

Minimum Flows and Levels Method of the St. Johns River Water Management District, Florida, USA

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Abstract The St. Johns River Water Management District (SJRWMD) has developed a minimum flows and levels (MFLs) method that has been applied to rivers, lakes, wetlands, and springs. The method is primarily focused on ecological protection to ensure systems meet or exceed minimum eco-hydrologic requirements. MFLs are not calculated from past hydrology. Information from elevation transects is typically used to determine MFLs. Multiple MFLs define a minimum hydrologic regime to ensure that high, intermediate, and low hydrologic conditions are protected. MFLs are often expressed as statistics of long-term hydrology incorporating magnitude (flow and/or level), duration (days), and return interval (years). Timing and rates of change, the two other critical hydrologic components, should be sufficiently natural. The method is an event-based, non-equilibrium approach. The method is used in a regulatory water management framework to ensure that surface and groundwater withdrawals do not cause significant harm to the water resources and ecology of the above referenced system types. MFLs are implemented with hydrologic water budget models that simulate long-term system hydrology. The method enables a priori hydrologic assessments that include the cumulative effects of water withdrawals. Additionally, the method can be used to evaluate management options for systems that may be over-allocated or for eco-hydrologic restoration

projects. The method can be used outside of the SJRWMD. However, the goals, criteria, and indicators of protection used to establish MFLs are system-dependent. Development of regionally important criteria and indicators of protection may be required prior to use elsewhere.

Keywords Environmental flows · Wetlands protection · Hydrologic regime · Significant harm · Non-equilibrium

Introduction

Anthropogenic modifications of natural hydrologic regimes caused by large dams (Postel and Richter 2003), withdrawals from surface (Tyus 1992) and groundwater sources (Six State Study 1982 as reviewed by Grigg 1996), and land use changes (Guillory 1979) have greatly altered aquatic and wetland systems. The negative effects caused by such alterations have resulted in conflicts and debates over uses of river water (Arthington and others 2006). The terms instream flows (Gillilan and Brown 1997), minimum flows (Beecher 1990), ecosystem support allocation (Postel and Richter 2003), and environmental flow assessment (Tharme 2003) have been used to refer to the process of retaining some water in rivers to protect environmental and recreational benefits. Globally, 207 flow protection methods have been identified, classified, and discussed (Tharme 2003).

Minimum flows represent the minimum amount of water required to protect defined criteria that often address the needs of aquatic biota (Annear and Conder 1984). Minimum flows also represent the maximum depletion of natural flows allowable without impairing the ecological services of rivers (Silk and others 2000). The concept of a single minimum flow was developed from western United

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States of America (USA) water law to reserve an amount of water from future legal consumptive use appropriations, to provide an instream water right for fish (Stalnaker 1990). The single flow concept was expanded when four types of flows (i.e., Valley Maintenance, Riparian Maintenance, Channel Maintenance, and Instream Flows) were identified to protect instream and out-of-bank biota (Hill and others 1991). The identification of multiple flow types resulted in two schools of thought (Nilsson 2000). One school advocated the importance of low flows and focused on instream ecology while the other advocated the importance of high flows or major floods. The current environmental flows paradigm asserts that all flows are important (King and others 2003) and that healthy aquatic and wetland populations and communities require variable flow regimes to protect habitat and life history processes (Poff and others 1997). Five critical components of flow regimes are recognized: magnitude, return interval, duration, timing, and rate of change (Poff and others 1997; Richter and others 1996, 1997). The biotas of river ecosystems have evolved in response to these critical components (Bunn and Arthington 2002).

Historically, ecosystem support allocations have focused on lotic systems with dams (Postel and Richter 2003). However, the high- and low-flow concepts and the five critical flow regime components may be applied to lentic systems and aquifers. Hence, the environmental flows paradigm can be expanded to include lotic, lentic, and aquifer systems, called minimum flows and levels (MFLs) in Florida, USA (Munson and others 2005).

The 1972 Florida Water Resources Act (Chapter 373, *Florida Statutes* [F.S.]) is the basis for establishing and protecting MFLs in Florida (Purdum and others 1998). The five water management districts (WMDs; Fig. 1) derive authority to establish MFLs from Sections 373.042 and 373.0421, *F.S.* Water management districts are required to establish minimum flows for certain surface watercourses, which “shall be the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.” Additionally, WMDs are required to establish minimum water levels, which “shall be the level of groundwater in an aquifer and the level of surface water at which further withdrawals would be significantly harmful to the water resources of the area.” Although the term “significantly harmful,” (a.k.a., significant harm) is not defined, a statewide rule provides guidance regarding the establishment of MFLs. Section 62-40.473, *Florida Administrative Code* (F.A.C.), directs WMDs to consider natural seasonal fluctuations in water flows or levels, nonconsumptive uses, and environmental values associated with coastal, estuarine, riverine, spring, aquatic, and wetlands ecology, including: recreation in and on the water; fish and wildlife habitats

and the passage of fish; estuarine resources; transfer of detrital material; maintenance of freshwater storage and supply; aesthetic and scenic attributes; filtration and absorption of nutrients and other pollutants; sediment loads; water quality; and navigation.

The St. Johns River Water Management District (SJRWMD) developed and implemented a MFLs method to protect instream and out-of-bank ecological structure and functions in 1991 (Hupalo and others 1994). Information from elevation transects that extend from open water to uplands is typically used to determine MFLs (Fig. 2). Seminal ideas and criteria used for MFLs determinations were developed in the Upper St. Johns River Basin (Brooks and Lowe 1984) and the Greater Lake Washington Basin (Hall 1987). The method was also used to determine MFLs for lakes, wetlands, and springs (Table 1). This article presents the SJRWMD MFLs method with a discussion of its strengths, limitations, and other potential uses. New material includes (1) a biologically relevant event-based mechanism that does not average away critical hydrologic components, (2) a non-equilibrium perspective where not all changes to hydrology result in ecological changes, and (3) a threshold-based approach for preventing significant harm.

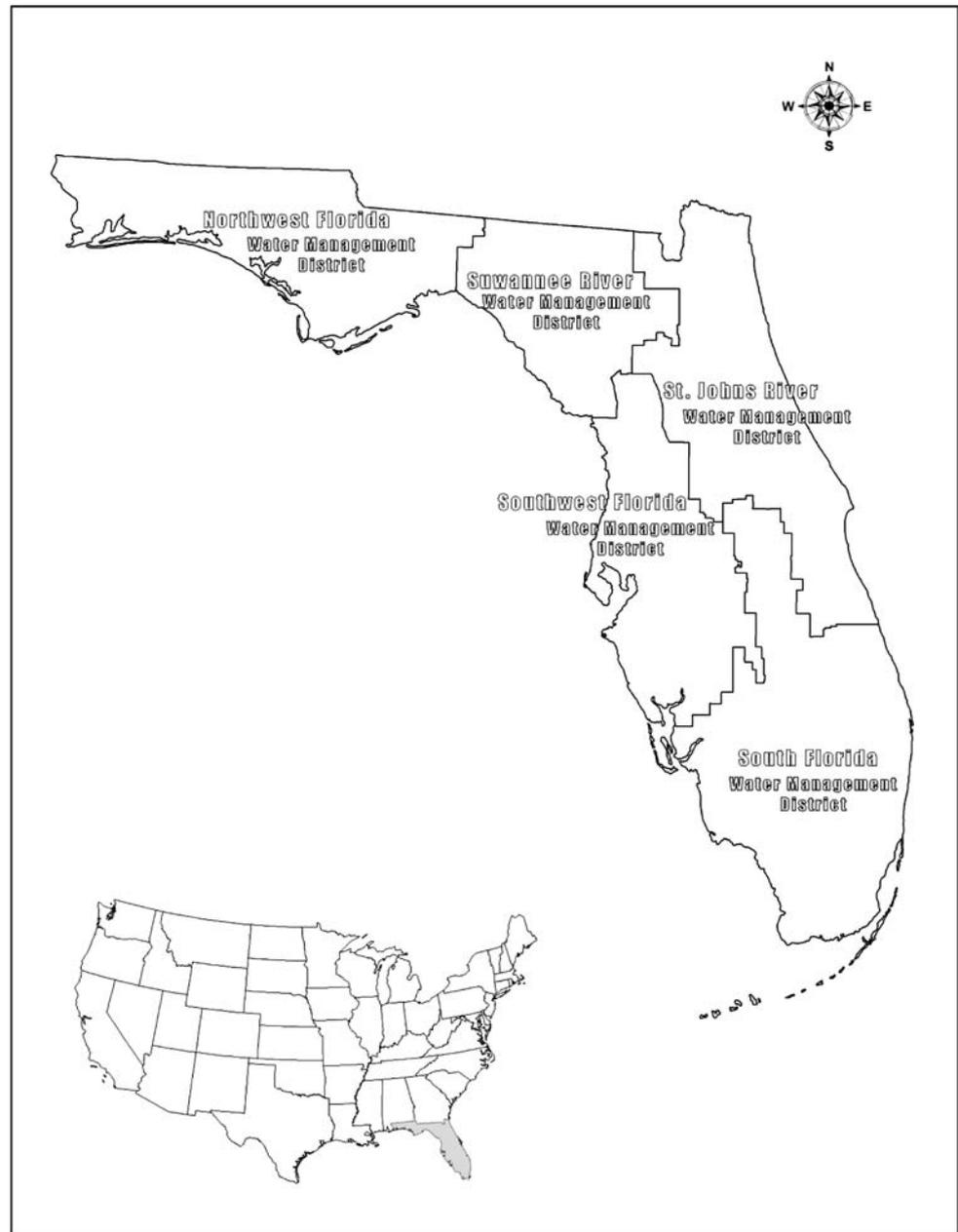
SJRWMD MFLs Method

The SJRWMD MFLs method is presented by focusing on the eight premises that provide the foundation for the approach. English system units are presented because groundwater and surface water modelers, land surveyors, and the regulated public use this system in Florida. Also, English-unit MFLs are adopted by rule (e.g., 40C-8, *F.A.C.*). Metric units are included in the text to improve readability. The use of English units does not limit the utility of the method.

The Method was Developed with a Top Down Approach

The method is based on identifying an acceptable degree of departure from the natural flow regime (Tharme 2003). Such departures may be visualized by modeling incremental increases in water withdrawals from a natural system with unaltered hydrology over the same, long (e.g., 50 years) period. First, very small withdrawals may result in changes to the hydrograph that are difficult to measure (Fig. 3, Alt 1). Second, larger withdrawals may cause measurable changes to the hydrologic regime (Fig. 3, Alt 2) that do not result in significant harm (the concept of significant harm will be discussed later in this article). Third, a threshold hydrologic regime exists (Fig. 3,

Fig. 1 Locations of Florida's five water management districts



Threshold) that results in a maximum hydrologic alteration that prevents significant harm. Finally, additional withdrawals, beyond the MFLs threshold, will cause significant harm (Fig. 3, Alt 4).

MFLs are Primarily Focused on Ecological Protection

A long-standing objective of instream flow studies is to recommend the flow requirements of selected species that maintain the population (Nestler and others 1989). A SJRWMD goal is to protect ecological structure and functions from significantly harmful water withdrawals.

Criteria may address the hydrologic needs of listed/endangered species, commercially or recreationally important species, endemic species, native species, or keystone species. A selected species should serve as an “umbrella species” (Lambeck 1997) with requirements for persistence focused on hydrology. For example, protecting the hydrologic regime needed to ensure sufficient warm-water habitat for the manatee population at Blue Spring, will protect endemic mollusks that inhabit this spring system.

The method can focus on higher levels of biological organization. Defining minimum hydrologic regimes

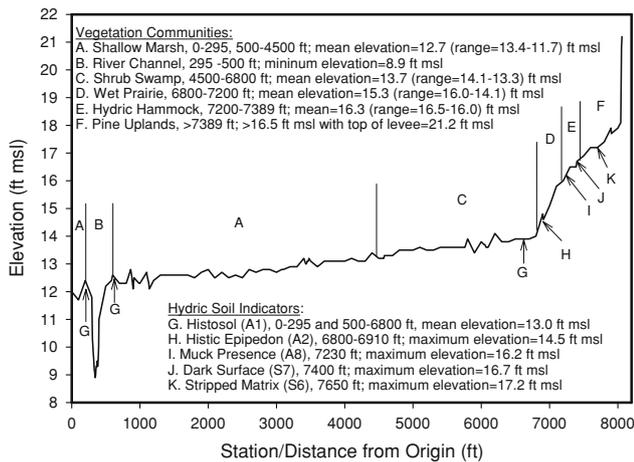


Fig. 2 Transect from the St. Johns River at a river hydraulic control location showing plant communities and soils elevation information used for the determination of multiple MFLs (Stations in feet from point of origin are shown on the x-axis and elevations are in feet msl are shown on the y-axis)

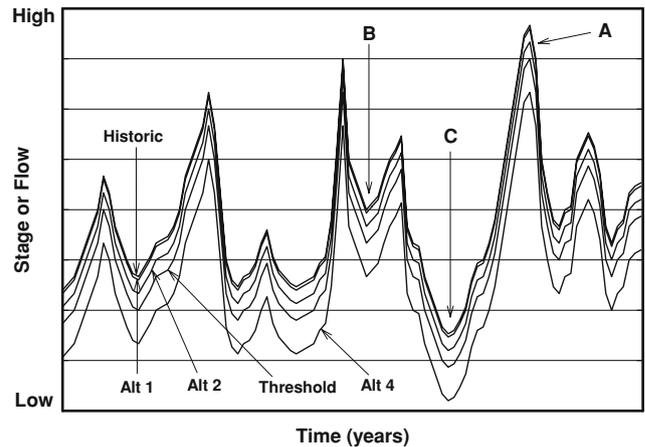


Fig. 3 Long-term historic and alternative (Alt 1, Alt 2, Threshold, Alt 4) withdrawal hydrographs for the same time period (e.g., 50 years) showing high (a), intermediate (b), and low (c) water conditions

Table 1 MFLs adopted for four water resource types in the SJRWMD (from the December 3, 2006 version of Chapter 40C-8, Florida Administrative Code)

System type	System name	MFLs name	MFLs values- Magnitude (ft msl or cfs), duration (days), return interval (years)	General indicators of protection	Specific indicators
River	Blackwater Creek	IH	27.0 ft, 340 cfs, 7 days, 5 years	Valley maintenance	Mean elevation upland/wetland ecotone
		FH	25.8 ft, 145 cfs, 30 days, 2 years	Wetlands flooding	Mean elevation of hardwood swamp (HS)
		MA	24.3 ft, 33 cfs, 180 days, 1.7 years	Muck soil maintenance	Mean elevation, HS (with muck) -0.26 ft
		FL	22.8 ft, 2.5 cfs, 90 days, 15 years	Wetlands dewatering	Mean elevation, HS (with muck) -1.7 ft
		IL	21.9 ft, 0 cfs, 7 days, 100 years	Fish passage	0.6 ft depth over 25% of riffle habitat
Lake	Weir	FH	57.2 ft, Seasonally flooded ^a	Wetlands flooding	Mean elevation, hardwood swamp
		MA	56.4 ft, Typically saturated ^b	Muck soil maintenance	Mean elevation, muck -0.3 ft
		FL	54.9 ft, Semipermanently flooded ^c	Wetlands dewatering	Mean elevation, muck -1.7 ft
Wetland	Boggy marsh	FH	117.3 ft, Seasonally flooded ^a	Wetlands flooding	Mean elevation, hardwood swamp
		MA	115.9 ft, Typically saturated ^b	Muck soils maintenance	Mean elevation, muck -0.3 ft
		FL	114.5 ft, Semipermanently flooded ^c	Wetland dewatering	Mean elevation, muck -1.7 ft
Spring	Blue Spring	See note ^d below	12/3/06–3/31/09, 133 cfs 4/1/09–3/31/14, 137 cfs 4/1/14–3/31/19, 142 cfs 4/1/19–3/31/24, 148 cfs after 3/31/24, 157 cfs	Warm-water wintering habitat maintenance	Specific capacity requirements for an increasing manatee population with recovery to historic long-term average spring flow conditions by 2024 to meet the projected population size using Blue Spring as winter warm-water refuge

^a Seasonally flooded is a hydroperiod category with a temporal component of 30 days, 2-year high

^b Typically saturated is a hydroperiod category with a temporal component of 180 days, 1.5-year low

^c Semipermanently flooded is a hydroperiod category with a temporal component of 120 days, 5-year low

^d Blue Spring minimum flow represented by minimum long-term mean flow to protect the projected increase in number of manatees using Blue Spring as a winter warm-water refuge and the water resource values listed in Rule 62-40.473, F.A.C.

needed to protect wetland plant communities from loss (Neubauer and others 2004) and that prevent oxidation and subsidence of organic soils (Stephens 1974) has been the

focus of some MFLs determinations. This focus may provide umbrella criteria that will likely maintain species dependent upon these communities and substrates.

The method can be used to address the minimum hydrologic regimes needed to protect important ecological functions. Examples might include: nesting, spawning/rearing, and resting sites for fish; sedimentation patterns; salinity distributions in estuaries; groundwater recharge of interstitial habitats; and landscape-perspective number and location of wetlands for refuge areas.

Site-specific goals, criteria, and indicators of protection are developed based on evaluations of the minimum hydrologic requirements of the most sensitive portions of a system. The most sensitive portions of the system can be determined by an investigator or team of investigators (Richter and others 2006). The criteria and indicators (presented later in this article) are written from broad narrative to specific descriptions with measurable elements (Committee on Characterization of Wetlands 1995).

Multiple MFLs are Required to Protect Aquatic and Wetland Systems

Natural system hydrology is variable through time (Hill and others 1991) and is shaped by spatial and temporal precipitation patterns. High (Fig. 3a), intermediate (Fig. 3b), and low (Fig. 3c) flows or levels (i.e., stages) will occur in all systems, including springs (Rosenau and others 1977). Multiple MFLs are used to address different portions of the flow regime (King and others 2003). The names of these different MFLs are the: (1) minimum infrequent high flow or level (IH), (2) minimum frequent high flow or level (FH), (3) minimum average flow or level (MA), (4) minimum frequent low flow or level (FL), and (5) minimum infrequent low flow or level (IL).

When applied to a river system, the IH is an extreme high flow or level that typically occurs for relatively short durations (e.g., days to weeks) with long return intervals (e.g., >10 years). The FH is a high flow or level that typically occurs for medium durations (e.g., weeks to months) with short return intervals (e.g., 2-year). The MA is a low flow or level that typically occurs for relatively long durations (e.g., 6 months) with short return intervals (e.g., 1.5-year). The FL is a low flow or level that typically occurs for shorter durations (e.g., 2–3 months) but with longer return intervals (e.g., 5–10 year) than the MA. The IL is an extreme low flow or level that typically occurs for short durations (e.g., days to weeks) with very long return intervals (e.g., >20 years).

MFLs are Usually Represented as Long-Term (>30–50 years) Hydrologic Statistics

MFLs are usually hydrologic statistics composed of: a flow (cubic feet per second [ft^3/s]) and/or a water level (feet above mean sea level [ft msl]); a duration (days); and a

return interval (years). Magnitude, duration, and return interval are the first hydrologic regime components of an undisturbed system that would be altered as withdrawals are increased from very small to very large amounts (Fig. 3). The timing (a.k.a., seasonality) and rate of change components, although variable among years, would follow natural patterns driven by weather and basin characteristics. Timing and rate of change hydrologic components would only be changed under more extreme anthropogenic alterations (e.g., large dams). Flooding events that tend to occur during the Florida wet season (e.g., June through May water year) and dewatering events that tend to occur during the dry season (e.g., October through September water year) are considered when determining and implementing MFLs. Thus, seasonality is addressed. The rate of change component is addressed when meaningful durations are developed for MFLs. For example, indicators of protection for first or second order streams would likely focus on shorter durations while longer durations would be more appropriate for higher order rivers. Therefore, defining a new MFLs hydrologic regime with magnitude, duration, and return interval components is appropriate if the timing and rate-of-change components are sufficiently natural. Notably, these latter two components, even when not easily corrected or changed, should be considered when developing environmental flow recommendations (Richter and others 2006).

The Method is Event Based

The magnitude and duration hydrologic components collectively define high and low water events that affect biota at the individual level. For example, an upland tree, growing in a wetland during an extended drought, will be killed by a post-drought, high water level that is continuously exceeded for a long enough duration. The return interval component defines the recurrence of events and affects biota at the population level. For example, an uplands edge will be maintained near a field elevation where the return interval of lethal, high water events recurs frequently enough to prevent permanent establishment of uplands plant populations at lower elevations. Return interval is often transformed into the number of events expected to occur, on average, in a century (e.g., 2-year return interval means 50 annual events per century, on average) and is considered the manageable hydrologic component. Thus, the MA, FL, and IL are minima because withdrawals should not cause low flow or level events to recur more frequently than the return interval of these MFLs. The IH and FH are minima because withdrawals must allow high flow or level events to recur no less frequently than the return interval of these MFLs.

MFLs are not calculated from annual maximum and minimum series frequency analysis of long-term historic or existing conditions hydrology but represent the minimum number of high water events or maximum number of low water events per century required to protect system-specific criteria. For example, the adopted FH flow for the Blackwater Creek at State Road 44 (Table 1) may be described as a flood flow event of 145 ft³/s (4.1 m³/s) or greater, for at least 30 continuous days that is exceeded at least 50 out of 100 years, on average. The return interval of this FH will allow this event to occur less frequently. That is, the same event had a 1.7-year return interval or would be exceeded 59 out of 100 years, on average under the existing conditions hydrology when the MFLs were adopted (Hupalo and others 1994). Thus, water withdrawals could allow this flooding event to occur nine fewer times per century, on average, without resulting in significant harm.

The Method was Developed with a Non-Equilibrium Paradigm

A method assumption is that steady state or dynamic equilibrium conditions do not exist (Meffe and others 1994) between the hydrology and the ecology of a system. That is, not all measurable changes to system hydrology result in subsequent changes to the ecology or the water resources of a system. Thus, defining hydrologic thresholds of events (i.e., MFL return interval components) is more important than developing response curves that describe relationships between flow alteration and ecological responses (Arthington and others 2006), habitat-flow curves that define habitat availability at a given flow (Hatfield and Bruce 2000), or species-discharge relationships that predict numbers of fish species from mean annual discharge (Xenopoulos and Lodge 2006). Steady state/equilibrium conditions (Xenopoulos and Lodge 2006) and the importance of relatively short time scales (Arthington and others 2006) are assumptions made when developing and using such curves. For this paper, a threshold is the return interval of an event beyond which an effect begins to be produced. Examples of site-specific criteria, general indicators, and specific indicators of protection for the five MFLs that might be used to protect a river system are presented in Appendix A. Similarly, criteria and indicators may be developed for lakes, wetlands, or springs.

Significant Harm can be Prevented

SJRWMD has not adopted by rule, a definition of “significant harm.” However, four assumptions are implicit in the SJRWMD concept of significant harm.

First, significant harm is caused by excessive water withdrawals/diversions and not by naturally occurring floods or droughts. Naturally occurring annual floods and droughts, including very extreme events, are considered the hydrologic drivers of system structure and functions and contributors to species evolution through natural selection. Thus, naturally occurring hydrologic events that may result in the deaths of plants and animals are not considered harmful to a system because such lethal events would have occurred in the absence of human alterations (Fig. 3, Historic). For example, some extreme (e.g., 100- or 200-year) low flow event in the pre-European man condition, Colorado River, USA would likely have resulted in sufficiently high water temperatures for a sufficiently long duration to kill fish (Carlson and Muth 1989). The MFLs hydrologic regime represents the minimum number of high water events or the maximum number of low water events caused by natural hydrologic conditions and water withdrawals/diversions. Importantly, the return intervals or numbers of high and low water events per century, on average, rather than the causes (i.e., natural or anthropogenic) of the events are important.

Second, significant harm should be considered a function of the return interval of hydrologic events and the recovery time of ecological systems. For example, if a severe but very infrequent (e.g., 100-year) low water event occurred in a natural aquatic or wetland system (a.k.a., large, infrequent disturbances [Turner and Dale 1998]), but the ecosystem recovery time is short (e.g., 20 years for fish population recovery) compared to the frequency of the event, then significant harm will not occur. If withdrawals increase the number of such a low water event (e.g., two or three times in 100 years) and the recovery time is still short compared to the new return intervals (i.e., 50-year or 33-year, respectively), then significant harm will not occur. However, when withdrawals cause infrequent or frequent events to recur too often (i.e., low events) or too seldom (i.e., high events) to allow for system recovery, then significant harm will occur. The MFLs are hydrologic thresholds that can represent the driest return intervals or numbers of events per century, on average, that protect defined goals and criteria. For example, significant harm may include the unacceptable long-term changes to ecosystem structure (e.g., a down-slope shift in the position of wetland communities), or the long-term unacceptable decline of important ecosystem functions (e.g., not maintaining sufficient warm-water habitat in a spring run for manatees during winter months) caused by anthropogenic withdrawals that exceed (e.g., too few high water events or too many low water events) those allowed by MFLs.

Third, only no harm and significant harm conditions exist. That is, if significant harm is defined as any down-slope shift in the position of wetlands, then no harm occurs

until the water withdrawals decrease the number of high water events or increase the number of low-water events and result in a predicted downhill shift in wetlands. All hydrologic conditions beyond the MFLs-defined threshold (i.e., minimum number of high water events or maximum number of low water events) that are predicted to result in downhill shifts in wetlands are classified as significant harm. Thus, natural rivers with unaltered or minimally altered hydrology can be classified to a no-harm category and serve as reference sites for the development of criteria and indicators of protection. (e.g., see SWIDS discussed later in this article). Conversely, low quality systems (e.g., systems with a net loss of wetlands and organic soils) may be classified to a significant harm category if the low quality is the result of human altered hydrology. Criteria and driest return intervals of events, developed from no-harm systems, may be compared with eco-hydrologic assessments (e.g., annual maximum and annual minimum series flow/stage frequency analyses) of significant harm class systems to help quantify the hydrologic thresholds (Arthington and others 2006). That is, data from existing systems can provide the event-based information needed to define minimum hydrologic regimes, and might reduce the need for adaptive management practices. However, adaptive management experiments might still be needed for seasonally or rate-of-change altered systems with large dams.

Fourth, the likelihood of significant harm can be predicted by assessment of the cumulative effects of separate water withdrawals from lotic, lentic, and aquifer systems on the return interval components of adopted MFLs. Significant harm would not occur if cumulative withdrawals are less than or equal to the maximum withdrawal allowed by the MFLs defined hydrologic regime. Alternatively, significant harm will occur if the cumulative withdrawals exceed the maximum withdrawal.

Computer Modeling is Used to Assess Water Withdrawals

MFLs implementation requires the use of calibrated and verified water budget computer models. The effects of proposed new surface or groundwater withdrawals are modeled and evaluated with previously permitted water uses to ensure that all MFLs are protected. This is a cumulative and a priori regulatory approach because the effects of proposed and existing water uses are assessed before each new allocation is permitted.

Three modeling scenarios may be developed: (1) long-term historic condition, (2) long-term existing condition, and (3) long-term MFLs condition. The long-term historic condition (Fig. 3, Historic) estimates pre-development water flows/levels that would have occurred had no

withdrawals existed during the modeled period. MFLs can be compared with the annual maximum and annual minimum series flow/stage frequency analyses from the model output to assess if each MFL would have been met. MFLs should have been attainable under historic conditions because MFLs define a minimum hydrologic regime. The long-term existing condition scenario (Fig. 3, Alt 1 or Alt 2) estimates water flows/levels that would have occurred if the current basin morphology and water withdrawals had existed during the same modeled period. MFLs can be compared with the hydrologic statistics calculated from this model scenario output to determine if the system is over-allocated. If system hydrology meets or exceeds all of the MFLs, then the system is not over-allocated. Then, incremental increases in withdrawals can be simulated until the return interval component of one MFL is no longer protected. Reducing the simulated withdrawals until system hydrology again meets MFLs results in the long-term MFLs condition (Fig. 3, Threshold). The long-term MFLs condition scenario estimates water flows/levels that would have occurred during the simulation period if existing conditions withdrawals and permitted future withdrawals had occurred.

A long-term period of record duration curve is the simplest way to illustrate MFLs as related to hydrologic statistics (Fig. 4). The area between the historic regime and the MFLs hydrologic regime represents the amount of water that may be available for consumptive use. Alternatively, an estimate of how much water must be returned to the system can be developed if the existing conditions scenario results show the system is over-allocated (Fig. 4, Alt 4). Using the same simulation period for each scenario allows for a comparison of changes in return intervals for defined events

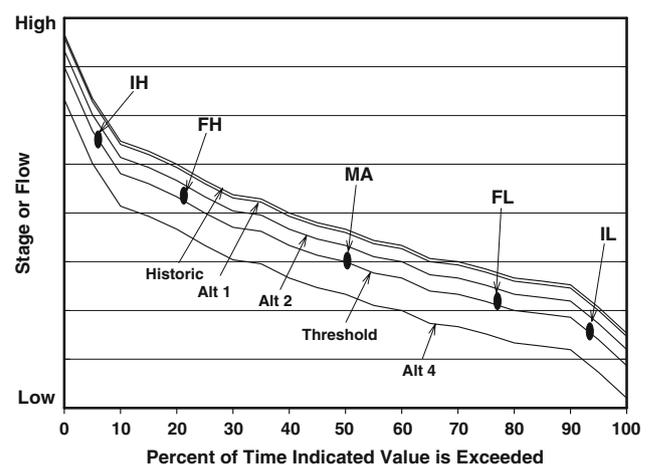


Fig. 4 Long-term historic and alternative (Alt 1, Alt 2, Threshold, Alt 4) withdrawals, period of record duration curves with the elevation components of the five minimum flows and levels (IH, FH, MA, FL, IL) indicated at a theoretical percent time exceeded value

among different withdrawal conditions and allows for the consideration of the water resource values listed in Rule 62-40.473, *F.A.C.* (HSW Engineering, Inc. 2007).

Discussion

The discussion is focused on the strengths, limitations, and other potential applications of the method.

Method Strengths

The Method can be Used to Protect Lotic, Lentic, and Aquifer Systems

Florida law requires WMDs to establish MFLs for certain surface watercourses, surface water bodies, and aquifers. The first SJRWMD MFLs determination was completed in the 396 square mile (1026 km²), Wekiva River System in 1991 (Hupalo and others 1994). MFLs for the Wekiva River, Black Water Creek, and eight named springs were determined and adopted by rule. More than 130 MFLs determinations have been completed. These determinations included: rivers with (e.g., Hall and Borah 1998, Neubauer 1999) and without (e.g., Mace 2006) water control structures, lakes (e.g., Neubauer 2000a), wetlands (e.g., Neubauer 2000b), and a first magnitude spring (Rouhani and others 2006).

The Method Allows for the Protection of a Minimum Hydrologic Regime

Ideally, MFLs would be set for a system prior to permitting water withdrawals (Fig. 3, Historic). Water could then be allocated until the MFLs defined hydrologic regime is established. A withdrawal that is projected to not protect any MFL would not be permitted. As a result, this last proposed withdrawal would be reduced or denied so that all MFLs are protected.

Evaluations of systems with permitted water withdrawals may result in a determination that one or more newly adopted MFLs are not protected. Florida law requires that a recovery strategy be implemented for systems that are below established MFLs (Section 373.0421(2), *F.S.*). Water use permits are granted for fixed time periods and must be renewed (Hamann 1998). Permits may be modified or denied at the time of renewal. Additionally, the required use of all available water conservation practices and the use of lower quality sources (e.g., reclaimed water) can result in a reduction of a permitted allocation at renewal (Hamann 1998). Therefore, mechanisms exist to reassess allocated water and achieve recovery to adopted MFLs.

The Method can be Used Outside of SJRWMD

The method may be used to define minimum hydrologic regimes elsewhere. However, different goals, criteria, and indicators of protection may be appropriate (Richter and others 2006). Wetland communities with organic soils may be the focus of MFLs in some southeastern USA systems (Appendix A). Salmon populations might be the focus of MFLs in the northwestern USA while endangered fish species (e.g., Colorado squawfish [now called northern pikeminnow]) might be used in the southwestern USA. For example, multiple MFLs might be determined to protect Chinook salmon populations. Preferred water depths (e.g., 0.5–3.5 ft) for sufficient durations (e.g., 40–60 days) may define an event to support egg laying and egg development. Egg development may require continuous inundation to maintain sediment free gravel and sufficiently high dissolved oxygen concentrations. Protection of alevins and fry may require different flow events. A frequent high flow event associated with snowmelt-runoff might be determined to facilitate the transport of fingerlings to the sea (Gillilan and Brown 1997). Assigning appropriate return intervals for these events might result in multiple MFLs that may help maintain these salmon populations. Similarly, multiple MFLs can be used to define a minimum hydrologic regime and water budget models can be used to assess the effects of management decisions in other regions of the world. The northern pikeminnow example is discussed in the method limitations section.

The Method can be Used at Variable Spatial Scales

The method is spatially scalable to address on-site hydrologic requirements of small ponds and streams to large lakes and rivers with extensive wetlands. The method was successfully applied in the Wekiva River Basin and the St. Johns River Basin. The potential exists to use the method at larger spatial scales.

The Method Accounts for a Wide Range of Hydrologic Conditions

The method allows for management decisions that include long time scales. Such time scales allow for consideration of extreme high and low water events of multi-decadal cycles (Enfield and others 2001). Long time frames are also appropriate because aquatic and wetland biota have evolved and continue to evolve through natural selection in response to a continuum of hydrologic events.

The Method Does not Require Long-Term Hydrologic Data

MFLs can be determined for systems with no hydrologic data because MFLs are not calculated with such information. However, sufficient on-site rainfall, stage, and/or flow data must then be collected to calibrate and verify the water budget models that are used to implement MFLs. Clearly, the amount of time needed to implement MFLs would be shorter for systems with long-term hydrologic data.

Not all Systems Require the Determination of all Five MFLs

SJRWMD frequently determines three MFLs, one high MFL (FH) and two low MFLs (MA, FL). Establishing one high MFL is considered adequate for many Florida systems because most water withdrawals have a lesser effect on system hydrology at high flows or levels. More MFLs are usually established to define the low water portion of the hydrologic regime because water withdrawals during low flow or level events usually account for a greater proportion of system hydrology. An IH or IL can be established when needed. Alternatively, an IH and IL might be sufficient to protect some sandhill-type lakes which tend to have large ranges of fluctuation. Finally, long-term mean flows have been adopted for some springs (Table 1) because steady state groundwater models are currently used to implement MFLs.

Method Limitations

Period of Record Duration Curves Cannot be Used to Implement MFLs

Many environmental flow assessments have only focused on magnitude and duration component requirements. Magnitude and duration are often presented graphically as traditional flow-duration curves (FDCs) that display the relationship between flow and the percentage of time a particular flow is exceeded (Gordon and others 1992). Unfortunately, FDCs (Fig. 4) are not sufficient to characterize or implement SJRWMD MFLs because these curves are: period of record dependent (Vogel and Fennessey 1994), tend to oversimplify (Vogel and Fennessey 1995), and essentially average the data (Gordon and others 1992). FDCs do not maintain the return interval and duration component information of flooding or dewatering events. FDCs also result in the loss of timing and rates of change component information. For example, a flow that is exceeded 10% of a year may represent one flood event with 36.5 days duration or 52 flood events with 0.7 days duration each. Extending this example to a lake with a water level that is exceeded 10% of the time during a 50-year period, could be the result of stage data collected during

five consecutive wet years (i.e., 1826 consecutive days above the 10% time exceeded water level) or yearly flood events that last for 36.5 days duration each. The wetland communities associated with the lake would likely be very different under these two, long-term hydrologic regimes that cannot be distinguished by assessment of FDCs alone.

Magnitude, Duration, and Return Interval Information is not Always Available

The specific indicators of protection may need to be based on professional judgment (e.g., scientific panels [Arthington and others 2003]) or adapted from the scientific literature. For example, fish passage depths may be derived from the scientific literature for similar size species (e.g., Thompson 1972, as discussed by Stalnaker and Arnette 1976). However, duration and return interval information for fish passage may be lacking from the literature and may need to be based on professional judgment alone.

Specific indicators use by SJRWMD from the scientific literature include the 0.30 ft (0.08 m) water level component to protect organic soils from oxidation and subsidence and the 1.67 ft (0.5 m) drawdown water level component for seasonal wetland dewatering. The 0.30 ft water level was calculated by extrapolation of data collected for peat oxidation studies from the Florida Everglades (Stephens 1974). The 1.67 ft water level was developed from soils surveys information of the Soil Conservation Service (SCS 1974, 1979, 1980) and was further supported by a drawdown study of 20 Florida marshes (Environmental Sciences and Engineering, Inc. 1991).

Another example of a literature-based indicator is the recommended instream flow requirements for the endangered northern pikeminnow. Milhous (1998) proposed a frequent high flushing flow (354 m³/s) with duration (4 days) and return interval (2-years) to periodically remove fine sediments from gravel spawning sites. A frequent low flow (27 m³/s) was recommended to protect riffle areas from fine sediment deposition during the late June to mid August spawning season with a return interval of every year. These flows with temporal components might serve as a minimum frequent high flow and minimum frequent low flow, respectively. Other criteria and indicators of protection might be developed and expressed as an IH, MA, or IL to more completely define a long-term minimum hydrologic regime needed to protect this species.

An example of specific research focused on magnitude, duration, and return interval components resulted in surface water inundation/dewatering signatures (SWIDS) for the minimum, mean, and maximum elevations of riparian plant communities in northeast Florida. Annual maximum and annual minimum series stage frequency analyses of these plant community elevations indicate that equivalent plant communities have similar flooding and dewatering

signatures at different sites (Neubauer and others 2004). MFLs can be set with the drier to driest return intervals for biologically relevant events (Appendix A).

Other Potential Uses

The Method can be Used for Eco-Hydrologic Restoration Projects

Optimum hydrologic requirements of species, communities, or ecological functions can be used to meet restoration goals/objectives (Robison and others 1997) rather than the minimum hydrologic requirements needed to prevent significant harm. For example, defining a hydrologic regime that protects existing organic soils from oxidation and subsidence may be an example of a criterion for an MA. Defining a more optimum hydrologic regime that results in the accumulation of “new” organic soils may be an environmental restoration goal. Such a regime might have more high water events and fewer low water events than a MFLs hydrologic regime.

The method may also be used for wetland creation projects. Long-term water budget models can be combined with SWIDS information to allow for a determination of the elevations where wetland plant communities would likely occur based upon the engineering design of the system. Planting the appropriate species within the appropriate elevation ranges should increase the success and efficiency of wetland creation projects.

The Method may be Used to Modify Large Dam Regulation Schedules

The method may be used to enhance the survival of selected species at locations downstream from a large dam. The “naturalness” of timing and rate of change components should first be evaluated before prescribing magnitude, duration, and return interval hydrologic components. Consider a river reach downstream from a large dam with seasonality altered by half a year such that high flows occur during the dry season and low flows occur during the wet season. The reach might be prescribed the appropriate magnitude, duration, and return interval components from high- and low-stage/flow frequency SWIDS analysis as this same system with “natural” seasonality. However, significant harm would likely occur in the seasonally altered system because the biota had evolved with “natural” seasonality that existed before the dam was constructed. Likewise, a system that is managed for hydroelectric power generation may be impacted because there is no natural analogue in freshwater systems to hydropeaking (Poff and others 1997). Finally, the method may be used to determine seasonally and inter-annually variable flow releases from the control structure rather than a uniform low flow release each year.

Conclusions

The SJRWMD multiple MFLs method is unlike most other methods. The method defines a long-term minimum hydrologic regime designed to protect lotic, lentic, and aquifer systems from significantly harmful withdrawals. The “top down” method can address magnitude, duration, return interval, seasonality and rates of change components; the latter two should be sufficiently natural. SJRWMD MFLs, focused on the protection of the most sensitive high- and low-water event related system components, are implemented in a cumulative and a priori approach with long-term hydrologic water budget models.

The SJRWMD MFLs method is often focused on biologically relevant events that affect biota at the individual level and return intervals of events that affect biota at the population level. Importantly, the event-based, non-equilibrium approach is focused on thresholds rather than gradient- or continuum-based flow response curves, habitat-flow curves, or numbers of species-discharge curves. Such curves are considered more appropriate with a steady state, equilibrium perspective of ecological systems. Thus, SJRWMD MFLs method may reduce the need for adaptive management experiments because existing systems with non-impacted, mildly impacted, and severely impacted hydrology can provide event-based information needed to define minimum hydrologic regimes. Adaptive management practices will likely be needed for seasonally or rate-of-change component altered systems.

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Appendix A

Examples of MFLs Criteria, General Indicators, and Specific Indicators of Protection

Each MFL is usually developed with a three step process. First, the magnitude component is often defined from transect information (Fig. 2). Second, a duration component is developed to define a meaningful event. For example, a 7-day flood duration might be used for an IH to address a

sediment transport criterion. Similarly, a 30-day flood of seasonally flooded wetlands might be used for a FH. Third, the return intervals component or minimum numbers of flood events or maximum numbers of dewatering events are developed to protect the MFLs criteria. The following criteria are similar to those used for the Wekiva River Basin MFLs determination (Hupalo and others 1994). The specific indicators (i.e., MFLs) are presented and may include information developed since 1991.

Riparian Inundation Criterion to Determine an IH

Extreme high water flow or level events occur in systems with unaltered hydrology that provide for out-of-bank flooding at a return interval sufficient to maintain river valley and floodplain structure and functions (Hill and others 1991). These high water events support important ecological functions by providing for floodplain-building processes, such as the transport of sediment, detritus, nutrients, and seeds between the river channel and associated riparian areas. These infrequent events can also recharge surficial aquifers and raise water table levels in areas adjacent to the river. These events can result in freshwater pulses to estuarine areas causing biologically relevant effects of temporarily reduced salinity. These types of flooding events do not require inundation of upland plant communities, but may maintain the location of the upland ecotone.

General Indicator of Protection of the Riparian Inundation Criterion

River valley type and riparian areas will be protected if withdrawals do not reduce the number of short-duration floods of riparian plant communities near uplands beyond the return interval threshold of the IH. These high flow/level events are associated with wet season rainfall events and usually occur during or following periods of well above normal precipitation.

Specific Indicator of Protection of the Riparian Inundation Criterion

The indicator is a high water level and associated flow that corresponds to the maximum elevation of the cabbage palm (*Sabal palmetto*) hammock community (Neubauer and others 2004) located adjacent to uplands for a duration of 7 continuous days with a 10-year return interval (i.e., 10 such high water events per 100 years, on average).

Wetland Inundation Criterion to Determine a FH

Seasonally high water flow or level events occur in systems with unaltered hydrology that provide for out-of-

bank flooding of the wetlands adjacent to the main stem of a river at a return interval sufficient to support important ecological processes (Hill and others 1991). These processes include maintaining plant community structure and serving the needs of aquatic biota that utilize the habitat for feeding, reproduction, and refuge (Junk and others 1989). Such frequent flooding events should also be of sufficient return interval to allow for strong recruitment year classes of fish that utilize the floodplain resources during these high water events (Killgore and Baker 1996).

General Indicator of Protection of the Wetland Inundation Criterion

The locations, structure, and functions of seasonally flooded wetland plant communities adjacent to the main channel of the river will be protected if withdrawals do not reduce the number of medium duration floods beyond the return interval threshold of the FH. Such high water events should also protect floodplain-dependent fish that require access to the seasonally inundated wetland resources. These high flow/level events usually occur for extended durations during many wet seasons.

Specific Indicator of Protection of the Wetland Inundation Criterion

The indicator is a high water level and associated flow that inundates the mean elevation of a seasonally flooded maple (*Acer rubrum*) swamp community (Neubauer and others 2004) for a duration of 30 continuous days with a 2-year return interval (i.e., 50 such high water events per 100 years, on average).

Organic Substrate Protection Criterion to Determine a MA

Seasonally low water flow or level events occur in systems with unaltered hydrology that may dewater substrates but provide for predominantly anoxic soil conditions that maintain organic soils (Stephens 1974) of the wetlands adjacent to the main stem of a river. These anoxic conditions also impede the long-term encroachment of upland plant species into seasonally flooded wetland plant communities with organic soils (Davis 1943).

General Indicator of Protection of the Organic Substrate Protection Criterion

Organic soils within wetlands will be protected from oxidation and subsidence if withdrawals do not increase the number of long duration dewatering events beyond the

return interval threshold of the MA. These low flow/level events usually occur for extended durations (months) during normal dry seasons.

Specific Indicator of Protection of the Organic Substrate Protection Criterion

The indicator is a low water level and associated flow, that is 0.3 ft (0.08 m) lower than the mean elevation of organic soils (Stephens 1974) defined as histic epipedon (organic horizon ≥ 8 inches [20 cm] depth) and histosols (organic horizon ≥ 16 inches [41 cm] depth), with a duration of 180 days, mean non-exceedence and 1.5-year return interval (i.e., 67 such low water events per 100 years, on average).

Floodplain Drawdown Criterion to Determine a FL

Low water flow or level events occur in systems with unaltered hydrology that provide for periodic dewatering of seasonally flooded wetlands. Periodic dewatering supports important ecological processes that allow for seed germination in wetland plant communities (e.g., *Taxodium sp.* (Demaree 1932)), the concentration of aquatic biota in isolated floodplain pools that enable wading birds to feed (Bancroft and other 1990), and allow access to floodplain resources by wildlife species that usually inhabit upland and seldom-inundated plant communities (Harris and Gosselink 1990).

General Indicator of Protection of the Floodplain Drawdown Criterion

The locations, structure, and functions of seasonally flooded wetland plant communities adjacent to the main channel of the river will be protected if withdrawals do not increase the number of medium duration dewatering events beyond the return interval threshold of the FL. These low flow/level events usually occur during dry seasons with mild droughts and result in dewatering seasonally flooded wetlands while allowing for continued inundation of within bank, aquatic communities.

Specific Indicator of Protection of the Floodplain Drawdown Criterion

The indicator is a low water level and associated flow, that corresponds to an elevation that is 1.67 ft (0.5 m) lower than the mean elevation of seasonally flooded plant community (Environmental Sciences and Engineering, Inc. 1991) with organic soils defined as histic epipedon and histosols (SCS 1974, 1979, 1980) with a duration of 120 continuous days and 5-year return interval (i.e., 20 such dewatering events per 100 years, on average).

Fish Passage Protection Criterion to Determine an IL

Low water flow or level events occur in systems with unaltered hydrology that cause shallow inundation of hydraulic control areas within the main stem of a river channel that may impede fish passage (e.g., Thompson 1972, as discussed by Stalnaker and Arnette 1976) or that may reduce fish access between aquatic and deep water wetland habitats. These environments usually have hydrologic conditions sufficient to support aquatic species during most years. Maintaining fish passage at hydraulic control areas during all years is not necessary if refugia exist where fish can survive when hydraulic control area water depths are too low for short periods. Fish species considered, may include, endangered, endemic, listed, regionally rare, recreationally or commercially important, or keystone species.

General Indicator of Protection of the Fish Passage Criterion

Populations of fish and other aquatic species that inhabit the main channel of a river will be protected if withdrawals do not increase the number of short duration dewatering events that result in insufficient depth and cross-sectional areas at hydraulic controls beyond the return interval threshold of the IL. These low flow/level events occur during dry seasons, accentuated by more extreme droughts.

Specific Indicator of Protection of the Fish Passage Criterion

The indicator is a low water level and associated flow, that corresponds to a water depth less than 0.8 ft (0.2 m) over 25% of the channel width, at a hydraulic control elevation of the river channel (Thompson 1972, as discussed by Stalnaker and Arnette 1976) with a duration of 7 continuous days and 20-year return interval (i.e., 5 such dewatering events per 100 years, on average).

References

- Annear TC, Conder AL (1984) Relative bias of several fisheries instream flows methods. *North American Journal of Fisheries Management* 4:531–539
- Arthington AH, Rall JL, Kennard MJ, Pusey BJ (2003) Environmental flow requirements of fish in Lesetho rivers using the DRIFT methodology. *River Research and Applications* 19:641–666
- Arthington A, Bunn SE, Poff NL, Naiman RJ (2006) The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16(4):1311–1318
- Bancroft GT, Jewell SD, Strong AM (1990) Foraging and nesting ecology of herons in the Lower Everglades relative to water

- conditions: Final Report to the South Florida Water Management District, National Audubon Society Ornithological Research Unit
- Beecher HA (1990) Standards for instream flows. *Rivers* 1(2):97–109
- Brooks JF, Lowe EF (1984) U.S. EPA Clean Lakes Program, Phase I, diagnostic-feasibility study of the upper St. Johns River chain of lakes, vol II: Feasibility study. Technical Publication SJ84-15. St. Johns River Water Management District, Palatka, Fla. (http://www.sjrwmd.com/technicalreports/pdfs/TP/SJ84-15_vol2.pdf)
- Bunn SE, Arthington AH (2002) Basic principles and ecological consequences of altered flows regimes for aquatic biodiversity. *Environmental Management* 30(4):492–507
- Carlson CA, Muth RT (1989) The Colorado River: lifeline of the American southwest. In: Dodge DP (ed) Proceedings of the International Large River Symposium [LARS]. Canadian Special Publication of the Fisheries and Aquatic Science 106, 629 pp
- Committee on Characterization of Wetlands (1995) *Wetlands: Characteristics and boundaries*. National Academy Press, Washington, DC
- Davis JH (1943) The natural features of southern Florida: especially the vegetation of the Everglades. State of Florida, Department of Conservation, Florida Geological Survey, Geological Bulletin No. 25. Tallahassee, Florida, 311 pp
- Demaree D (1932) Submerging experiments with *Taxodium*. *Ecology* 13:258–262
- Enfield DB, Mestas-Nunez AM, Trimble PJ (2001) The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letter* 28(10):2077–2088
- Environmental Science and Engineering, Inc. (1991) *Hydroperiod and water level depths of freshwater wetlands in South Florida: a review of the scientific literature*. Prepared for the South Florida Water Management District, West Palm Beach, Florida
- Gillilan DM, Brown TC (1997) *Instream flow protection: seeking a balance in western water use*. Island Press, Washington, DC
- Gordon ND, McMahon TA, Finlayson BL (1992) *Stream hydrology: an introduction for ecologists*. Wiley, New York
- Grigg NS (1996) *Water resources management: principles, regulations, and cases*. McGraw Hill, New York, NY, USA, 541 pp
- Guillory V (1979) Utilization of an inundated floodplain by Mississippi River fishes. *Florida Scientist* 42(4):222–228
- Hall GB (1987) Establishment of minimum surface water requirements for the Greater Lake Washington Basin. Technical Publication SJ87-3. St. Johns River Water Management District, Palatka, Fla. (<http://www.sjrwmd.com/technicalreports/pdfs/TP/SJ87-3.pdf>)
- Hall GB, Borah A (1998) Minimum surface water levels determined for the Greater Lake Washington Basin, Brevard County. St. Johns River Water Management District, Palatka, FL
- Hamann RG (1998) Law and policy in managing water resources. In: Fernald EA, Purdum ED (eds) *Water Resources Atlas of Florida*. Institute of Science and Public Affairs. Florida State University, Tallahassee
- Harris LD, Gosselink JG (1990) Cumulative impacts of bottomland hardwood forest conversion on hydrology, water quality, and terrestrial wildlife. In: Gosselink JG, Lee LC, Muir TA (eds) *Ecological processes and cumulative impacts: illustrated by bottomland hardwood wetland ecosystems*. Lewis Publisher, Chelsea, MI, 708 pp
- Hatfield T, Bruce J (2000) Predicting salmonid habitat-flow relationships for streams from western North America. *North American Journal of Fisheries Management* 20:1005–1015
- Hill MT, Platts WS, Beschta RL (1991) Ecological and geomorphological concepts for instream and out-of-channel flow requirements. *Rivers* 2(3):198–210
- HSW Engineering, Inc (2007) Evaluation of the effects of the proposed minimum flows and levels regime on water resource values on the St. Johns River between SR 528 and SR 46 (update). Special Publication SJ2007-SP 13. St. Johns River Water Management District, Palatka, Fla. (<http://www.sjrwmd.com/technicalreports/pdfs/SP/SJ2007-SP13.pdf>)
- Hupaldo RB, Neubauer CP, Keenan LW, Clapp DA, Lowe EF (1994) Establishment of minimum flows and levels for the Wekiva River System. Technical Publication SJ94-1. St. Johns River Water Management District, Palatka, Fla. (<http://www.sjrwmd.com/technicalreports/pdfs/TP/SJ94-1.pdf>)
- Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. In: Dodge DP (ed) Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences, pp 110–127
- Killgore KJ, Baker JA (1996) Patterns of larval fish abundance in a bottomland hardwood wetland. *Wetlands* 16(3):288–295
- King J, Brown C, Sabet H (2003) A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* 19:619–639
- Lambeck RJ (1997) Focal species, a multi-species umbrella for nature conservation. *Conservation Biology* 11(4):849–856
- Mace J (2006) Minimum flows and levels determination: St. Johns River at SR 44 near DeLand, Volusia County, FL. Technical Publication SJ2006-5, St. Johns River Water Management District, Palatka, Fla. (<http://www.sjrwmd.com/technicalreports/pdfs/TP/SJ2006-5.pdf>)
- Meffe GK, Carroll CR, Contributors (1994) *Principles of conservation biology*. Sinauer, Associates, Inc., Sunderland, MA, USA, 601 pp
- Milhou RT (1998) Modelling of instream flow needs: The link between sediment and aquatic habitat. *Regulated Rivers Research and Management* 14:79–94
- Munson AB, Delfino JJ, Leeper DA (2005) Determining minimum flows and levels: the Florida experience. *Journal of the American Water Resources Association* 41(1):1–10
- Nestler JM, Milhou RT, Layzer JB (1989) Instream habitat modeling techniques. In *Alternatives in Regulated River Management*. CRC Press, Boca Raton, Florida
- Neubauer CP (1999) Recommended surface water MFLs for Taylor Creek determined at transect 4, downstream of S-164 control structure, Osceola/Orange Counties. St. Johns River Water Management District technical memorandum, Palatka, Florida, USA
- Neubauer CP (2000a) Re-evaluation of recommended minimum surface water levels determined for Lake Weir, Marion County. St. Johns River Water Management District technical memorandum, Palatka, Florida, USA
- Neubauer CP (2000b) Preliminary minimum levels determination: Boggy Marsh, Lake County. St. Johns River Water Management District technical memorandum, Palatka, Florida, USA
- Neubauer CP, Robison CP, Richardson TC (2004) Using magnitude, duration, and return interval to define specific wetlands inundation/dewatering signatures in northeast Florida, USA [abstract]. In: Society of Wetland Scientists, Charting the Future: A Quarter Century of Lessons Learned, 25th Anniversary meeting program; July 18–23, 2004, Seattle, Washington, USA, p 179, Abstract #20.5
- Nilsson C (2000) Minimum river flow. *Rivers* 7(2):171–174
- Poff NL, Allan D, Bain MB, Darr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* 47(11):769–784
- Postel S, Richter B (2003) *Rivers for life: managing water for people and nature*. Island Press, Washington, USA, 254 pp
- Purdum EE, Burney LC, Swihart TM (1998) History of water management. In: Fernald EA, Purdum ED (eds) *Water Resources*

- Atlas of Florida. Institute of Science and Public Affairs. Florida State University, Tallahassee
- Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10(4):1163–1174
- Richter BD, Baumgartner JV, Braun DP (1997) How much water does a river need? *Freshwater Biology* 37:231–249
- Richter BD, Warner AT, Meyer JL, Lutz K (2006) A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* 22:297–318
- Robison CP, Hall GB, Ware C, Hupalo RB (1997) Water management alternatives: effects of lake levels and wetlands in the Orange Creek Basin. St. Johns River Water Management District, Special Publication SJ97-SP8, Palatka, Fl. (<http://www.sjrwmd.com/technicalreports/pdfs/SP/SJ97-SP8.pdf>)
- Rosenau JC, Faulkner GL, Hendry CW Jr, Hull RW (1977) Springs of Florida. Bulletin 31 (revised). Florida Bureau of Geology, Tallahassee
- Rouhani S, Sucsy PV, Hall GB, Osburn WL, Wild M (2006) Analysis of Blue Spring discharge data to determine a minimum flow regime. Report prepared by New Fields Companies, LLC, Atlanta, GA, for St. Johns River Water Management District, Special Publication SJ2007-SP17, Palatka, Florida. (<http://www.sjrwmd.com/technicalreports/pdfs/SP/SJ2007-SP17.pdf>)
- Silk N, McDonald J, Wigington R (2000) Turning instream flow water rights upside down. *Rivers* 7(4):298–313
- Soil Conservation Service (1974) Soil Survey of Brevard County, Florida. U.S. Department of Agriculture
- Soil Conservation Service (1979) Soil Survey of Volusia County, Florida. U.S. Department of Agriculture. 148 pp. + 174 illustrations
- Soil Conservation Service (1980) Soil Survey of Volusia County, Florida. U.S. Department of Agriculture
- Stalnaker CB (1990) Minimum flow is a myth. In: Bain MB (ed) *Ecology and assessment of warmwater streams: workshop synopsis*. Biological Report 90(5). U.S. Fish and Wildlife Service, Washington, DC
- Stalnaker CB, Arnette JL (1976) Methodologies for determining instream flows for fish and other aquatic life. In: Stalnaker CB, Arnette JL (eds) *Methodologies for the determination of stream resource flow requirements*. Report FWS/OBS-76-03. U.S. Fish and Wildlife Service, Washington, DC, pp 89–138
- Stephens JC (1974) Subsidence of organic soils in the Florida Everglades—A review and update. In: Gleason PJ (ed) *Environments of South Florida*. Memoir 2. Miami Geological Society, Miami, Fla
- Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19:397–441
- Turner MG, Dale VH (1998) Comparing large, infrequent disturbances: what have we learned? *Ecosystems* 1:493–496
- Tyus HM (1992) An instream flow philosophy for recovering endangered Colorado River fishes. *Rivers* 3(1):27–36
- Vogel RM, Fennessey JM (1994) Flow duration curves I: a new interpretation and confidence intervals. *Journal of Water Resource Planning and Management* 120(4):485–504
- Vogel RM, Fennessey JM (1995) Flow duration curves II: a review of applications in water resources planning. *Water Resources Bulletin* 31(6):1029–1039
- Xenopoulos MA, Lodge DM (2006) Going with the flow: using species-discharge relationships to forecast losses in fish diversity. *Ecology* 87(8):1907–1918