenges and Opportunities

The conceptual framework and case study presented here involve the application of existing flow–ecology relationships for DSS development. We recognize that, while the science on flow–ecology relationships is now substantial [15,16], it is neither complete nor universally available in the form of locally specific predictive flow–ecology equations [28]. In particular, stratified flow–ecology relationships based on ecologically relevant characteristics (e.g., guilds, functional traits, habitat preference) are unavailable for many river systems.

The conceptual framework presented here is intended to make use of the best available data and predictive models, and to be updated as flow–ecology relationships are refined and improved over time. Because existing flow–ecology relationships commonly rely on a number of simplifying assumptions, an important frontier of water-resources DSS development involves improved methods to characterize flow–ecology relationships that are more sophisticated and reflective of real-world ecohydrologic processes. For example, nonlinear ecological responses to flow alteration (e.g., thresholds) may exist that are inadequately accounted for in linear flow–ecology relationships, such as those from [52] that were employed in our case study. Correlations among ecologically relevant components of the flow regime may exist, with potential to bias predictions of ecological response; in which case modeling approaches robust to multicollinearity (e.g., machine learning techniques) could be explored. Furthermore, the interactive effects of streamflow, water quality, and physical habitat characteristics on ecological responses are widely recognized [72–74] but rarely incorporated into flow–ecology relationships [28,75]. Data on other limiting factors in fluvial ecosystems (e.g., concentrations of nutrients, dissolved oxygen, and suspended sediment) are typically not available at the same temporal extent and resolution as streamflow data (i.e., daily observations spanning decades), however a variety of existing modeling approaches (e.g., [76,77]) may prove useful to incorporate estimates for these variables into predictive models of stream ecology. Additionally, most existing flow–ecology relationships (including [52]) do not explicitly model ecological processes such as competition, predation, migration, or population genetic changes. As flow–ecology relationships are refined and updated, they can be readily incorporated into our conceptual approach (Figure 1); however if these relationships predict ecological responses to drivers other than streamflow, additional methods would be needed to translate water-management scenarios into these additional independent variables.

Ideally, predictions of ecological response to water-management scenarios would be accompanied by quantified measures of uncertainty (e.g., confidence intervals) surrounding those predictions. In practice, uncertainty quantification is challenging—and in some cases impossible—due to the presence of multiple interacting (and often unmeasured) forms of uncertainty including observational limitations, parameterization, feedbacks, and stochastic effects [78,79]. For example in our case study, sources of uncertainty included: (a) input data, e.g., stream-gauge data, fish community data, and water-use data; (b) statistical models, e.g., regional regression equations from [61] to estimate streamflow characteristics at ungauged sites; and (c) process-based models, e.g., hydrologic accounting methods that assumed temporally static water-use rates; none of which were accompanied by estimates of uncertainty. Such situations are common in multi-disciplinary modeling applications that link multiple, complex components [78]. Therefore, a research frontier in designing useful DSS for water-resource managers involves the rigorous assessment of uncertainty associated with each dataset and model component, coupled with state-of-the-art computational techniques for propagating uncertainty through complex hierarchical systems (e.g., [79,80]).

In addition to methodological challenges, stakeholder engagement and real-world DSS application are ongoing challenges to the integration of ecological flows science into water-management decisions [19,29]. In most cases, flow–ecology relationships alone do not constitute a useful DSS, because water-resource managers and other stakeholders do not decide flow regimes directly. Rather, they consider particular hydrologic alterations that are integrated over space and time with other natural and anthropogenic components of the river system to determine flow regimes. For this reason, the integration of flow–ecology relationships with hydrologic accounting frameworks provides a promising approach toward development of DSS that provide timely and relevant information to support water-management decisions. This integration allows water-resource managers to weigh the economic and social benefits of a particular proposed flow alteration against its predicted ecological outcomes. As new flow–ecology relationships are developed and existing relationships are refined over time using new data, this integrated approach has the potential to provide timely and effective translation of these scientific advancements into evidence-based water-resource management.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/9/3/196/s1, Figure S1: Annotated workflow for development of flow–ecology relationships used in the case study, Table S1: Interquartile ranges defining hydrologic reference conditions for the Cumberland Plateau in northern Middle Tennessee and southeast Kentucky, Figure S2: Flow–ecology relationships for 138 sites on the Cumberland Plateau of Tennessee and Kentucky, Table S2: Streamflow characteristics, expressed as hydrology departure from reference conditions, used in ecological limit functions for the Cumberland Plateau in northern Middle Tennessee and southeast Kentucky and ecological limit function parameter estimates, Table S3: Streamflow characteristics describing modeled streamflow time-series for water-management scenarios at model Location 1, Table S4: Streamflow characteristics describing modeled streamflow time-series for water-management scenarios at model Location 2.

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