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Is Mean Discharge Meaningless for Environmental Flow Management?

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PURPOSE: River ecosystems are highly dependent on and responsive to hydrologic variability over multiple time scales (e.g., hours, months, years). Fluctuating river flows present a key challenge to river managers, who must weigh competing demands for freshwater. Environmental flow recommendations and regulations seek to provide management targets balancing socio-economic outcomes with maintenance of ecological integrity. Often, flow management targets are based on average river conditions over temporal windows such as days, months, or years. Here, three case studies of hydrologic variability are presented at each time scale, which demonstrate the potential pitfalls of mean-based environmental flow criteria. Each case study shows that the intent of the environmental flow target is not met when hydrologic variability is considered. While mean discharge is inadequate as a single-minded flow management target, the consequences of mean flow prescriptions can be avoided in environmental flow recommendations. Based on these case studies, a temporal hierarchy of environmental flow thresholds is proposed (e.g., an instantaneous flow target coupled with daily and monthly averages), which would improve the efficacy of these regulations.

INTRODUCTION: Hydrologic variability is a key determinant of ecological processes in aquatic ecosystems and can be measured over a nested hierarchy of temporal scales ranging from hours to years to millennia (Naiman et al. 2008). Fluctuations can be periodic, stochastic, or catastrophic sources of variation (e.g., seasonal flow dynamics, convective thunderstorms, and large floods, respectively, Sabo and Post 2008), and a growing body of literature is focused on quantifying hydrologic variability and associated ecological outcomes across time scales (e.g., Poff and Ward 1989; Olden and Poff 2003; Poff et al. 2006; Jager and Smith 2008; Haas et al. 2014). More broadly, temporal variability in ecological response is emerging as a principle sub-discipline of ecology analogous to landscape ecology's role in investigating spatially dependent ecological processes (Wolkovich et al. 2014).

While hydrologic variability can affect ecological dynamics in wetlands (Dvorett et al. 2013), estuaries (Buzzelli et al. 2013), and drylands (Stafford Smith et al. 2007), the challenge of managing variability and managing for variability have been key issues in setting environmental and instream flows in rivers (Poff 2009; Arthington 2012). "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). Two principal challenges for environmental flow management include:

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(1) identifying ecologically relevant components of hydrologic processes (Poff et al. 1997, 2010), and (2) incorporating hydrologic variability across multiple time scales into management recommendations (Poff et al. 2006; Richter and Thomas 2007; Jager and Smith 2008; Naiman et al. 2008; Poff 2009).

Environmental flow recommendations have been developed using many analytical methods ranging from simple hydrologic statistics to multi-stakeholder, interdisciplinary analyses of numerous socio-ecological outcomes (Arthington 2012). Regardless of the method, flow prescriptions must, by necessity, be associated with a time scale, and recommendations typically use mean discharge values for a given time scale (e.g., monthly averaged flow targets). While mean discharge provides a logical starting point, real world application of average values can lead to non-intuitive and ecologically damaging outcomes (Haas et al. 2014).

The objective of this technical note is to highlight the hazards of mean-based environmental flow management and promote the application of a nested hierarchy of time scales in environmental flow recommendations. Three case studies are presented, where mean-based environmental flow rules are insufficient to meet the intended environmental flow goals. This paper concludes with a discussion of how the consequences of mean flow prescriptions can be overcome in environmental flow recommendations.

MEANINGLESS MEANS IN ACTION: Three case studies are presented at annual, monthly, and daily intervals to demonstrate the adverse impacts of mean discharge as a single-minded target for flow management. Case studies were selected to represent diverse examples of the challenges associated with specifying environmental flow criteria. Each case study presents the hydrologic setting, source of hydrologic alteration, and pitfalls of management decisions based on mean discharge. All analyses and computations were done in the R Statistical coding language (R Development Core Team 2012), and code used for all analyses is available upon request from the author. All data were downloaded from the US Geological Survey (USGS) National Water Information System (www.waterdata.usgs.gov) unless otherwise noted.

Case Study #1: Middle Oconee River, Georgia: The Middle Oconee River near Athens, Georgia is a sixth order river draining a rapidly suburbanizing landscape (Campana et al. 2012). Numerous municipal and industrial sources withdraw water from the river, and state regulators must make challenging surface water permitting decisions based not only on economic demands but also ecological needs. In 2002, a four-county authority constructed Bear Creek Reservoir, an off-channel reservoir storing Middle Oconee River water for municipal use. In addition to an existing extraction permit for 0.70 m^3/s (16 million gallons per day, MGD), a permit was granted to pump 2.63 m^3/s (60 MGD) to Bear Creek reservoir subject to meeting a monthly minimum flow criteria associated with the "7Q10" (i.e., the 7-day low flow with a 10-yr recurrence interval, GA DNR 2001).

The USGS has maintained a long-term continuous streamflow record from 1938-present (USGS Gage Number 02217500), but significant withdrawals did not begin until the late 1990s. From 1938-1997 (60 years), mean daily discharge was 14.8 m^3/s (521 cfs), but minimum and maximum daily discharge ranged over four orders of magnitude from 0.23 to 356.7 m^3/s (8 to 12,600 cfs, Figure 1A). Figure 1A presents the combined permitted withdrawal rate relative to 60 years of observed annual hydrographs for the Middle Oconee River. Permitted withdrawals are less than

23% of mean daily discharge. While certainly not without consequence, a 23% reduction in river flow is not drastically beyond the 20% “moderate” level of protection proposed by Richter et al. (2011) as a “sustainability boundary.” Furthermore, the sum of the permitted withdrawal rate and the minimum flow are met by the mean discharge for every day of the year.

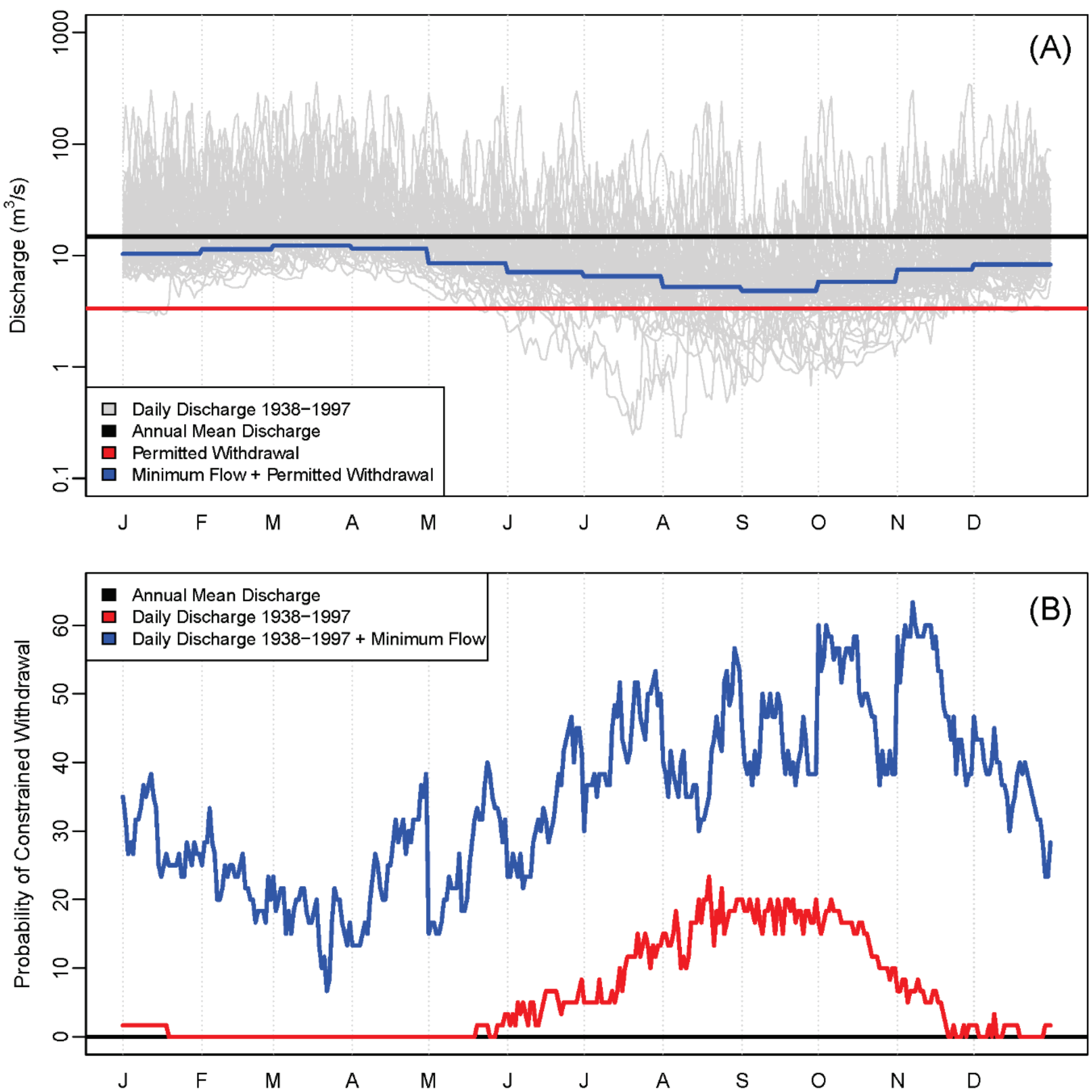

Figure 1. Middle Oconee River near Athens, Georgia (USGS Gage Number 02217500). (A) Annual discharge hydrographs from 1938-1997 (light grey) were minimally impacted by withdrawals. The 60-yr mean discharge (black), permitted withdrawal rates (red), and the sum of required minimum flows and permitted withdrawals (blue) are shown for reference. (B) Percent of years that discharge of a given level is exceeded by the withdrawal rate. Mean conditions are never exceeded by the withdrawal (black), daily discharge data from 1938-1997 are exceeded less than 20% of the years during dry summer months (red), and discharge commonly is below the combined threshold of minimum flows and withdrawals (blue).

However, when the data are presented using non-mean parameters, different observations of the hydrologic impact emerge. Based on 60 years of minimally impacted flows (i.e., without reservoir withdrawals), Figure 1B shows the percent of years the withdrawal exceeds historic river flows for each day of the year (red line). During dry months of August and September, 17% of years have river discharge less than the permitted withdrawal rate (i.e., there is not enough water in the river to meet the permit). Said differently, based on historic records, water should be unavailable for municipal withdrawal on 17% of August and September days. If withdrawal rates and minimum flows are included (blue line), the results are more dramatic with 35% of days ineligible for withdrawal on average throughout the entire year.

Based solely on annual mean discharge, the Middle Oconee River can reliably meet permitted municipal withdrawal rates. These data even indicate that minimum flow thresholds can be met while accommodating water extraction. However, when judged based on non-mean conditions, these two permits over allocate the rate of water that can be reliably supplied by the river for municipal use, and environmental flows may not be met one third of the year.

Case Study #2: Rio Sabana, Puerto Rico: Rio Sabana is a middle order stream draining Puerto Rico's El Yunque National Forest. This tropical river hosts a variety of migratory taxa using both freshwater and estuarine ecosystems to complete their life cycle, including shrimp, snails, and fishes (Greathouse et al. 2006). These taxa migrate long distances and overcome natural barriers such as waterfalls through adaptations such as climbing and jumping abilities. Over 34 water withdrawals exist throughout the National Forest for municipal water supply, two of which are in the Sabana watershed (Crook et al. 2007). While these small, low-head dams have the potential to disconnect migratory routes, numerous researchers have shown that upstream shrimp migrations can persist even under heavy withdrawal, if water overtops the dam face or spillway (Benstead et al. 1999; Greathouse et al. 2006). While other environmental flow criteria have been developed (Scatena and Johnson 2001), the simplest and least stringent view of environmental flows in this system addresses the binary outcome of water overtopping the dam or not.

In a recent hydrologic budget, Christian et al. (2019) estimated that, based on human population within the watershed and expected per capita use rates, the combined effect of the two withdrawals in the Sabana basin were approximately 0.060 m^3/s (2.14 cfs). Based on mean annual discharge of 0.558 m^3/s (19.7 cfs, 1980-2008, USGS Gage Number 50067000), these withdrawals represent approximately 11% of average flow conditions, well within Richter et al.'s (2011) 20% recommendation. Withdrawals are also never more than 22% of discharge for any given monthly average. Accordingly, we would expect minimal disturbance to shrimp migratory patterns due to withdrawals. However, when considered relative to daily discharge for 2007 (the second driest year on record), withdrawal capacity exceeds river discharge 22.5% of days (Figure 2), which would make the river run dry below the dam. Monthly distributed environmental flow criteria are common, and this case study demonstrates that even for temporally distributed criteria and a crude environmental flow threshold (flow / no flow), hydrologic variability can render mean-based environmental flows obsolete.

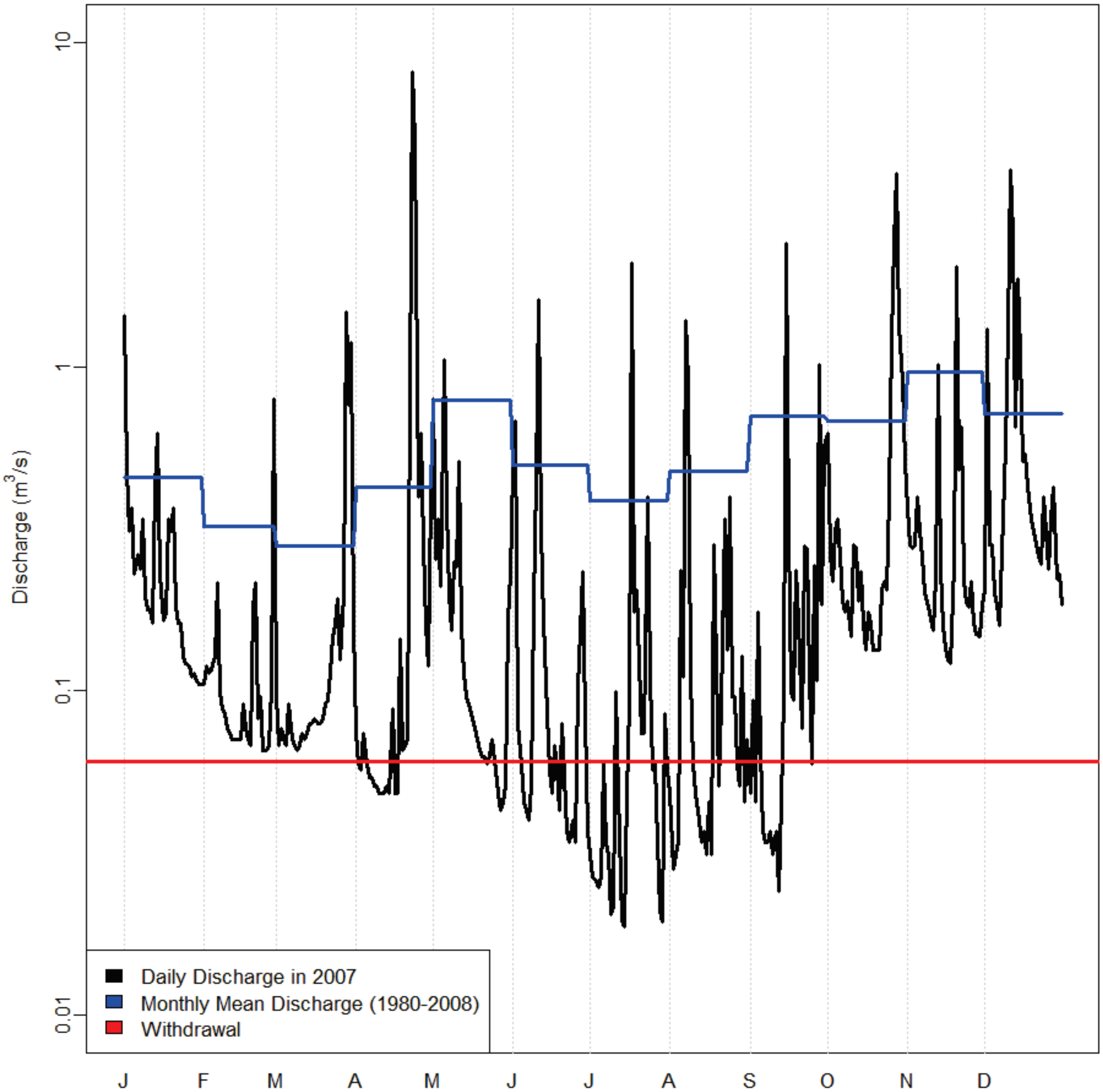

Figure 2. Rio Sabana at Sabana, Puerto Rico (USGS Gage Number 50067000). Estimated withdrawals represent a relatively small fraction of monthly mean discharge from 1980-2008 (blue line). Estimated withdrawal rates (red) exceed daily discharge in 2007 (black) frequently.

Case Study #3: Oconee River, Georgia: Approximately 24 river kilometers (15 river miles) downstream of Athens, Georgia on the Oconee River is the Barnett Shoals dam, a 15 m tall (50 ft), privately owned hydropower structure (USACE 2010). Using daily discharge data from 1978-2014 (USGS Gage Number 02218300), the annual 7Q10 for this gage is 1.70 m^3/s (60 cfs), which is used as a daily averaged minimum flow threshold (GA DNR 2001). Figure 3 shows a 7-day period of streamflow observations in July 2014, which is representative of common “hydropeaking” operations (Richter and Thomas 2007; Haas et al. 2014). Mean flow for this 7-day period is

2.43 m^3/s (86 cfs), which easily exceeds environmental flow requirements for the entire period and for each day individually (Figure 3).

However, hydropeaking induces strong intra-daily fluctuations with minimum and maximum discharge of 0.59 and 3.99 m^3/s (21 and 141 cfs) over this period. These operational regimes consistently meet the permit requirements associated with a daily averaged minimum flow, but the permit does not address within day fluctuation or instantaneous discharge limits. The 15-min discharge hydrograph shows large periods of time below the minimum flow regulation and significant intra-daily fluctuation. Intra-daily fluctuations from hydropower often induce strong ecological effects due to rapid changes in downstream habitat availability, hydrodynamic environment, and temperature regimes (Moog 1993; Freeman et al. 2001; Richter and Thomas 2007; Haas et al. 2014; Jones 2014).

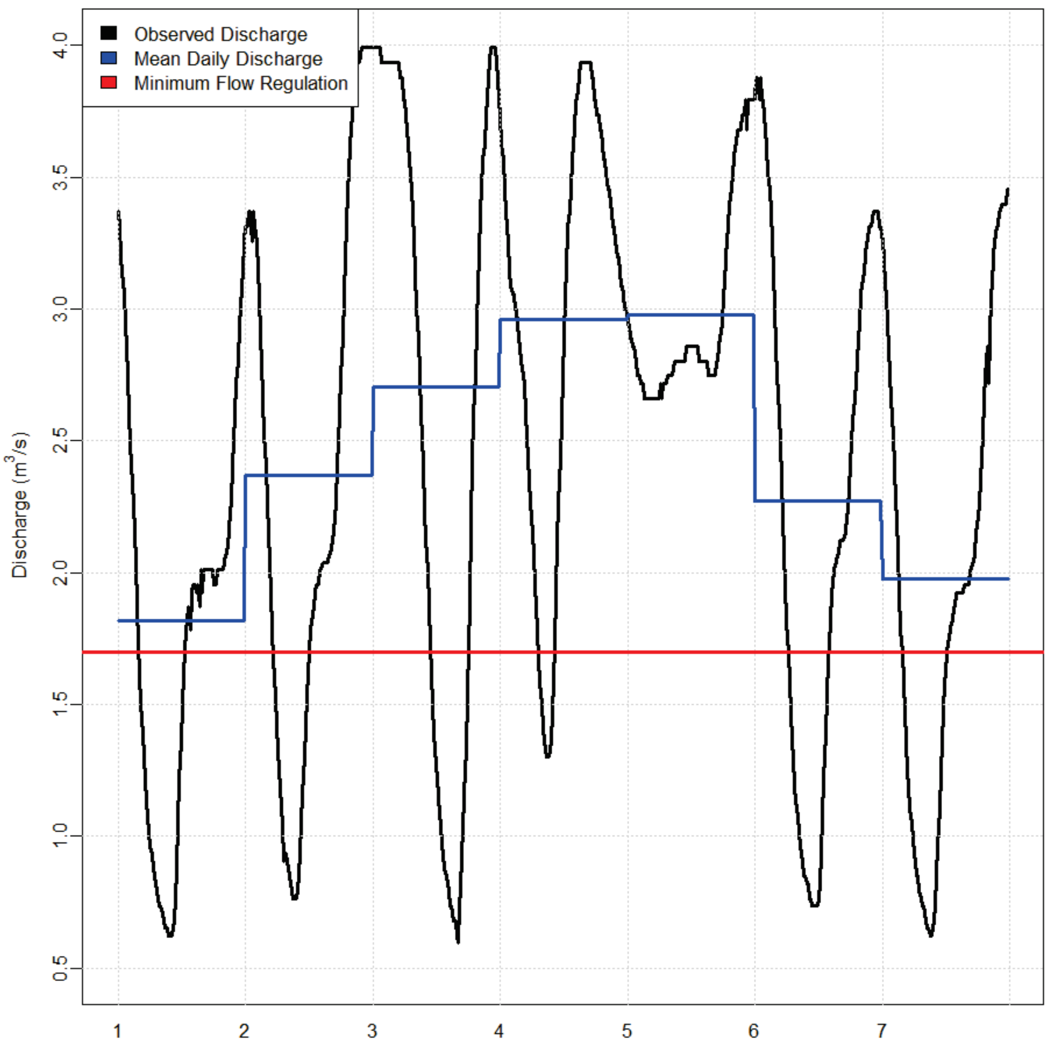

Figure 3. Oconee River near Penfield, Georgia (USGS Gage Number 02218300). Seven-day hydrograph of mean daily discharge (blue) consistently meets the minimum flow regulation (red). Conversely, 15-minute discharge hydrograph (black) shows large periods of time below the minimum flow regulation and significant intra-daily fluctuation.

ADDING MEANING BACK TO THE MEAN: Three case studies have been presented, which highlight potential pitfalls associated with setting environmental flow management thresholds based on mean conditions at annual, monthly, and daily time scales. Hydrologic variability within the regulatory time interval (i.e., hourly fluctuation within a daily mean or daily fluctuations within a monthly mean) leads to overallocation of the water resource in all three case studies. Importantly, current regulations are being met in all examples shown, and in the case of Middle Oconee River withdrawals, typical water extraction is currently one third of permitted withdrawal rates (Campana et al. 2012). Thus, these permitting and river management decisions are meeting the "letter of the law," but are they meeting the "spirit of the law?"

The examples emphasize a need for a temporal hierarchy of environmental flow regulations or recommendations. Mean conditions have been and will continue to be important tools for management recommendations, but recommendations must also consider hydrologic variability within an averaging period (e.g., daily fluctuation within a monthly mean, Haas et al. 2014). For instance, this more nuanced approach could apply mean monthly, mean daily, and instantaneous flow targets to a hydropower dam. Discharge measurement technology providing real-time data was not readily available when many environmental flow thresholds were developed. For instance, Georgia's minimum flow criteria were proposed in 2001 (GA DNR 2001), and USGS 15-min data were not widely distributed in real-time in this region until approximately 2007. Real-time measurement technology is providing an opportunity to improve environmental flow management decisions that was, until recently, unavailable (Haas et al. 2014).

Nuanced permitting and environmental flow recommendations will be crucial to avoid both conflicts over limited water resources as well as ecological damage, particularly during drought (Campana et al. 2012). For instance, considering the hydrologic variability and strong seasonality of the Middle Oconee River, permits could be issued to withdraw during wet winter months only, rather than annual permits. Alternatively, permits could be conditioned based on long-term ambient conditions (e.g., wet versus dry years). Conditional permitting could enhance the capacity to meet economic needs and avoid ecological damage, but conditional water rights have also been shown to introduce uncertainty into water management in the western United States (Podolak and Doyle 2015).

These case studies are from areas historically thought of as having plentiful freshwater supplies, and, on average, precipitation is more than 1.02 m (40 in.) for all three sites. Hydrologic variability is, however, dramatic in these systems, which introduces a key source of uncertainty to river management. With land use and climate change, hydrologic processes are experiencing non-stationary conditions, where historical patterns may no longer be predictive of future conditions (Milly et al. 2008; Patterson et al. 2012). Additionally, water resources development for energy and water supply continues (e.g., McManamay et al. 2015). Because of these uncertainties, environmental flow recommendations and regulations should be viewed as experimental and iterative (Auerbach et al. 2013). For instance, withdrawal permits could be issued with clear and frequent timelines for renewal (e.g., 10 yr), which require reevaluation and adjustment of an environmental flow target based on newly available hydrologic and ecological data. An iterative renewal process is currently used in federal relicensing of hydropower structures with some successes (e.g., Haas et al. 2014). This format could also be adapted for issuing withdrawal permits and coping with challenges brought on by aging infrastructure and climate change (Pittock and

Hartmann 2011). Although iterative renewal provides an opportunity for adaptive permitting based on changing conditions, such a renewal process could potentially introduce risks to industries or communities reliant on water withdrawal and create tension between stakeholders, a risk that must be considered.

CONCLUSIONS: Environmental flow recommendations have been proposed using more than 200 methods, which rely on a variety of hydrologic, hydraulic, habitat, and holistic techniques (Arthington 2012). As the body of knowledge of environmental flows has grown, a growing emphasis has been placed on recommendations inclusive of multiple ecological and social outcomes (e.g., Poff et al. 2010; Pahl-Wostl et al. 2013). Minimum flows remain one of the simplest and most controversial methods of environmental flow provision (Poff 2009; Richter et al. 2011). Example projects with minimum flow criteria are used here not because of their ecological value, but instead because they remain broadly used in practice (i.e., the primary instream flow standards in many states) and clearly demonstrate the potential challenges associated with mean-based environmental flow thresholds. Other more nuanced approaches may often be preferred, but the same pitfalls of mean-based management exist. Clearly, flow thresholds based on instantaneous discharge would be significantly more protective than daily or monthly averages, regardless of the method for selecting environmental flow targets.

Environmental flows will continue to be a challenge for regulatory agencies, and future research will be required to understand the ecological thresholds to flow regime changes as well as the economic effects of alternative policies. In the interim, managers should attempt to reconcile mean-based flow recommendations with local hydrologic variability and develop a temporal hierarchy of environmental flow thresholds (e.g., instantaneous thresholds nested within daily and monthly averages). Mean conditions have been and will continue to be important tools for management recommendations, but meaningless means create a potential stumbling block to meeting the spirit of environmental flow management.

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