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QUANTIFYING TRADEOFFS ASSOCIATED WITH HYDROLOGIC ENVIRONMENTAL FLOW METHODS[1]

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ABSTRACT: Freshwater management requires balancing and tradingoff multiple objectives, many of which may be competing. Ecological needs for freshwater are often described in terms of environmental flow recommendations (e.g., minimum flows), and there are many techniques for developing these recommendations, which range from hydrologic rules to multidisciplinary analyses supported by large teams of subject matter experts. Although hydrologic rules are well acknowledged as overly simplified, these techniques remain the state-of-the-practice in many locations. This article seeks to add complexity to the application of these techniques by studying the emergent properties of hydrologic environmental flow methodologies. Two hydrologic rules are applied: minimum flow criteria and sustainability boundaries. Objectives and metrics associated with withdrawal rate and similarity to natural flow regimes are used to tradeoff economic and environmental needs, respectively, over a range of flow thresholds and value judgments. A case study of hypothetical water withdrawals on the Middle Oconee River near Athens, Georgia is applied to demonstrate these techniques. For this case study, sustainability boundaries emerge as preferable relative to both environmental and economic outcomes. Methods applied here provide a mechanism for examining the role of stakeholder values and tradeoffs in application of hydrologic rules for environmental flows.

(KEY TERMS: environmental flows; instream flows; minimum flows; sustainability boundaries; tradeoffs; Middle Oconee River.)

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INTRODUCTION

As declared by more than 750 scientists from 50 countries in the Brisbane Declaration (2007), "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." At the crux of this definition is the balance of water provision between ecological and human needs, which can be synonymous (Baron *et al.*, 2002; Richter, 2010; Bryan *et al.*, 2013). However, river flow regimes exhibit numerous sources of variability relative to the magnitude, frequency, timing, duration, and rate-of-change of river discharge or stage (Poff *et al.*, 1997), which can result in numerous effects on ecological processes (Bunn and Arthington, 2002; Arthington, 2012). A primary challenge before river managers is to equitably balance and tradeoff alternative needs for freshwater in light of hydrologic variability (Arthington *et al.*, 2006; Auerbach *et al.*, 2012; Grantham *et al.*, 2013; Mubako *et al.*, 2013).

Environmental flow methodologies attempt to facilitate tradeoffs by structuring water management decision making. Given the diversity of potential

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ecological endpoints (e.g., habitat for macroinvertebrates, population demographics of endangered fishes, phosphorous uptake) and perspectives on river management (e.g., municipal water manager, fisheries ecologist, river engineer), a large number and variety of methods exist to identify environmental flow requirements (Arthington, 2012). These techniques are often placed into four categories (Jowett, 1997; Tharme, 2003; Acreman and Dunbar, 2004; Arthington *et al.*, 2006): hydrologic methods, hydraulic rating, habitat analysis, and holistic methodologies. However, recent environmental flow analyses are also utilizing optimization methods (e.g., Harman and Stewardson, 2005; Suen and Eheart, 2006; Yin *et al.*, 2012; Bryan *et al.*, 2013) and regionalization approaches (e.g., Poff *et al.*, 2010; Sanderson *et al.*, 2011; Snelder *et al.*, 2011; Kendy *et al.*, 2012) as tools for identifying environmental flow recommendations (McKay, 2013).

While many methods exist, hydrologic methods relying on straightforward operational rules remain easier to implement and are commonly applied (Arthington *et al.*, 2006; Poff, 2009; Richter, 2010). In particular, minimum flow criteria are often still used as default methods for water regulation decisions across large spatial scales (Shiau and Wu, 2004; Richter, 2010; Snelder *et al.*, 2011; Ouyang, 2012). The deficiencies in minimum flow criteria are well characterized and include issues such as lack of consideration of an entire river's flow regime (Poff *et al.*, 1997), an ecologically inappropriate "one size fits all" approach (Poff, 2009), "flat-lining" of hydrographs (Richter *et al.*, 2011), and selection of ecologically arbitrary hydrologic thresholds (Arthington *et al.*, 2006). Other hydrologic rules have been proposed such as "high flow skimming" where water withdrawals occur only during high flows (Richter and Thomas, 2007), "sustainability boundaries" where withdrawals occur on the basis of a percentage of unmodified river discharge (Postel and Richter, 2003; Richter, 2010; Richter *et al.*, 2011), and management based on environmental flow components summarizing a river's flow regime (Postel and Richter, 2003; Matthews and Richter, 2007).

Although other environmental flow methods have been encouraged over hydrologic rules (Arthington *et al.*, 2006), the broad application of hydrologic methods justifies continued investigation (Richter, 2010; Snelder *et al.*, 2011; Ouyang, 2012). The objective of this article is to examine the hydrologic implications of simple operational rules for defining environmental flows. In particular, I examine tradeoffs between water withdrawal and river levels over a range of minimum flows and sustainability boundaries. This analysis is not meant to imply that these environmental flow methodologies are preferable, but instead to add complexity and objectivity to the most common methods of environmental flow analysis that potentially provide for improved decision making.

METHODS

Study Site

The Middle Oconee River is a sixth-order tributary of the Altamaha River in northeast Georgia, United States (U.S.). This region was historically dominated by row crop agriculture, but suburban, urban, and pasture land uses are currently predominate (Grubaugh and Wallace, 1994; Fisher *et al.*, 2000). The U.S. Geological Survey operates a streamflow monitoring station near Athens, Georgia (1,031 km^2 [398 mi^2] watershed, Gage No. 02217500), where continuous, daily discharge records have been collected from 1938 to present. Over this period of record, mean discharge is 1,213 ML/day (496 cubic feet per second, cfs) and median discharge is 805 ML/day (329 cfs). However, significant hydrologic variability exists at this site with observed daily minimum and maximum flows of 8.6 ML/day (3.5 cfs) and 32,540 ML/day (13,300 cfs), respectively.

As the population of the region has grown, increasing pressure has been placed on local rivers for municipal water supply (Campana *et al.*, 2012). In 2002, a four-county authority constructed Bear Creek Reservoir to meet regional municipal water needs. This reservoir is an off-channel, pump-storage reservoir designed to extract and store Middle Oconee River water. Although off-channel reservoirs can reduce direct effects on fluvial habitat and water quality, withdrawals can still provide a substantive change in ecological communities due to changes in the flow regime (Freeman and Marcinek, 2006). The reservoir's off-channel location provides an opportunity to examine alternative environmental flow regimes in isolation from the confounding effects of connectivity. The reservoir is permitted to withdraw a maximum of 220 ML/day on average (58 million gallons per day, mgd; Georgia Environmental Protection Division Permit Number 078-0304-05) with a pump capacity of 227 ML/day (60 mgd). State environmental flow regulations establish a monthly minimum flow downstream of the intake corresponding to the seven-day low flow with a 10-year recurrence interval (i.e., the "7Q10") for each month (Georgia Department of Natural Resources, 2001).

Hydrograph Modification

The long period of pre-reservoir discharge records provided an opportunity to examine the potential effects of alternative environmental flow schemes and associated withdrawal patterns. For the purpose of this analysis, only data from 1938 to 1997 were applied. Although the reservoir was completed in 2002, 1997 was used as a temporal break point for this analysis because these data were available to regulators prior to reservoir permitting and this time period is not influenced by the withdrawal.

The 60-year discharge record was modified based on three simple environmental flow regimes: (1) an unconstrained minimum flow, (2) a constrained minimum flow, and (3) an unconstrained sustainability boundary approach. Unconstrained minimum flows (UMF) refer to the withdrawal of water at any time when the river is sufficiently high to meet minimum flow criteria (Equation 1). Constrained minimum flows (CMF) refer to withdrawal of water based on the environmental flow requirement and a common operational constraint (Richter and Thomas, 2007), a preference for less turbid water (Equation 2). Local water operators generally prefer to withdraw water when river discharge is low due to increased treatment cost associated with turbid high flows (Will Cottrell, personal communication, May 6, 2014). Based on two alternative models, a maximum river discharge of 1,223 ML/day (500 cfs) is used as a ceiling for suspended sediment constraints (see Appendix). The final environmental flow regime is based on an unconstrained "sustainability boundary approach" (SB), which represents a percentage of river discharge that may be withdrawn (Equation 3, Richter, 2010; Richter *et al.*, 2011). Importantly, constrained operations associated with storage availability (i.e., reservoir volume) were not included in this analysis in order to focus on hydrologic effects rather than site-specific constraints.

$$\text{UMF} \quad Q_{\mathrm{w}} = \begin{cases} Q_{\mathrm{w,max}} & Q_{\mathrm{r}} > Q_{\mathrm{w,max}} + Q_{\mathrm{r,min}} \\ Q_{\mathrm{r}} - Q_{\mathrm{r,min}} & Q_{\mathrm{w,max}} > Q_{\mathrm{r}} > Q_{\mathrm{r,min}} \\ 0 & Q_{\mathrm{r,min}} > Q_{\mathrm{r}} \end{cases} \tag{1}$$

$$\text{CMF} \ Q_{\mathrm{w}} = \begin{cases} 0 & Q_{\mathrm{r}} > Q_{\mathrm{r,max}} \\ Q_{\mathrm{w,max}} & Q_{\mathrm{r,max}} > Q_{\mathrm{r}} > Q_{\mathrm{w,max}} + Q_{\mathrm{r,min}} \\ Q_{\mathrm{r}} - Q_{\mathrm{r,min}} & Q_{\mathrm{w,max}} > Q_{\mathrm{r}} > Q_{\mathrm{r,min}} \\ 0 & Q_{\mathrm{r,min}} > Q_{\mathrm{r}} \end{cases} \tag{2}$$

$$\text{SB} \quad Q_{\mathrm{w}} = \begin{cases} Q_{\mathrm{w,max}} & \%_{\mathrm{SB}} Q_{\mathrm{r}} > Q_{\mathrm{w,max}} \\ \%_{\mathrm{SB}} Q_{\mathrm{r}} & \%_{\mathrm{SB}} Q_{\mathrm{r}} < Q_{\mathrm{w,max}} \end{cases} \tag{3}$$

where Q_{w} is withdrawal rate, Q_{r} is the unmodified river discharge, $Q_{\mathrm{r,min}}$ is the minimum flow standard, $Q_{\mathrm{w,max}}$ is the maximum withdrawal capacity (227 ML/day, 60 mgd), $Q_{\mathrm{r,max}}$ is the maximum acceptable river discharge for constrained operations, and $\%_{\mathrm{SB}}$ is the sustainability boundary.

These environmental flow alternatives and accompanying withdrawal patterns were applied to each day in the 60-year period of record. For each alternative, daily, annual, and long-term mean withdrawal rates were computed and converted to mgd for comparison with the permitted withdrawal rate of 220 ML/day (58 mgd). The following range of environmental flow thresholds was considered:

1. UMF: minimum flow varied from 0 to 1,835 ML/day by 12.2 ML/day (0 to 750 cfs by 5 cfs)
2. CMF: minimum flow varied from 0 to 1,835 ML/day by 12.2 ML/day (0 to 750 cfs by 5 cfs)
3. SB: percentage withdrawn was varied from 0 to 50% of river discharge by 0.33%

Decision Analysis

Alternative environmental flow regimes were compared based on two objectives: (1) maximize withdrawal rates and (2) maximize similarity to the natural flow regime. These objectives only partly represent the economic and environmental endpoints of what could be a more nuanced discussion of environmental flows. However, these objectives are suitable for a first-order analysis comparing the relative merits of alternative environmental flow methods.

The first objective was measured using average withdrawal rates. Long-term (i.e., 60-year) average withdrawal rate ($Q_{\mathrm{w,avg}}$) provides a useful measure of municipally available water yield (Vogel *et al.*, 2007). Withdrawal rate was then normalized using the maximum permitted withdrawal rate of 58 mgd with any values greater than one truncated at one to reflect achievement of the objective. The resulting metric ($Q_{\mathrm{w,norm}}$) provides a consistent zero to one scale for comparison with the flow regime metric.

The second objective was measured using seven "fundamental daily streamflow statistics (FDSS)" (Archfield *et al.*, 2013) calculated for the simulation period: mean, coefficient of variation, skewness, kurtosis, the auto-regressive lag-one correlation coefficient, amplitude of the seasonal signal, and phase shift of the seasonal signal. Table 1 provides a summary of each statistic, its computation, and its relevance to elements of the natural flow regime. Although many other discharge statistics could be applied (Richter *et al.*, 1996; Olden and Poff, 2003; Shiau and Wu, 2004; Vogel *et al.*, 2007), these were selected based on their utility in parsimoniously summarizing flow regimes (Archfield *et al.*, 2013). Follow-

TABLE 1. Fundamental Daily Streamflow Statistics (FDSS, Archfield *et al.*, 2013) Used in This Study. All statistics are computed from daily-averaged discharge for a 60-year period of record (1938-1997) on the Middle Oconee River.

FDSS	Description	Components of Flow Regime[1]	Unregulated Values
1	Mean	M	1,275 ML/day (521 cfs)
2	Coefficient of variation	M	1.36
3	Skewness	M	6.60
4	Kurtosis	M	66.3
5	Auto-regressive lag-one (AR[1]) correlation coefficient of the daily discharge time series[2]	D, R	0.784
6	Seasonal amplitude Daily discharge was expressed as the addition of the sine and cosine functions as: $q_t = a\sin(2\pi y) + b\cos(2\pi y)$ where q_t is discharge at day t, a and b are model coefficients, and y is the decimal year (1 day = 1/365) Coefficients a and b were fit using linear regression. Seasonal amplitude was then computed as: $A = \sqrt{a^2 + b^2}$	T	741 ML/day (303 cfs)
7	Seasonal phase shift Coefficients a and b were computed as in the description of seasonal amplitude. Seasonal phase shift was then computed as: $\phi = \tan^{-1}\left(\frac{a}{b}\right)$	T	−1.10

[1]As categorized and described by Archfield *et al.* (2013): M, magnitude; D, duration; T, timing; and R, rate-of-change. While flow frequency is not explicitly addressed in this classification, frequency is implicit to the assessment of the probability distribution captured by FDSS 1-4.
[2]Archfield *et al.* (2013) deseasonalize and standardize data for the purpose of between site comparison. However, this was not conducted due to the single site application.

ing computation, each metric was normalized using the baseline condition of no withdrawal, where one is identical to the no withdrawal scenario (Equation 4).

$$Q_{i,\mathrm{norm}} = 1 - \left|\frac{Q_i - Q_{i,u}}{Q_{i,u}}\right| \tag{4}$$

where $Q_{i,\mathrm{norm}}$ is the normalized flow metric, Q_i is one of the seven flow metrics examined, $Q_{i,u}$ is the unaltered value of the metric, and u denotes the unaltered condition with no withdrawal.

Normalization provides a relative scale for comparison between unaltered and managed conditions (Poff *et al.*, 2010) and multiple metrics with different scales. Metrics were assumed to function as limiting factors given the importance of each metric in characterizing the flow regime (Archfield *et al.*, 2013). As such, a summary metric for flow regime impacts was calculated as the geometric mean of the normalized seven FDSSs (Equation 5).

$$Q_{\mathrm{r,combined}} = \sqrt[7]{Q_{1,\mathrm{norm}} * Q_{2,\mathrm{norm}} * \ldots * Q_{7,\mathrm{norm}}} \tag{5}$$

where $Q_{\mathrm{r,combined}}$ is a combined flow metric summarizing hydrologic impact.

The ability of a given environmental flow regime to meet both objectives (i.e., maximize withdrawal rate without compromising the flow regime) was assessed using a combined metric capturing the overall utility of a plan. Utility was calculated as a weighted average using varying value judgments to reflect preferences for water use (Equation 6). Preferences were assessed based on a zero to one proportion of preferences for maximizing withdrawal (w_{w}) or similarity to the natural flow regime (w_{r}), where one weight is determined by the other (i.e., $w_{\mathrm{w}} = 1 - w_{\mathrm{r}}$). If a user wished to only maximize withdrawal rate, then $w_{\mathrm{w}} = 1$ and $w_{\mathrm{r}} = 0$. Conversely, if a user wished to only maximize hydrologic similarity to the unaltered hydrograph, then $w_{\mathrm{w}} = 0$ and $w_{\mathrm{r}} = 1$. Rather than imposing a value judgment, a range of weights (w_{w} = 0.00, 0.01,…, 1.00) was applied to examine sensitivity of decision making to values (Bryan *et al.*, 2013).

$$U = w_{\mathrm{w}}Q_{\mathrm{w,norm}} + w_{\mathrm{r}}Q_{\mathrm{r,combined}} \tag{6}$$

where U is the overall utility of an environmental flow scenario.

All computations were conducted using the R scripting language (R Core Development Team, 2007).

RESULTS

Alternative environmental flow regimes uniquely altered river hydrographs and withdrawal volumes. Figure 1 demonstrates modification of river hydrographs by these methods for the year 1941, which was a modestly dry year (10th lowest annual discharge on record). These figures demonstrate common elements of this analysis such as "flat-lining" of hydrographs for minimum flow regulations, large alteration of low flow conditions by the constrained minimum flow conditions, and maintenance of flow variability by sustainability boundary scenarios. For consistent comparison, environmental flow thresholds were selected which produce equivalent long-term withdrawal rates of 57, 132, and 208 ML/day (15, 35, and 55 mgd). These rates roughly correspond to water demand projections on the reservoir in 2010, 2040, and 2060 under a low usage scenario (Campana *et al.*, 2012). Figure 1 also shows flow duration curves for each hydrograph presented, which serve as a useful comparative tool for the overall effects of a management scenario (Vogel *et al.*, 2007; Snelder *et al.*, 2011; Ouyang, 2012). Flow duration curves for minimum flow scenarios again demonstrate "flat-lining" effects and large alterations relative to the unaltered condition. Conversely, sustainability boundaries result in flow duration curves similar to unaltered conditions, but shifted to lower flows. For both hydrographs and flow duration curves, the difference in environmental flow regimes becomes more pronounced as withdrawal rates increase, but notably, even for the 57 ML/day (15 mgd) scenario, the difference between constrained and UMF is readily apparent. For instance, a 57 ML/day (15 mgd) withdrawal rate is possible with a 1,260 ML/day (515 cfs) UMF compared to a 661 ML/day (270 cfs) CMF.

Owing to natural variability in river discharge, the annual withdrawal rate of a single environmental

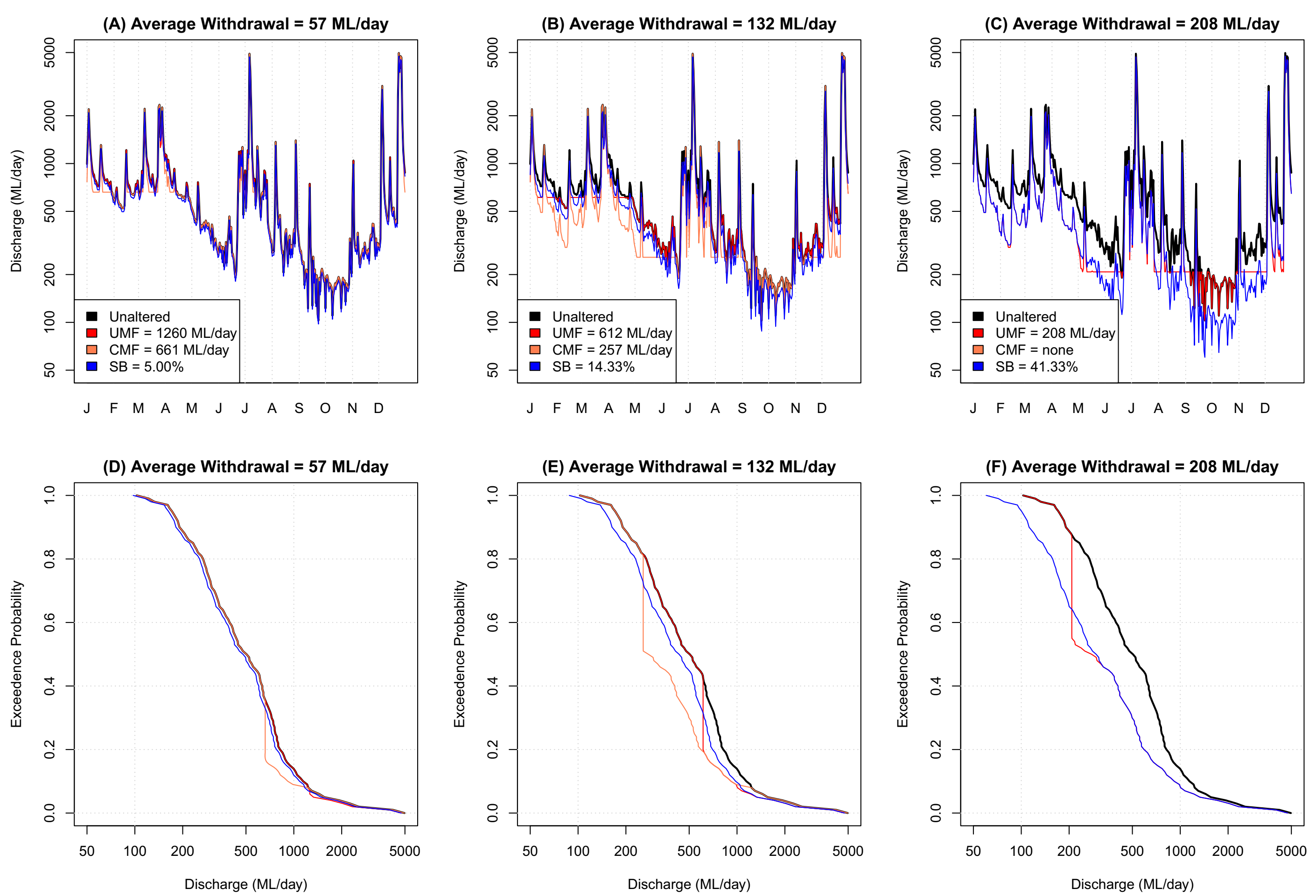

FIGURE 1. Effects of Alternative Environmental Flow Decisions on River Hydrographs for the Year 1941. These scenarios were selected to produce nearly equivalent long-term average withdrawal rates for each environmental flow regime of 57, 132, and 208 ML/day (15, 35, and 55 mgd) for A, B, and C, respectively. Unaltered and altered flow duration curves for long-term average withdrawal rates of 57, 132, and 208 ML/day (15, 35, and 55 mgd) for D, E, and F, respectively.

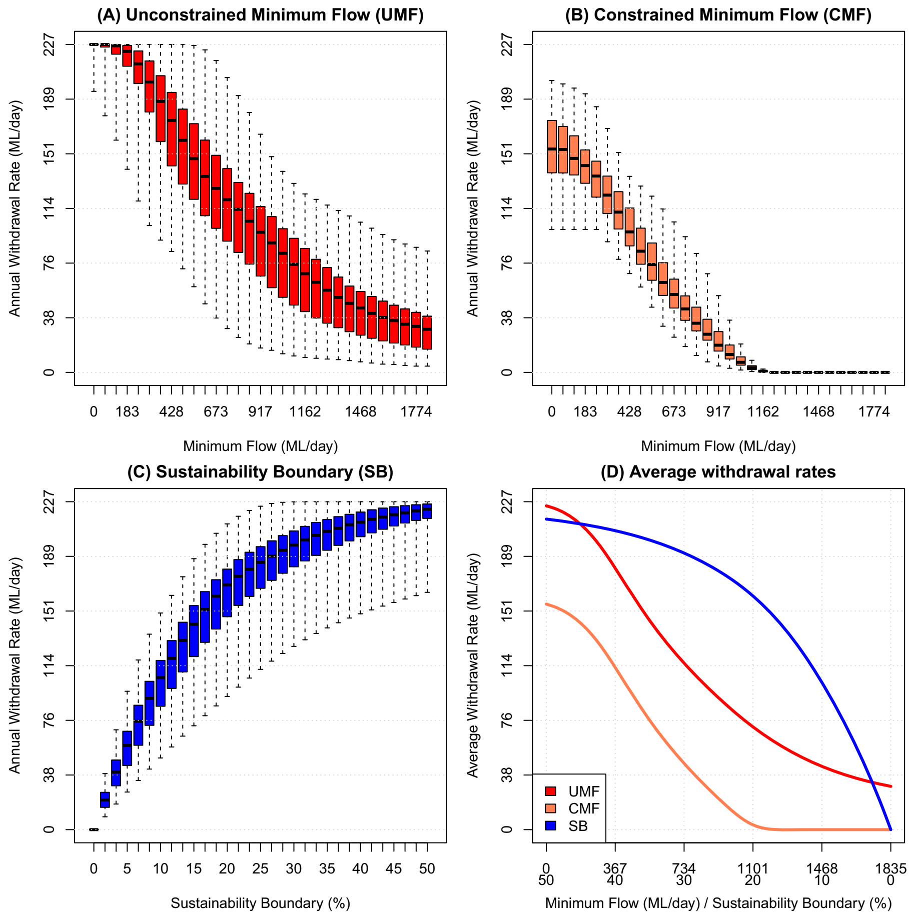

FIGURE 2. Annual Variability in Water Yield for: (A) Unconstrained Minimum Flows, (B) Constrained Minimum Flows, and (C) Sustainability Boundaries. In each box plot, the thick black line is the median, box extremes are the 25th and 75th percentile, and whiskers are minimum and maximum observed points. Although a finer resolution of flow thresholds was carried through analyses (e.g., minimum flow = 0, 12.2,…,1,835 ML/day [0, 5,…, 750 cfs]), every fifth data point is shown here (e.g., 0, 61.0,…,1,835 ML/day [0, 25,…, 750 cfs]). Figure D presents average withdrawal rates across all years for direct comparison between alternative environmental flow regimes.

flow scenario varied significantly from year-to-year. Figures 2A-2C show annual variability in water yield for each environmental flow scenario considered. For even the least stringent flow thresholds, the permitted withdrawal rate of 220 ML/day (58 mgd) cannot be obtained in all years. In fact, 220 ML/day (58 mgd) can only be obtained in 52 of 60 years for UMF = 0 ML/day (0 cfs) and 37 of 60 years for $\%_{SB}$ = 50%. When considering constrained operations to minimize treatment cost (CMF), the permitted withdrawal rate can never be obtained. Figure 2D shows average withdrawal rates across all years to compare the three alternative environmental flow methods.

Figures 3A-3G show the effects of increased withdrawal rate on the flow regime metrics for each environmental flow scheme. Each flow metric demonstrates a unique response to the environmental flow regimes, which indicates that even simple environment flow rules show unique flow regime responses across a diversity of hydrologic metrics. Figure 3H presents the combined flow regime metric for all environmental flow regimes. Without considering the utility analysis below, this could be used to assess the relative tradeoffs between different environmental flow schemes (Bryan *et al.*, 2013). For instance, at a given level of withdrawal, one would choose the environmental flow regime producing the least altered flow regime, and for a given level of flow regime alteration, one would choose the maximum withdrawal rate.

Although there is significant intra-annual variability in withdrawal rates, average conditions were used to assess the utility of alternative environmental flow thresholds and to examine the influence of preferences on decision making. Utility was computed for a single environmental flow method (e.g., UMF) across a range of flow thresholds (e.g., minimum flow = 489 ML/day, 200 cfs) for varying value judgments (Figure 4). For UMF and SB, maximum utility

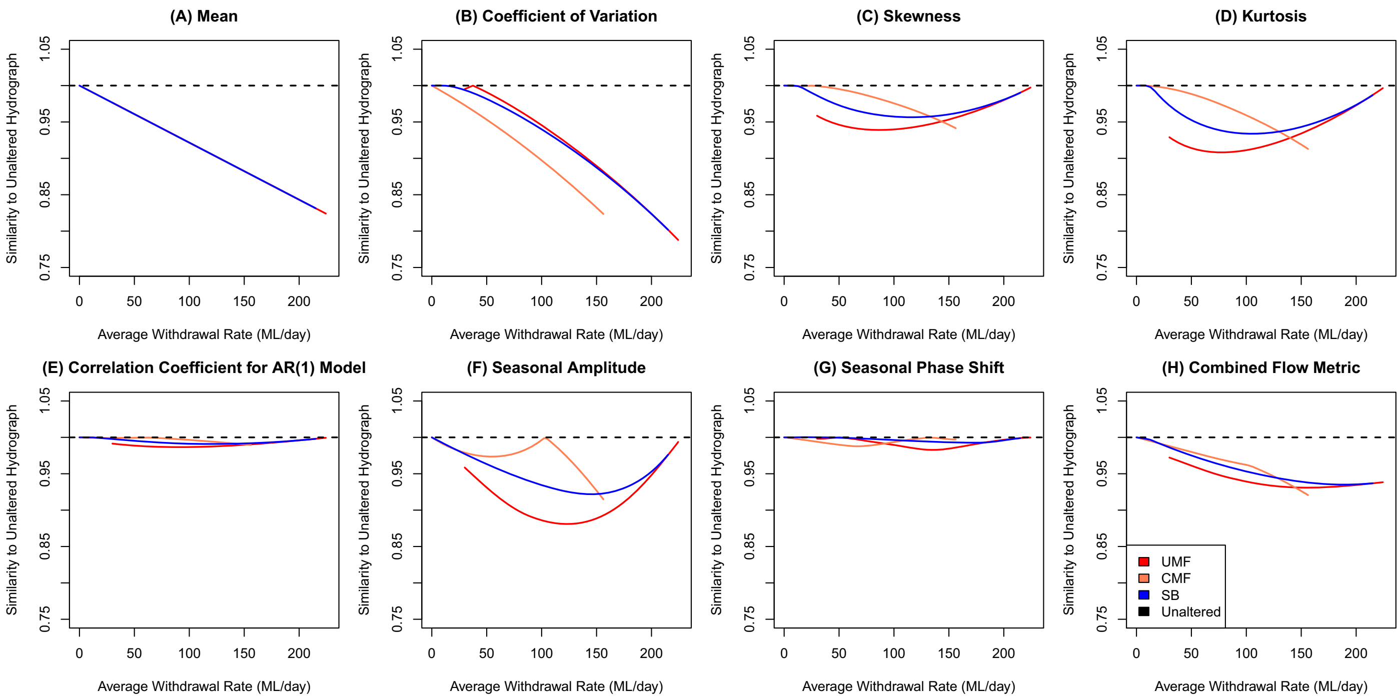

FIGURE 3. Hydrologic Effects of Environmental Flow Methodologies. (A-G) Seven fundamental daily stream statistics identified by Archfield *et al.* (2013) and described in Table 1. (H) A combined flow metric accounting for limiting hydrologic factors.

is obtained at different flow thresholds depending upon preferences. Examining the UMF method (Figure 4A), when withdrawal rate is preferentially valued, the maximum utility is obtained at the lowest minimum flow. Conversely, when river discharge is preferentially valued, the maximum utility is obtained at the highest minimum flow. These results are expected given these extreme scenarios. However, utility converges across value judgments at a UMF threshold of 232 ML/day (95 cfs) and SB threshold of 38.67%. These convergence points provide a defensible mechanism for selecting a site-specific, regulatory flow threshold with a hydrologic basis which is applicable across all potential stakeholder values. In contrast to the clear tradeoffs for UMFs and SBs, CMFs show diverging flow thresholds across varying value judgments, which indicates that consensus may not exist for this flow management strategy.

Figure 5 presents the total utility of the three alternative environmental flow methods (i.e., UMF, CMF, SB) for equivalent withdrawal volumes of 57, 132, and 208 ML/day (15, 35, and 55 mgd). The sustainability boundary approach out-competes the UMF approach for nearly all value judgments and withdrawal volumes. Constrained minimum flow approaches out-compete sustainability boundaries at

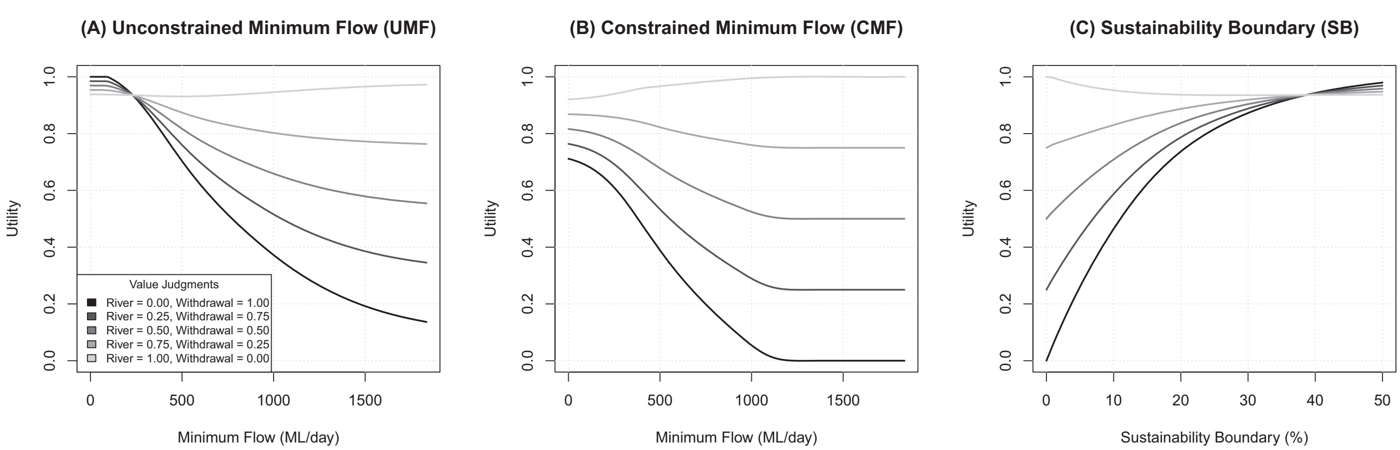

FIGURE 4. Comparing Flow Thresholds within an Environmental Flow Method Using Total Utility and Varying Value Judgment.

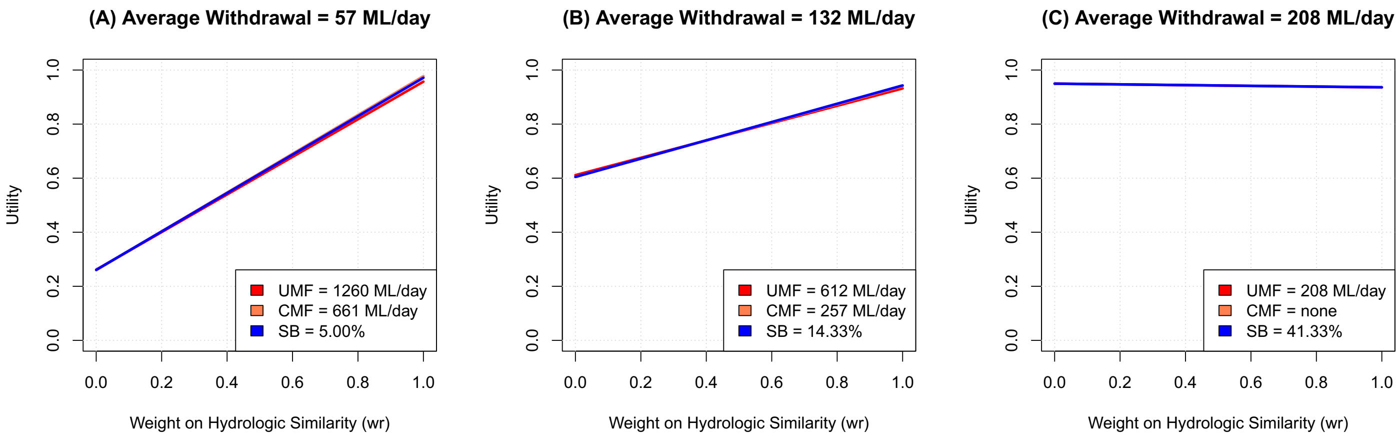

FIGURE 5. Comparing between Environmental Flow Methods for Scenarios with Nearly Equivalent Long-Term Average Withdrawal Rates of 57, 132, and 208 ML/day (15, 35, and 55 mgd) for A, B, and C, respectively.

low withdrawal rates, but these withdrawals cannot provide high abstraction rates.

DISCUSSION

The objective of this article is to examine the hydrologic implications of straightforward hydrologically derived operational rules for defining environmental flows. To do so, a case study of water withdrawals was developed that addresses two objectives: (1) maximize average withdrawal rates and (2) maximize hydrologic similarity to the natural flow regime. While this case study is overly simplified, it serves as a useful heuristic model to understand the effects of simple hydrologic methods of environmental flows.

Inter-annual variability in river discharge proved to be an important factor affecting average annual withdrawal rates. Even when no environmental flow was considered (UMF = 0 ML/day, 0 cfs), the permitted withdrawal rate was obtainable in only 87% of years. Without explicit consideration of variability, an inappropriate flow regime could be recommended (Poff, 2009). To minimize conflicts between multiple withdrawals or between ecological and human needs, regulators issuing permits should minimally address this by planning for the worst case scenario (the driest year). This finding also indicates that the Middle Oconee River is already over allocated at this location due to permitted withdrawal exceeding natural supply. While this problem is common in arid regions (Grantham and Viers, 2014), water conflicts are emerging in humid regions as well (Ruhl, 2005). To avoid future conflicts, regulators could either deny future permit applications or constrain the withdrawal permits relative to river discharge (e.g., only wet-period withdrawal, Eheart, 2004; Richter, 2014). These potential conflicts could become more pronounced under long-term drought, which could be exacerbated by a changing climate (Campana *et al.*, 2012; Patterson *et al.*, 2012).

This analysis has also highlighted the importance of considering real-world operational constraints in environmental flow recommendations (Richter and Thomas, 2007). For instance, the constraint of a maximum withdrawal to minimize turbidity led to lower utility in all scenarios presented. Importantly, this restriction in withdrawal also prevented the permitted withdrawal rate from being obtained in any year considered. Future efforts should also account for reservoir volume constraints, which were neglected here.

Comparisons between environmental flow methods also showed the importance of stakeholder preferences in recommending a flow regime (Poff *et al.*, 2010; Arthington, 2012; Bryan *et al.*, 2013; Pahl-Wostl *et al.*, 2013). Tradeoffs were shown both within a single method (e.g., multiple minimum flow thresholds, Figure 4) and across methods (e.g., UMFs *v.* SBs, Figure 5) depending on stakeholder values. Although the value-laden process presented was simplistic, more sophisticated methods for multi-criteria decision analysis and structured decision making are known to be useful to inform environmental decision making (Linkov and Moberg, 2011; Conroy and Peterson, 2013).

Incorporating value judgments also provides an additional mechanism for identifying environmental flow thresholds based on scientific evidence. More sophisticated methods exist and have been applied extensively to environmental flow decision making such as habitat simulation methods (e.g., the Instream Flow Incremental Method, Bovee and Milhous, 1978;

Stalnaker *et al.*, 1995), literature-based flow-ecology relationships (Sanderson *et al.*, 2011), demographic modeling techniques (Peterson *et al.*, 2011), and expert panel judgments (Richter *et al.*, 2006). However, many minimum flow decisions are often made using simplistic statistics such as the seven-day low flow with 10-year recurrence (7Q10), the 30-day low flow with two-year recurrence (30Q2), 80% flow exceedence (Ouyang, 2012), or 30% of mean annual flow (Tennant, 1976). For the Middle Oconee River case study, the 7Q10 = 110 ML/day (45 cfs), the 30Q2 = 379 ML/day (155 cfs, Carter and Putnam, 1978), 80% flow exceedence = 477 ML/day (195 cfs), and 30% of mean annual flow = 365 ML/day (149 cfs). The utility-based method presented here showed that an UMF of 232 ML/day (95 cfs) or a sustainability boundary of 38.67% maximized utility across value judgments. This approach provides an alternative method, where based on hydrologic properties of the system, a flow threshold may be determined that is appropriate across a range of stakeholder viewpoints. Although "no (scientifically credible) rule-of-thumb" can "satisfy environmental flow needs" (Richter, 2010), the methods presented here provide a rational framework for identifying a minimum flow threshold or sustainability boundary beyond what can be ecologically arbitrarily hydrologic statistics.

In many situations, a site-specific analysis may be prohibitive and a regional approach must be used (Poff *et al.*, 2010). These instances require broadly applicable environmental flow methods and thresholds. Here, a site-specific sustainability boundary of 38.7% was found, which is larger than the "presumptive standard" of 20% proposed by Richter *et al.* (2011). However, their standard was scoped to be conservative and precautionary with respect to ecological integrity. Because of their analytical tractability, the methods presented here could be applied rapidly throughout a region to determine a regionally appropriate "presumptive standard" for multiple environmental flow methods (e.g., minimum flow, sustainability boundary).

This article has examined the hydrologic implications of environmental flow methods that apply simplistic hydrologic rules. Many more methods exist for defining environmental flows that often include more ecological variables and nuanced analysis of flow regimes and environmental flow components (Tharme, 2003; Acreman and Dunbar, 2004; Arthington, 2012; McKay, 2013). Tools for examining alternative flow regimes are actively being developed (Vogel *et al.*, 2007; Hickey, 2012; Payne and Jowett, 2013). However, simple hydrologic methods remain frequently utilized in practice (Arthington *et al.*, 2006; Richter *et al.*, 2011; Ouyang, 2012). This analysis is not intended to endorse or discourage these methods, but instead to promote thoughtful application of these methods and the full exploration of the hydrologic effects of environmental flow recommendations.

APPENDIX

Eighty-three observations of total suspended sediment have been made at the USGS streamflow gage on the Middle Oconee River near Athens, Georgia, U.S. (Gage Number 02217500). These suspended sediment concentrations (mg/L) were used in conjunction with instantaneous volumetric discharge estimates to develop a suspended sediment rating curve (Figure A1). Following common practice (e.g., Julien, 2010), a power function was fit to these data to provide a continuous estimate of suspended sediment with variable discharge (Equation A1). Using the inverse form of Equation (A1), a withdrawal threshold of 1,140 ML/day (466 cfs) was estimated from a sediment concentration of 50 mg/L. Owing to variability in suspended sediment measurements at low discharges, a second approach to assess a withdrawal threshold was applied. The maximum observed discharge associated with suspended sediment less than 50 mg/L in the 83 observations was 2,163 ML/day (884 cfs). A maximum withdrawal of 1,223 ML/day (500 cfs) was assumed to be a conservative threshold

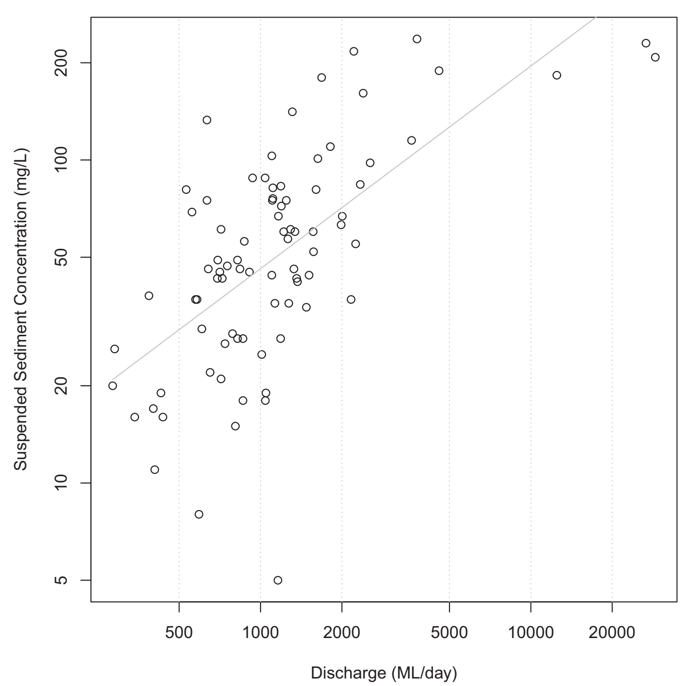

FIGURE A1. Suspended Sediment Rating Curve for the Middle Oconee River near Athens (n = 83).

in line with typical operations of the water authority (S. Kyle McKay, May 6, 2014, personal observation), and thus was applied in the environmental flow analyses of the main text.

$$C = 0.604Q^{0.63} \quad R^2 = 0.42 \qquad (A1)$$

where C is the suspended sediment concentration in mg/L and Q is river discharge in ML/day.

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