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RESEARCH

Application of Effective Discharge Analysis to Environmental Flow Decision-Making

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Abstract Well-informed river management decisions rely on an explicit statement of objectives, repeatable analyses, and a transparent system for assessing trade-offs. These components may then be applied to compare alternative operational regimes for water resource infrastructure (e.g., diversions, locks, and dams). Intra- and inter-annual hydrologic variability further complicates these already complex environmental flow decisions. Effective discharge analysis (developed in studies of geomorphology) is a powerful tool for integrating temporal variability of flow magnitude and associated ecological consequences. Here, we adapt the effectiveness framework to include multiple elements of the natural flow regime (i.e., timing, duration, and rate-of-change) as well as two flow variables. We demonstrate this analytical approach using a case study of environmental flow management based on long-term (60 years) daily discharge records in the Middle Oconee River near Athens, GA, USA. Specifically, we apply an existing model for estimating young-of-year fish recruitment based on flow-dependent metrics to an effective discharge analysis that incorporates hydrologic variability and multiple focal taxa. We then compare three alternative methods of environmental flow provision. Percentage-based withdrawal schemes outcompete other environmental flow methods across all levels of water withdrawal and ecological outcomes.

Keywords Flow regime · Functional-equivalent discharge · Hierarchical linear models · Water management · Trait-based models

List of Symbols

β_{0-7}	Coefficients of the Craven et al. (2010) model shown in Table 1
B_j	Binary variable denoting broadcast spawning (1 = Yes, 0 = No)
cfs	Cubic feet per second
CI	Confidence interval (90 % for all uses herein)
C_j	Binary variable denoting whether or not a species has a cruising morphology (1 = Yes, 0 = No)
$D_{ad,i-1,j}$	Density of adults and juveniles in the prior year
i	Year
j	Species
k	Flow regime
MFL	Annual minimum flow
MGD	Million gallons per day
mMFL	Monthly minimum flow
Q	Volumetric river discharge
Q_{m}	Monthly average discharge
Q_{mean}	Mean discharge
$Q_{\mathrm{re},i,j}$	Minimum 10-day standard deviation of discharge observed during the rearing period in year i for species j
$Q_{\mathrm{sp},i,j}$	Maximum 10-day average discharge observed during the spawning period in year i for species j
SB	Sustainability boundary

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u	Unaltered flow regime
V_{eff}	Area under the effectiveness curve
$V_{norm,j,k}$	Normalized value of the area under the effectiveness curve for each species and flow regime
$V_{norm,k}$	Normalized value of effectiveness for all species for a given flow regime
YOY	Young of year density (no/ha)

Introduction

With freshwater biodiversity in sharp decline (Strayer and Dudgeon 2010; Collen et al. 2014) and over half of the world's large rivers dammed (Nilsson et al. 2005), the need for ecologically effective river management is increasing (Baron et al. 2002; Poff and Mathews 2013; Richter 2014). A key component of conserving, managing, and restoring river ecosystems is the environmentally sensitive operation of water resource infrastructure such as diversions, locks, and dams (Freeman and Marcinek 2006; Richter et al. 2006; Rolls and Arthington 2014). The following definition states that "Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration 2007). This definition succinctly summarizes the potential for trade-offs between ecological and socio-economic objectives in water management. However, environmental flow decision-making is further complicated by many feasible flow management regimes (Tharme 2003; McKay 2013), numerous ecological endpoints (Richter et al. 2006), various ecologically relevant components of a river's flow regime (Poff et al. 1997; Bunn and Arthington 2002; Matthews and Richter 2007), and hydrologic variability (Poff 2009).

Environmental variability is a well-known driver of ecological processes in rivers (Poff and Ward 1989; Sabo and Post 2008; Auerbach et al. 2012). Hydrologic variability is defined broadly as both predictable and stochastic changes in river discharge, water level, or other hydrologically mediated variables. Hydrologic variability can serve as a "filter" for the adaptation of aquatic and riparian species (Lytle and Poff 2004), a driver of community composition (Poff and Allan 1995; Mims and Olden 2012; Rolls and Arthington 2014), and a governing mechanism for ecosystem process rates (Doyle 2005). Thus, for environmental flows to be effective, ecologists suggest that river managers must not only *manage variability*, but also *manage for variability* (Arthington et al. 2009; Poff 2009).

Effective discharge analysis (also referred to as effectiveness analysis) is a well-studied technique for coupling hydrologic variability and river processes. This analytical framework has a long history in geomorphology and river engineering (Wolman and Miller 1960; Doyle et al. 2007; Meitzen et al. 2013), and is being increasingly extended to ecological processes (e.g., Doyle et al. 2005; Wheatcroft et al. 2010; Ensign et al. 2013). Effectiveness analysis combines the magnitude of a response to discharge with the probability of that discharge occurring. Multiple indices may then be computed to summarize the response (Vogel et al. 2003; Doyle and Shields 2008; Klonsky and Vogel 2011).

Effective discharge analysis is also a useful tool for integrating hydrologic variability and discharge-mediated ecological processes (Doyle et al. 2005). However, to date, applications have considered response variables dependent only on daily discharge (e.g., sediment and organic matter transport, habitat availability, nutrient uptake; Doyle 2005; Doyle et al. 2005; Wheatcroft et al. 2010; Zarris 2010). In this study, we examine trade-offs between municipal water availability and an ecological response variable, fish recruitment, under alternative river flow patterns. Our objectives are to (1) adapt effectiveness analysis to incorporate elements of a flow regime beyond magnitude and frequency (i.e., to include timing, duration, and rate-of-change) and (2) demonstrate the application of effectiveness analysis to inform environmental flow decision-making.

Table 1 Parameter estimates for hierarchical linear model predicting young-of-year fish density (Eq. 1)

	Model parameter							
	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7
Estimate	2.182	0.619	−1.063	−0.509	−2.536	1.115	−2.022	0.313
Standard error	0.608	0.172	0.274	0.219	1.092	0.211	1.008	0.029
Lower CI	0.918	0.277	−1.601	−0.938	−4.722	0.699	−4.002	0.255
Upper CI	3.445	0.961	−0.525	−0.080	−0.350	1.530	−0.042	0.371

All parameters are directly from Craven et al. (2010) and include the estimate, standard error, and 90 % confidence intervals

Methods

Study Site

This study examines ecological and economic trade-offs associated with alternative environmental flow schemes for the Middle Oconee River near Athens, GA, USA. In 2002, the Upper Oconee Basin Water Authority constructed Bear Creek Reservoir to serve as a municipal water supply source for a four-county region. Bear Creek is a tributary to the Middle Oconee River, and the off-channel reservoir is filled by pumping water from the main stem of the Middle Oconee River (Campana et al. 2012). Since 1938, the U.S. Geological Survey has operated a streamflow monitoring gage downstream of where the reservoir intake location was constructed in 2002 (Gage Number 02217500). This long period of daily records prior to reservoir construction provides a sufficient data set with which to examine potential withdrawal schemes and accompanying environmental flows relative to a minimally altered reference condition (Stoddard et al. 2006).

Daily discharge records from 1938 to 1997 were used in the following analyses to represent the period of record available to planners and regulators prior to reservoir permitting and construction. Over this 60-year period, daily mean, median, minimum, and maximum discharges were 521, 350, 8.2, and 12,600 cubic feet per second (cfs), respectively. The reservoir is permitted to withdraw a maximum of 60 million gallons per day (MGD; Georgia EPD Permit Number 078-0304-05) subject to meeting minimum flow criteria. Currently, the reservoir typically withdraws less than 20 MGD (Campana et al. 2012), but the permitted rate represents a substantial portion of river discharge (60 MGD = 92.8 cfs), particularly during the late summer months when flow rates are lowest (September mean = 237 cfs).

Alternative Environmental Flows

Four alternative flow regimes were examined. For each simulation, the unaltered hydrograph was modified for the entire 60-year observational period (i.e., 1938–1997). Water was abstracted at a maximum rate of 60 MGD in accordance with existing pump capacity. Environmental flow thresholds were systematically varied across a wide range of values, as described below. Although previously acknowledged as operational constraints (Vogel et al. 2007), neither reservoir volume limitations nor increased water treatment costs due to turbidity of high flows were included in this analysis. The four examined scenarios of withdrawal and environmental flow requirements were as follows:

1. *Unaltered* A reference condition without any withdrawal was applied in this analysis as the best attainable ecological condition (Stoddard et al. 2006).
2. *Annual minimum flow (MFL)* This method assigns a single, year-round flow threshold below which water may not be withdrawn. Although well acknowledged as a limited approach for environmental flow provision (Arthington et al. 2006; Freeman and Marcinek 2006; Poff 2009; Richter et al. 2011), minimum flows remain extensively applied in practice (Tharme 2003; Kanno and Vokoun 2010). To assess the influence of minimum flow magnitude on ecological condition, MFL was varied from 0 to 1000 cfs by 10 cfs.
3. *Monthly minimum flow (mMFL)* This method assigns a monthly varied flow threshold below which water may not be withdrawn. This common adjustment to the MFL approach incorporates elements of flow timing not captured in MFLs (Hughes and Mallory 2008). Current regulations in the state of Georgia recommend mMFLs associated with the 7-day low flow with a 10-year recurrence interval (i.e., the "7Q10") for each month (GA DNR 2001). Similar to the minimum flow analysis, mMFL was varied in 101 intervals from the minimum observed monthly averaged flow to the maximum observed monthly averaged flow for the 60-year record for each of the 12 months.
4. *Sustainability boundaries (SB)* As a simple, first-order alternative to minimum flows, Richter (2010) and Richter et al. (2011) offer a percent-of-discharge approach, which they call sustainability boundaries and propose as the "presumptive standard" for hydrologic environmental flow rules. In our study, the percent of daily discharge available for abstraction (SB) was varied from 0 to 50 % by 0.5 %.

Ecological Response Modeling

An existing model was applied to examine ecological response to changes in the flow regime. Craven et al. (2010) present a flow-dependent model for predicting young-of-year fish recruitment for multiple species with varying traits. This hierarchical linear model (Eq. 1) incorporates flow regime variables for spawning and rearing periods as well as species traits pertaining to spawning strategy (egg broadcasting vs. non-broadcasting) and locomotion morphology (cruiser vs. non-cruiser). This model represents the best-supported of multiple alternative models for variation in juvenile fish abundances over multiple years in three eastern U.S. rivers, based on species traits and flow characteristics. To generalize the model, Craven et al. (2010) present all flow metrics for species-specific spawning and rearing periods as values normalized by the long-term mean discharge.

$$\ln(\mathrm{YOY})_{i,j} = \beta_0 + \beta_1 \frac{Q_{\mathrm{sp},i,j}}{Q_{\mathrm{mean}}} + \beta_2 \beta_j + \beta_3 \frac{Q_{\mathrm{sp},i,j}}{Q_{\mathrm{mean}}} \beta_j + \beta_4 \frac{Q_{\mathrm{re},i,j}}{Q_{\mathrm{mean}}} + \beta_5 C_j + \beta_6 \frac{Q_{\mathrm{re},i,j}}{Q_{\mathrm{mean}}} C_j + \beta_7 D_{\mathrm{ad},i-1,j}, \quad (1)$$

where YOY is young of year density (no/ha), β_{0-7} are model coefficients shown in Table 1, i is year, j is species, $Q_{\mathrm{sp},i,j}$ is the maximum 10-day average discharge observed during the spawning period in year i for species j, Q_{mean} is the mean discharge for the unaltered period of record (1938–1997), B_j is a binary variable denoting whether or not a species broadcast spawns (1 = Yes, 0 = No), $Q_{\mathrm{re},i,j}$ is the minimum 10-day standard deviation of discharge observed during the rearing period in year i for species j, C_j is a binary variable denoting whether or not a species has a cruising morphology (1 = Yes, 0 = No), and $D_{\mathrm{ad},i-1,j}$ is the density of adults and juveniles in the prior year.

More than 28 species of fish have been observed in the study reach of the Middle Oconee River near the reservoir intake (R.A. Katz and M.C. Freeman, unpublished data). Five species were selected for this analysis representing a range of life histories and species traits observed locally (Table 2): two minnow (Cyprinidae) taxa, *Cyprinella spp*. and *Notropis hudsonius*; two taxa representing sunfishes and basses (Centrarchidae), *Lepomis spp*. and *Micropterus spp*.; and one darter (Percidae) species, *Etheostoma inscriptum*. Craven et al. developed their model using data for multiple species in each of these five genera, although not necessarily the same species. Their model allowed us to predict juvenile density for Middle Oconee River taxa based on species traits and annual flow data, with the exception of the effect of prior year fish density (for which we lacked data). Following a sensitivity analysis to determine the model's dependence on this parameter (Online Appendix A), we applied a global value of six individuals per hectare for all species. Furthermore, the time-dependent property of this parameter (i.e., sequencing and dependence on the prior year density) was neglected to simplify analyses. Importantly, the objective of this analysis was not to estimate the absolute YOY density, but instead to provide a relative comparison between YOY densities under alternative flow regimes (Shenton et al. 2012).

Effectiveness Analysis

In a landmark paper for fluvial geomorphology (Meitzen et al. 2013), Wolman and Miller (1960) proposed and developed the concepts of dominant and effective river discharges. Dominant discharge is a simplifying theoretical concept that postulates there is a discharge or range of discharges disproportionately important to long-term river channel evolution. Effective discharge combines the rate of sediment transport at a given discharge (i.e., magnitude) and the probability of that discharge (i.e., frequency) to estimate the "effectiveness" of a given discharge over long time scales—a measure of geomorphic work done by flowing water. Effective discharge is calculated by multiplying the probability distribution of river discharge with a sediment rating curve to develop a sediment transport effectiveness curve; the peak of this curve is the "effective" discharge (Wolman and Miller 1960; Fig. 1a). Doyle and Shields (2008) propose the functional-equivalent discharge as a second metric of discharge effectiveness, which represents the continuous discharge required to produce the long-term sediment load (i.e., the area under the effectiveness curve; Fig. 1b). Effective discharge analyses have been extensively developed and applied to geomorphic and sediment transport processes as evidenced by broad applications (Shields et al. 2003), guidelines for computation (Biedenharn et al. 2000), software (Bledsoe et al. 2007), and review in river morphology texts (Garcia 2008). Owing to its successful application in geomorphology, Doyle et al. (2005) proposed effective discharge analysis as a promising tool for assessing ecological endpoints. Effectiveness analysis has been applied successfully to a variety of ecological processes including algal growth, macroinvertebrate drift, habitat availability (Doyle et al. 2005), organic matter transport (Doyle et al. 2005;

Table 2 Species traits for taxa examined in this analysis of the Middle Oconee River (following Craven et al. 2010)

Taxon	Broadcast spawning	Cruising morphology	Spawning season	Rearing season
Cyprinella spp.		X	April–July	May–August
Etheostoma inscriptum			April–May	May–August
Lepomis spp.			May–August	June–August
Micropterus spp.		X	April–May	May–August
Notropis hudsonius	X	X	April–July	May–August

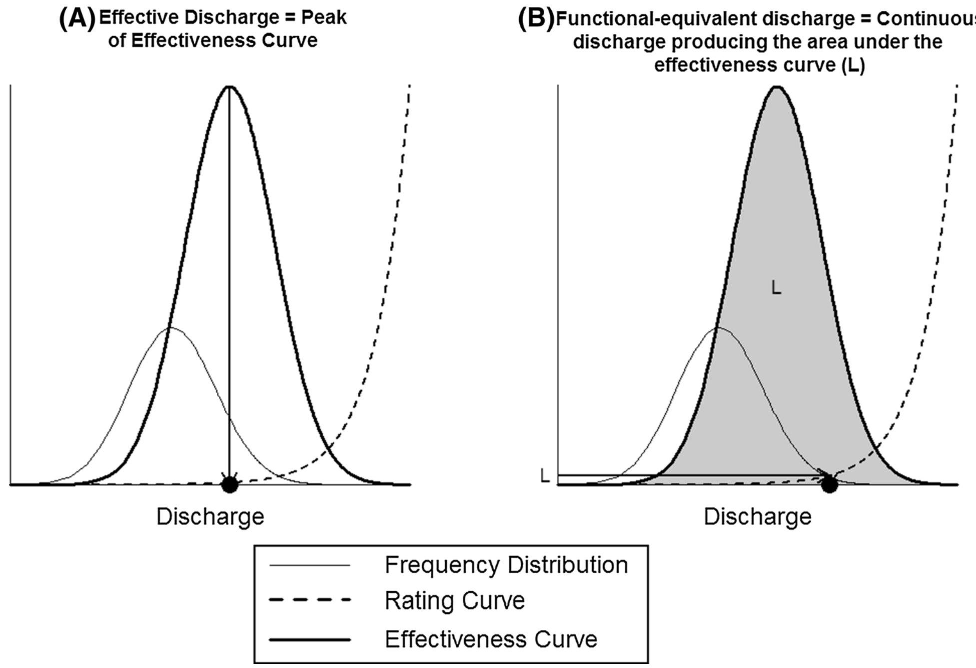

Fig. 1 Schematic drawing of effectiveness metrics (after Doyle and Shields 2008). The *y* axis of each variable has been scaled to fit onto a single plot. The effectiveness *curve* shows the product of the frequency distribution and the rating *curve*, and thus, represents the frequency-weighted rating *curve*. Multiple metrics may be derived from the effectiveness *curve*, such as the **a** effective and **b** functional-equivalent discharges

Wheatcroft et al. 2010), nutrient retention (Doyle 2005), and denitrification (Ensign et al. 2013).

Here, we adapted effectiveness analysis for use with Craven et al.'s (2010) fish recruitment model described above. Flow metrics ($Q_{\mathrm{sp},i,j}$ and $Q_{\mathrm{re},i,j}$) were calculated for each species for each year in the period of record (60 years). We then calculated a frequency distribution of these flow metrics using a nonparametric kernel density approach with a Gaussian kernel and 512 equally spaced discharge bins bound from 0 to 4,100 cfs for $Q_{\mathrm{sp},i,j}$ and 0 to 30 for $Q_{\mathrm{re},i,j}$. (Klonsky and Vogel 2011). This approach for estimating frequency distributions maintains an empirical basis rather than assuming a theoretical distribution, and has proven more repeatable and objective than techniques applying user-specified bins (Klonsky and Vogel 2011). Because the model includes two flow metrics, a joint probability distribution was obtained by multiplying the probability of each spawning season discharge with the probability of each rearing season discharge. This approach follows Craven et al.'s assumption of statistical independence of flow parameters. Craven et al.'s (2010) model was then applied to every combination of spawning and rearing season discharges as the ecological rating curve for each species. A three-dimensional effectiveness curve was computed as the product of the joint probability distribution and the rating curve (Fig. 2).

Using this approach, effectiveness curves were computed for each species and flow regime scenario. Although other metrics have been applied in effectiveness analysis such as effective, functional-equivalent, and "half-load" discharges (Wolman and Miller 1960; Vogel et al. 2003; Doyle and Shields 2008; Ferro and Porto 2012), we focus on an alternative metric due to its readily interpretable ecological meaning. We compute the volume under the effectiveness curve (V_{eff}) as the sum of effectiveness given the joint distribution of spawning and rearing season discharges for a given flow management scenario and the Craven et al. (2010) rating curve. This metric summarizes the total amount of ecological processing over the entire distribution of flows, for a particular alternative flow regime. In this case, the volume under the effectiveness curve represents a frequency-weighted estimate of total young-of-year fish recruitment. This variable is related to the functional-equivalent discharge, but is not transformed to discharge units via the rating curve (Doyle and Shields 2008).

This analysis resulted in an effectiveness metric (V_{eff}) for each combination of species and flow regime with units of fish per hectare. To increase interpretability, these metrics were normalized from zero to one and combined. First, frequency-weighted, young-of-year recruitment for each flow scenario was normalized relative to the unaltered flow regime (Eq. 2). Second, all species were combined by averaging the normalized values, which resulted in a single metric for each flow regime (Eq. 3). Averaging usefully summarizes the simulations, but species-specific information is reduced by this approach.

$$V_{\mathrm{norm},j,k} = 1 - \frac{\left|V_{\mathrm{eff},j,u} - V_{\mathrm{eff},j,k}\right|}{V_{\mathrm{eff},j,u}} \quad (2)$$

$$V_{\mathrm{norm},k} = \frac{1}{5}\left|\sum_{j} V_{\mathrm{norm},j,k},\right. \quad (3)$$

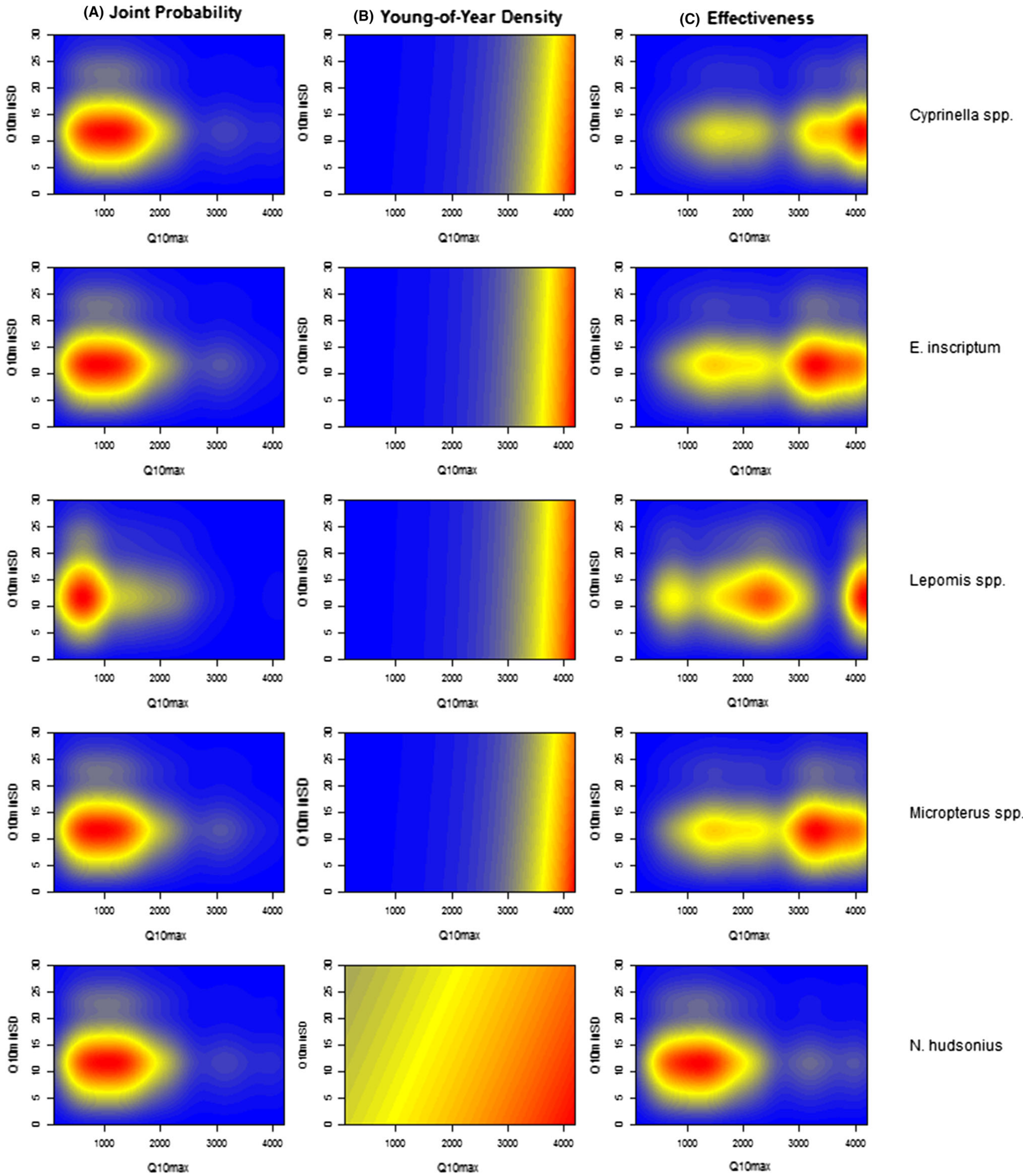

Fig. 2 Effectiveness analysis for the five focal taxa for the unaltered flow regime estimated using expected values of model coefficients. **a** Joint probability represents the joint distributions of maximum 10-day spawning period discharge ($Q_{10\mathrm{max}}$) and minimum 10-day standard deviation of rearing period discharge ($Q_{10\mathrm{minSD}}$) for the Middle Oconee River period of record. **b** Young-of-year density shows taxa-specific rating relations. **c** Effectiveness surfaces illustrate frequency-weighted young-of-year density. *Cool colors* indicate low values of probability, density, or effectiveness, while *warm colors* indicate high values. Colors are scaled from zero (*blue*) to the maximum (*red*) values for each taxon and associated figure (Color figure online)

where V_{eff} is the area under the effectiveness curve, j is a given species, k is a given flow regime, u is the unaltered flow regime, $V_{\mathrm{norm},j,k}$ is a normalized value of the effectiveness metric for each species and flow regime, and $V_{\mathrm{norm},k}$ is a normalized value representative of all species for a given flow regime.

In order to examine trade-offs with municipal water supply, flow regimes were compared relative to the average annual withdrawal rate for municipal use (in MGD) over the 60 years simulation. This allowed us to compare municipal water supply and normalized young-of-year fish recruitment ($V_{\mathrm{norm},j,k}$ and $V_{\mathrm{norm},k}$) in relation to alternative values of MFL level, mMFL level, or sustainability boundary. Three alternative parameterizations of the Craven et al. (2010) model were used to test the sensitivity of decision-making to model uncertainty (Table 1).

All computations were performed in the R statistical software package (version 2.15.2; R Development Core Team 2012), and code and data are available from the authors upon request.

Results

Frequency-weighted estimates of total young-of-year fish recruitment (V_{eff}) for the unaltered flow condition in the Middle Oconee River varied among taxa due to differences in traits, and in spawning and rearing seasons (Table 3). In particular, the taxa that combined non-broadcast spawning with the "cruiser" locomotion mode (*Cyprinella* and *Micropterus* spp.) had the highest estimated young-of-year densities. However, rating curve uncertainty resulted in an order of magnitude greater variation in density estimates within than among taxa (Table 3, Online Appendix A). To compare outcomes across alternative flow management regimes, the resulting V_{eff} values were normalized to the expected values for the unaltered scenario shown in Table 3.

For each of the alternative management regimes (MFL, mMFL, SB), increasing the threshold of required instream flow (i.e., increasing the minimum flow, or the percentage of range in natural monthly flow required above the monthly minimum, or decreasing the allowable percentage flow alteration compared to unaltered) decreased water available for municipal use (Fig. 3a–c). The corresponding effects of increasing minimum flow requirements (or loosening sustainability boundary requirements) generally were to increase similarity of expected young-of-year densities to those under the unaltered hydrograph scenario (Fig. 3d–f). An unanticipated outcome involved the positive ecological response (i.e., higher similarity to the unaltered hydrograph) for annual and mMFL alternatives with extremely high withdrawal rates (and correspondingly low minimum flow requirements; Fig. 3d, e). This result emerged as an artifact of the recruitment model, which associated low levels of discharge variability during rearing seasons with high young-of-year densities. High withdrawal rates coupled with minimum flow criteria reduced discharge variability, likely by "flat-lining" hydrographs during minimum flows (Fig. 4). In contrast, sustainability boundaries by design reduce flows while maintaining natural levels of variability (Richter et al. 2011), and a similar positive ecological response at highest withdrawal levels was not produced (Fig. 3f). The normalized effectiveness metric was also higher and less variable (>0.9 for all taxa and withdrawal levels) under the sustainability boundary alternative, compared to the two minimum flow alternatives (e.g., ranging below 0.7 for all taxa under the MFL scenarios; Fig. 3d).

The five focal taxa showed different magnitudes of response to changes in the river's hydrograph, although patterns of response in relation to changes in flow requirements were broadly similar (Figs. 3d–f). Variation in response magnitude reflected differences among taxa in spawning and rearing seasons (Table 2), and thus the effects of hydrologic change on the joint probability distribution of flow metrics ($Q_{\mathrm{sp},i,j}$ and $Q_{\mathrm{re},i,j}$). For example,

Table 3 Effectiveness metrics for each fish taxon for the unaltered flow regime

Taxon	V_{eff} (lower CI)	V_{eff} (expected value)	V_{eff} (upper CI)
Cyprinella spp.	92	3499	217,854
Etheostoma inscriptum	49	1110	39,461
Lepomis spp.	42	777	23,635
Micropterus spp.	89	3196	182,052
Notropis hudsonius	2	153	77,796

Values of V_{eff} represent the number of young-of-year individuals per hectare on a frequency-weighted basis, and are derived as the area under the effectiveness surfaces for each taxon. Values are presented with mean model coefficients (Expected Value) and the 90 % confidence intervals

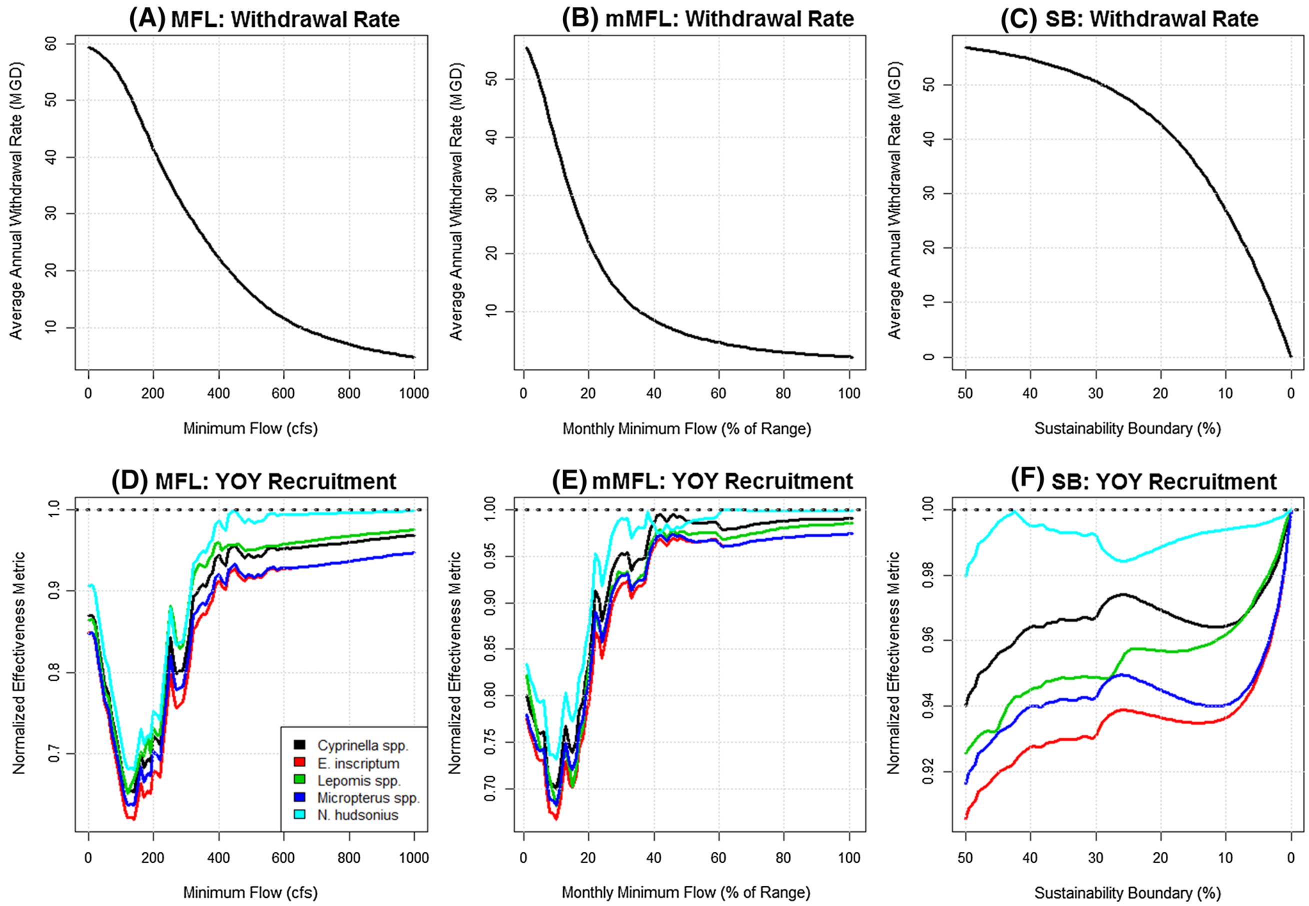

Fig. 3 Comparison of alternative flow regimes based on two metrics: **a–c** average annual withdrawal rates and **d–f** normalized young-of-year recruitment of five Middle Oconee River taxa. Alternative scales of the *y* axis are used in **d–f** to highlight among taxa differences within a single flow regime. *Dashed lines* in **d–f** represent the unaltered flow regime for comparison (Color figure online)

the hydrologic effects of all four scenarios are shown for an average annual withdrawal rate of approximately 40 MGD for the year 1941 (Fig. 4). Two example taxa (*E. inscriptum* and *Lepomis* spp.) are presented to demonstrate how hydrologic change can alter the joint probability distribution of flow metrics ($Q_{\mathrm{sp},i,j}$ and $Q_{\mathrm{re},i,j}$) over a time series including multiple years (Fig. 5). These taxa were selected because their spawning and rearing seasons represented the largest differences among focal taxa (Table 2).

Trade-off curves were developed to show a taxa-averaged view of the effectiveness metrics (i.e., $V_{\mathrm{norm},k}$) relative to withdrawal rates (Fig. 6). As with Fig. 3, minimum flow approaches show an unanticipated positive ecological response at extremely high withdrawal rates as an artifact of model construct. Importantly, sustainability boundary approaches consistently outperformed minimum flow approaches, particularly at high withdrawal rates. Results were consistent across three model parameterizations (i.e., lower confidence set, best estimate, and upper confidence set), lending confidence to the relative ranking of alternative flow regimes.

Discussion

The objectives of this paper are to (1) adapt effectiveness analysis to incorporate elements of a flow regime beyond magnitude and frequency; and (2) demonstrate the application of effectiveness analysis to environmental flow decision-making. The effective discharge framework has proven valuable in the field of geomorphology and is being applied successfully to ecological processes (Doyle et al. 2005). Previous applications of this analytical framework were limited to ecological processes with instantaneous responses to discharge (i.e., those correlated with daily discharge such as organic matter transport and habitat availability). Here, we have extended the effectiveness framework to include additional elements of a river's flow regime. To illustrate an application, we used this framework to reconsider Craven et al.'s (2010) model of fish recruitment that uses discharge metrics related to timing (i.e., spawning and rearing seasons), duration (i.e., 10-day flow windows), and rate-of-change (i.e., the standard deviation of discharge). We applied these metrics within

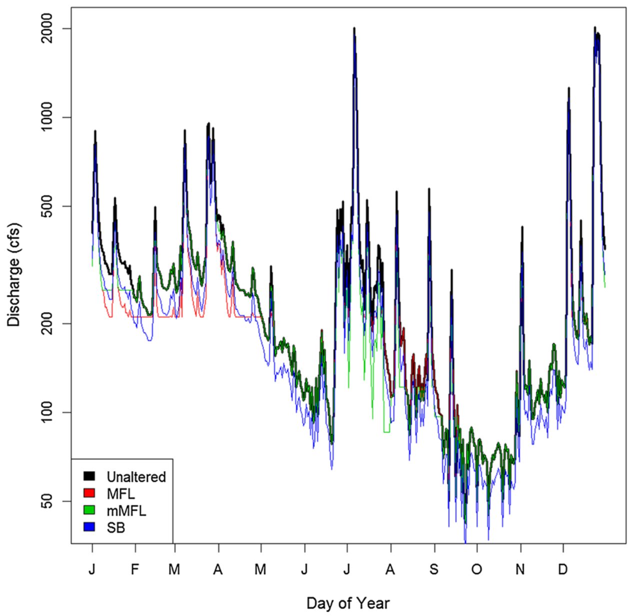

Fig. 4 Hydrographic effects of water withdrawal for an equal-volume scenario of 40 MGD average annual withdrawal rate. For each scenario the flow thresholds are as follows: MFL = 210 cfs, mMFL = $Q_{\mathrm{m,min}} + 0.08 \times (Q_{\mathrm{m,max}} - Q_{\mathrm{m,min}})$, SB = 18 %. Flow modification for the year 1941, which was a moderately dry year (10th lowest mean annual discharge on record) (Color figure online)

the effectiveness framework by calculating each metric on an annual basis and computing an associated frequency distribution. Moreover, we extended this framework to include multi-variate models with two independent variables ($Q_{\mathrm{sp},i,j}$ and $Q_{\mathrm{re},i,j}$) by using a joint probability approach. While not required to characterize sediment transport processes, multivariable models are much more common in ecological processes where complex life histories may depend on multiple components of a flow regime.

In traditional sediment transport analyses, effective discharge metrics are commonly used in channel design or assessment of an alternative flow regime's capacity to shape a channel (Shields et al. 2003). Here, we have presented an analysis that applies an effectiveness metric as an integrative response variable rather than a design target. Effectiveness analysis is shown to be a useful framework for coupling ecological processes and hydrologic variability, which can then be applied to assess large scale changes to a river's flow regime (i.e., the crux of environmental flow decision-making).

The effectiveness framework provided a powerful analytical tool for comparing the effects of alternative environmental flow regimes on fish recruitment. Comparisons across species (Fig. 3d–f) could be used not only to assess sensitivities to flow regimes (Konrad et al. 2011), but also to determine the potential for changes in community composition (Rolls and Arthington 2014) or food-web dynamics (Cross et al. 2011). Comparisons across many scenarios (Fig. 6) could allow decision-makers to assess trade-offs between ecological costs and economic benefits of alternative withdrawal schemes (Poff et al. 2010). How the decision-maker values these two endpoints could affect

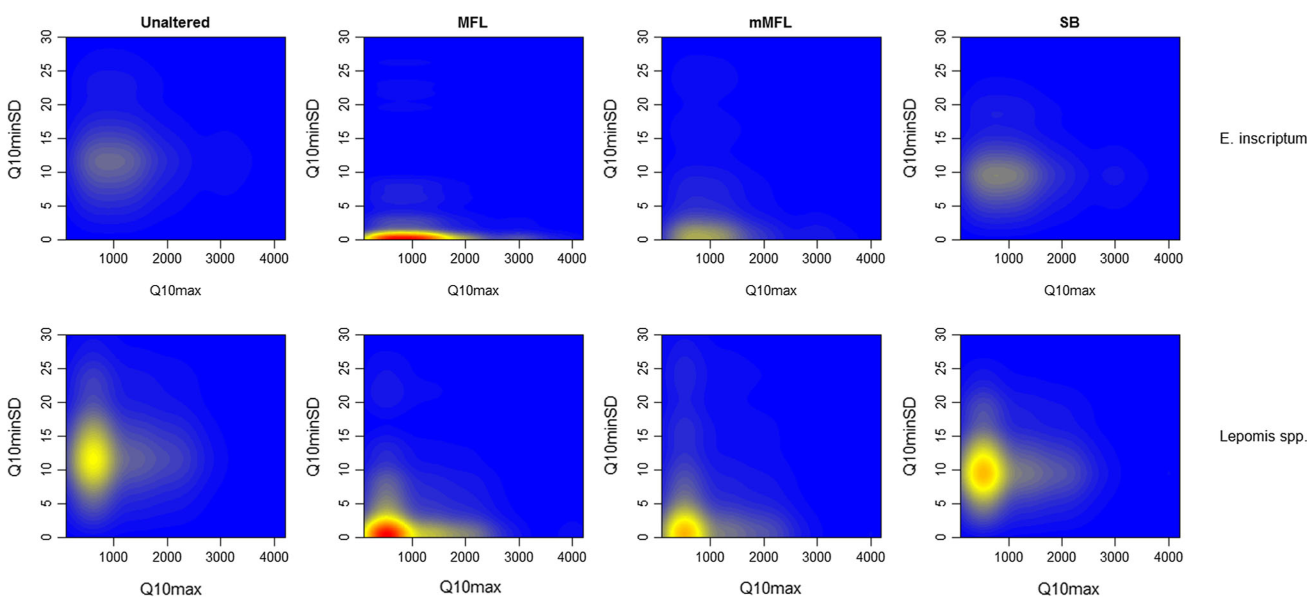

Fig. 5 Effects on the joint probability distribution of flow metrics relative to *E. inscriptum* and *Lepomis* spp. spawning and rearing seasons. As shown in Fig. 4, hydrographic effects of water withdrawal represent an equal-volume scenario of 40 MGD average annual withdrawal rate. For each scenario the flow thresholds are as follows: MFL = 210 cfs, mMFL = $Q_{\mathrm{m,min}} + 0.08 \times (Q_{\mathrm{m,max}} - Q_{\mathrm{m,min}})$, SB = 18 % (Color figure online)

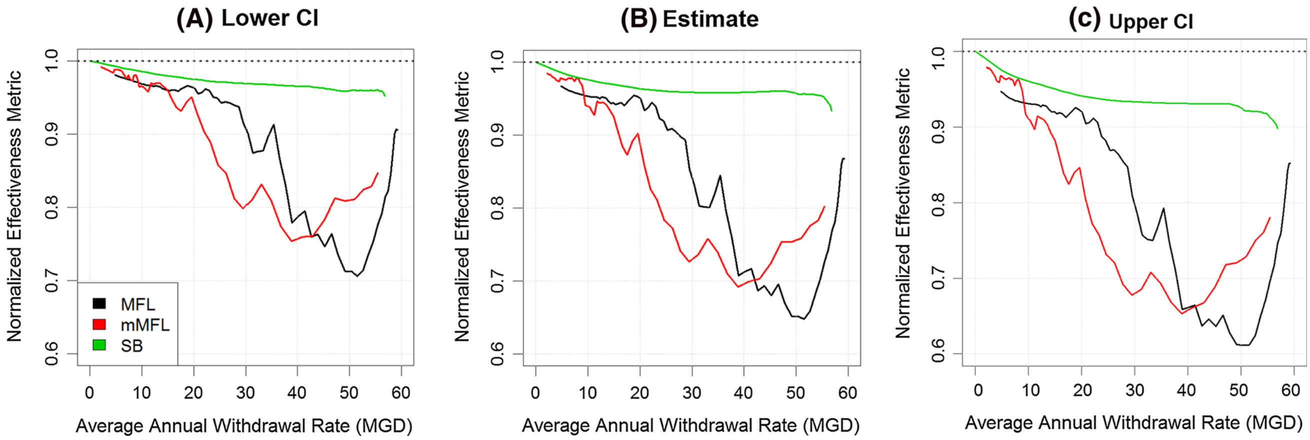

Fig. 6 Trade-offs *curves* for alternative flow regimes in the Middle Oconee River. Ecological endpoints are represented by the Craven et al. (2010) model, which has been parameterized for the **a** lower confidence set, **b** best estimate, and **c** upper confidence set. Note that alternative scales of the *y* axis are used in figures to highlight differences across parameterizations (Color figure online)

which decision may be preferable for implementation (Bryan et al. 2013). In our example, sustainability boundaries emerged as the preferred alternative for both objectives regardless of values. Interestingly, relative to fish recruitment, mMFLs under-performed MFLs for much of the withdrawal range examined, possibly as an artifact of effects on flow stability. Currently, the reservoir typically withdraws less than 20 MGD (Campana et al. 2012), but the permitted rate represents a substantial portion of river discharge (60 MGD = 92.8 cfs), particularly during the late summer months when flow rates are lowest (September mean = 237 cfs). Although environmental flow trade-offs in the Middle Oconee River are not currently contentious, conflicts over water allocation and withdrawal are most effectively addressed before they occur (Baron et al. 2002).

Habitat-based analyses have been applied broadly in environmental flow decision-making due to their repeatability, transparency, and capacity to inform trade-offs via incremental changes in flow regimes (Bovee and Milhous 1978; Jowett 1997; Jowett et al. 2008). Although they are widely applied, these approaches have been criticized due to their inherent use of a few focal taxa (often game fish species), the assumption that habitat is indicative of population processes, the lack of biological processes such as competition and predation, assumptions of "optimal" flows rather than distributions of discharge, and a lack of consideration of flow timing (Orth 1987; Shenton et al. 2012). The framework presented here directly addresses several of these concerns and provides a quantitative set of techniques for explicitly incorporating demographic processes into incremental environmental flow decision-making (Shenton et al. 2012). However, this approach requires a modeled or empirically based estimate of demographic response to flow regime, as provided by the Craven et al. (2010) model.

This analysis has examined a single ecological response variable, fish recruitment. Even using one rating curve, ecological responses were highly dependent on the taxa of interest. If these analyses were applied to multiple ecological processes (e.g., nutrient retention, habitat availability, and fish recruitment), the range of responses would likely be even larger (Konrad et al. 2011). The issue of multiple effective discharges or ranges of discharges has been highlighted in geomorphology as well (e.g., Ferro and Porto 2012; Zarris 2010). We normalized our effectiveness metrics to facilitate comparison across species, and this approach may facilitate combining and comparing disparate ecological responses.

Owing to uncertainty in the rating curve, the effectiveness metric had a large range of outcomes even under a single flow regime (e.g., the unaltered condition shown in Table 3). This result is not unexpected given that ecological rating curves often exhibit significant uncertainty (Kanno and Vokoun 2010). Sensitivity analysis provided a useful mechanism for bounding uncertainty in effectiveness metrics. Although effectiveness metrics varied widely for a single flow regime, the relative ranking of flow regimes remained the same across model parameterizations (Fig. 6), which provides confidence that analyses consistently compare the environmental flow regimes.

The expanded effectiveness framework presented here opens up additional future applications to flow-dependent ecological processes wherever a hydrologically mediated variable has sufficient data to develop a frequency distribution. Limiting analyses to responses relatable to daily discharge (Doyle et al. 2005) precludes incorporation of other influential flow components (e.g., mean spring discharge, Kiernan et al. 2012). In addition to expanded views of the flow regime, we encourage investigators to consider

Table 4 Examples of ecological rating curves containing non-traditional hydrologic variables and flow-dependent ecological processes that could be adapted to effectiveness analysis

Reference	Ecological variable or process	Hydrologically mediated variable
Gido and Propst (2012)	Native and nonnative fish density	Mean spring discharge, mean summer discharge, and days less than a threshold discharge
Hagler (2006)	Probability of occurrence of young-of-year of an imperiled fish species	Number of days above a discharge threshold during spring
Hall et al. (2002), Doyle (2005), Ensign and Doyle (2006), Tank et al. (2008)	Nutrient uptake and retention	Discharge, velocity, depth, specific discharge (discharge/width), and/or cross-sectional area
Hart et al. (2013)	Periphyton coverage	Velocity
Hester and Doyle (2011)	Standardized growth, development, reproduction, and survival rates of invertebrates and fishes	Temperature
Julian et al. (2011)	Macrophyte coverage	Light
Kiernan et al. (2012)	Proportion of fish species native to the river	Mean spring discharge
Mims and Olden (2012)	Life history composition of fish community	Annual coefficient of variation, high pulse count, flow predictability, and high pulse duration of discharge
Negishi et al. (2012)	Mussel growth rate	Mean daily water temperature
Peterson et al. (2011)	Mussel survival, recruitment, and capture probability	Median, minimum 10-day, and maximum 10-day discharge in spring, summer, and winter
Power et al. (1995), Schuwirth and Reichert (2013)	Food web models	Velocity, depth, light, temperature, width, nutrient concentration
Sakaris and Irwin (2010)	Young-of-year recruitment of a catfish (Ictaluridae) species	Number of spring discharge pulses
Statzner et al. (1988)	Benthic invertebrates	Velocity, depth, Reynolds number, and Froude number
Strayer (1999)	Mussel density	Depth, velocity, and grain size

alternative physical variables influenced by hydrologic variability (Arthington et al. 2009; Olden and Naiman 2010; Davies et al. 2013). For instance, stage, velocity (Ensign and Doyle 2006), light (Julian et al. 2011), Froude Number (Statzner et al. 1988), or temperature (Olden and Naiman 2010) data could be applied analogously with an accompanying ecological rating curve. Table 4 provides examples of literature-reported ecological rating curves that could potentially be adapted to the effectiveness framework.

Conclusions

Effective discharge analysis provides a unique and versatile tool for coupling ecological processes and hydrologic variability. Here, we have both expanded the use of this tool to address several elements of a river's natural flow regime (Poff et al. 1997) and demonstrated its application to environmental flow decision-making. As management decisions become more complex (e.g., incorporating more ecological processes, trade-offs among additional objectives), techniques that simplify outcomes will not only be needed, but will be increasingly helpful for informing decisions. The effectiveness framework may not only help us address these challenges, but also move beyond our focus on *managing variability* to *managing for variability*.

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