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ECOLOGICALLY SUSTAINABLE WATER MANAGEMENT: MANAGING RIVER FLOWS FOR ECOLOGICAL INTEGRITY

Brian D. Richter,[1,5] Ruth Mathews,[2] David L. Harrison,[3] and Robert Wigington[4]

[1]*The Nature Conservancy, 490 Westfield Road, Charlottesville, Virginia 22901 USA*
[2]*The Nature Conservancy, 410 North 4th Street, Mt. Vernon, Washington 98273 USA*
[3]*Moses, Wittemyer, Harrison, and Woodruff, P.O. Box 1440, Boulder, Colorado 80306-1440 USA*
[4]*The Nature Conservancy, 2060 Broadway, Suite 230, Boulder, Colorado 80302 USA*

Abstract. Human demands on the world's available freshwater supplies continue to grow as the global population increases. In the endeavor to manage water to meet human needs, the needs of freshwater species and ecosystems have largely been neglected, and the ecological consequences have been tragic. Healthy freshwater ecosystems provide a wealth of goods and services for society, but our appropriation of freshwater flows must be better managed if we hope to sustain these benefits and freshwater biodiversity. We offer a framework for developing an ecologically sustainable water management program, in which human needs for water are met by storing and diverting water in a manner that can sustain or restore the ecological integrity of affected river ecosystems. Our six-step process includes: (1) developing initial numerical estimates of key aspects of river flow necessary to sustain native species and natural ecosystem functions; (2) accounting for human uses of water, both current and future, through development of a computerized hydrologic simulation model that facilitates examination of human-induced alterations to river flow regimes; (3) assessing incompatibilities between human and ecosystem needs with particular attention to their spatial and temporal character; (4) collaboratively searching for solutions to resolve incompatibilities; (5) conducting water management experiments to resolve critical uncertainties that frustrate efforts to integrate human and ecosystem needs; and (6) designing and implementing an adaptive management program to facilitate ecologically sustainable water management for the long term. Drawing from case studies around the world to illustrate our framework, we suggest that ecologically sustainable water management is attainable in the vast majority of the world's river basins. However, this quest will become far less feasible if we wait until water supplies are further over-appropriated.

Key words: adaptive management; biodiversity; dam operations; ecological flow assessment; ecosystem management; ecosystem monitoring; freshwater ecosystems; hydrologic alteration; instream flow; river management; sustainable water development; water resources management.

It is one thing to find fault with an existing system. It is another thing altogether, a more difficult task, to replace it with another approach that is better.

—Nelson Mandela, 16 November 2000
(speaking of water resource management)

In many areas of the world, growing human populations are rapidly depleting available freshwater supplies. During the 20th century, the global human population increased fourfold to more than six billion (6×10^9). Water withdrawn from natural freshwater ecosystems increased eightfold during the same period (Gleick 1998). Facing an ominous specter of increasingly severe water-supply shortages in many areas of the world, social planners and government leaders are exploring strategies for managing water resources sustainably (IUCN 2000). This quest for sustainability typically centers on managing human uses of water such that enough water of sufficient quality is available for use by future generations.

In the endeavor to manage water to meet various human needs, however, the water needs of freshwater species and ecosystems have been largely neglected. The ecological consequences have been tragic (IUCN 2000, Pringle et al. 2000, Stein et al. 2000, Baron et al. 2002). The alteration of river flow regimes associated with dam operations has been identified as one of three leading causes, along with nonpoint source pollution and invasive species, of the imperilment of aquatic animals (Richter et al. 1997*a*, Pringle et al. 2000). Freshwater ecosystem services and products valued by society have been severely compromised as well (Postel and Carpenter 1997, IUCN 2000).

The water needs of humans and natural ecosystems are commonly viewed as competing with each other. Certainly, there are limits to the amount of water that can be withdrawn from freshwater systems before their natural functioning and productivity, native species,

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[5] E-mail: brichter@tnc.org

and the services and products they provide become severely degraded. Water managers and political leaders are becoming increasingly cognizant of these limits as they are being confronted with endangered species or water quality regulations, and changing societal values concerning ecological protection. During the past decade, many examples have emerged from around the world demonstrating ways of meeting human needs for water while sustaining the necessary volume and timing of water flows to support affected freshwater ecosystems. In fact, we believe that the compatible integration of human and natural ecosystem needs (identified here as *ecologically sustainable water management*) should be presumed attainable until conclusively proven otherwise. We offer this touchstone for such efforts:

> *Ecologically sustainable water management protects the ecological integrity of affected ecosystems while meeting intergenerational human needs for water and sustaining the full array of other products and services provided by natural freshwater ecosystems. Ecological integrity is protected when the compositional and structural diversity and natural functioning of affected ecosystems is maintained.*

In this paper we offer a general framework for developing an ecologically sustainable water management program, drawing upon examples from around the United States and beyond to illustrate its essential elements, with a focus on river systems. Before we elaborate on the elements of this framework, we further discuss the ecological degradation that we seek to alleviate.

Natural vs. Managed Flow Variability

Ecological degradation has generally been an unintended consequence of water management, stemming from a lack of understanding of water flows necessary to sustain freshwater ecosystems. Natural freshwater ecosystems are strongly influenced by specific facets of natural hydrologic variability. Of particular importance are seasonal high and low flows, and occasional floods and droughts (Stanford et al. 1996, Poff et al. 1997, Richter et al. 1997*b*). A river's flow regime is now recognized as a ''master variable'' that drives variation in many other components of a river ecosystem, e.g., fish populations, floodplain forest composition, nutrient cycling, in both direct and indirect ways (Sparks 1995, Walker et al. 1995, Poff et al. 1997; Instream Flow Council [available online][6]). The extraordinary species richness and productivity characteristic of freshwater ecosystems is strongly dependent upon, and attributable to, the natural variability of their hydrologic conditions.

But variability runs counter to the dominant goals of water resource management (Holling and Meffe 1996). Traditional water management has generally sought to dampen the natural variability of river flows to attain steady and dependable water supplies for domestic and industrial uses, irrigation, navigation, and hydropower, and to moderate extreme water conditions such as floods and droughts. For instance, by storing water in reservoirs, water managers capture high flows during wet years or seasons to supplement water supplies at drier times, thereby maximizing the reliability of water supplies and certain economic benefits each year.

When natural variability in river flows is altered too much, marked changes in the physical, chemical, and biological conditions and functions of natural freshwater ecosystems can be expected. When changes to natural flow regimes are excessive, causing a river ecosystem to degrade toward an altered character, the costs are high to both biodiversity and society (Postel and Carpenter 1997, IUCN 2000, WCD 2000) (Fig. 1). The transition to a new, altered ecosystem state can take tens to hundreds of years as chain reactions cascade through second- and third-order effects within an ecosystem (Petts and Calow 1996, IUCN 2000), thereby obscuring original causes.

Water management for human use necessarily alters a river's natural flow regime in various ways. However, there is some degree and types of alteration that will not jeopardize the viability of native species and the ability of an ecosystem to provide valuable products and services for society. Around the world, river scientists are seeking better understanding of the ways and degrees to which river flows can be modified for human purposes while maintaining an adequate semblance of the composition, structure, and function of natural ecosystems (Poff et al. 1997, Richter et al. 1997*b*, Arthington and Zalucki 1998, King and Louw 1998, Tharme, *in press*).

Toward Ecological Sustainability

The ultimate challenge of ecologically sustainable water management is to design and implement a water management program that stores and diverts water for human purposes in a manner that does not cause affected ecosystems to degrade or simplify. This quest for balance necessarily implies that there is a limit to the amount of water that can be withdrawn from a river, and a limit in the degree to which the shape of a river's natural flow patterns can be altered. These limits are defined by the ecosystem's requirements for water. Human extraction or manipulation that exceeds these limits will, in time, compromise the ecological integrity of the affected ecosystems, resulting in the loss of native species and valuable ecosystem products and services for society.

With human uses of water and our understanding of ecosystems continually evolving, the solutions for meeting both ecosystem and human needs will evolve over time as well. Thus, ecologically sustainable water

[6] URL: 〈http://www.instreamflowcouncil.org〉

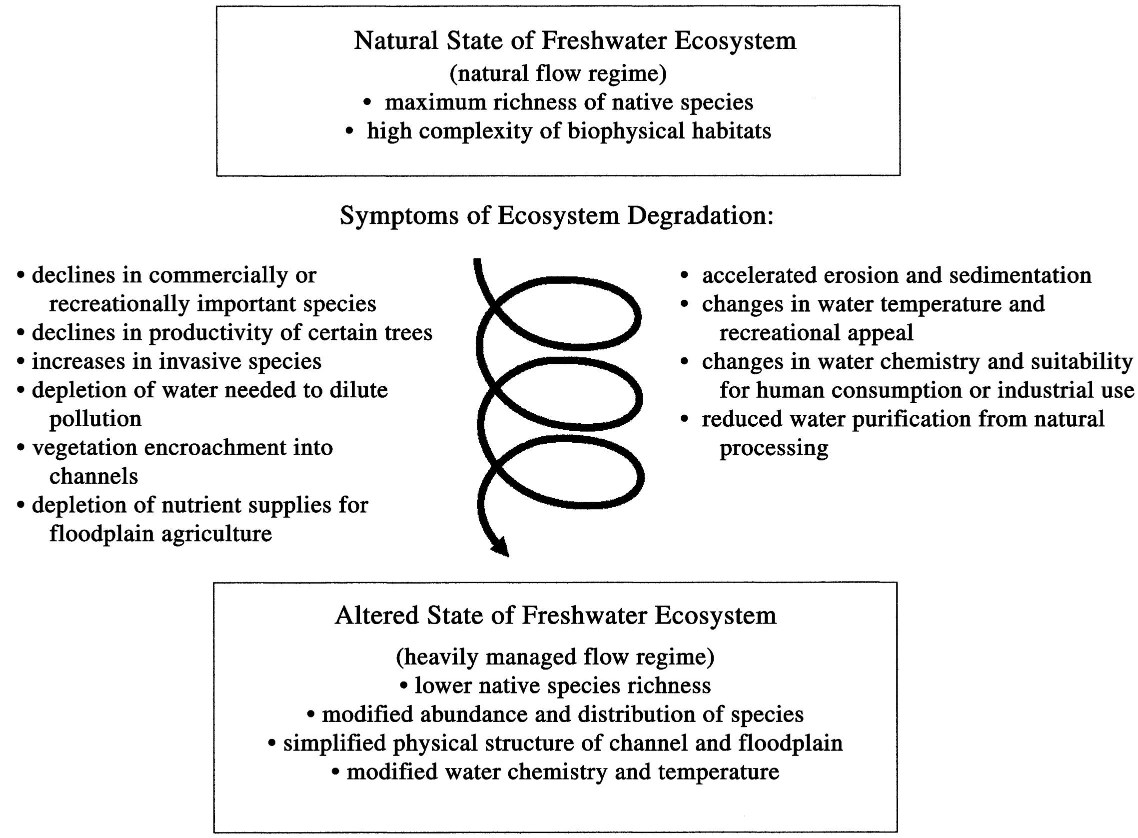

FIG. 1. When the natural flow regime of a river is altered too greatly, it will trigger a cascade of reactions that cause the river ecosystem to simplify over time, leading to a degraded state. As a result, many human uses, native species, and other ecosystem services and products can be adversely affected.

management is an iterative process in which both human water demands and ecosystem requirements are defined, refined, and modified to meet human and ecosystem sustainability now and in the future, rather than a single, one-time solution. This implies an aggressive and continual search for compatibility between ecosystem and human water needs, and requires a commitment from all parties to ongoing participation in an active dialogue.

We have developed a framework for initiating an ecologically sustainable water management program (Fig. 2). There are many entry points into this process, but our experience suggests that each step is essential to achieving ecological sustainability. Similar adaptive water management frameworks are now being employed in South Africa (Building Block Methodology, King and Louw 1998) and Australia (Holistic Methodology, Arthington and Zalucki 1998), as well as in some river basins or states in the United States. In essence, what we are describing in this paper is simply the translation and application of ecosystem management principles into a water management context. Interested readers are referred to Walters and Holling (1990), Lee (1993), Noss and Cooperrider (1994), Sparks (1995), Gunderson et al. (1995), and Christensen et al. (1996) as springboards into the voluminous literature of ecosystem management.

In the remainder of this paper we further discuss the steps included in our framework and provide examples of their application in river systems around the world. We also describe a case study from the Apalachicola–Chattahoochee–Flint River basin in Alabama, Florida, and Georgia to illustrate the application of this framework to a specific river basin.

STEP 1: ESTIMATING ECOSYSTEM FLOW REQUIREMENTS

Water management is driven by quantified objectives, e.g., specified levels of flood protection, generation of hydropower, or reliability of water supplies during drought. Similarly, water-related ecological objectives need to be quantitatively defined so that they can be integrated with other water management objectives (Rogers and Bestbier 1997).

Many different aspects of hydrologic variability can influence freshwater biota and ecosystem processes, but in constructing ecosystem flow prescriptions river scientists generally focus on these key components of flow regimes: wet- and dry-season base flows, normal high flows, extreme drought and flood conditions that

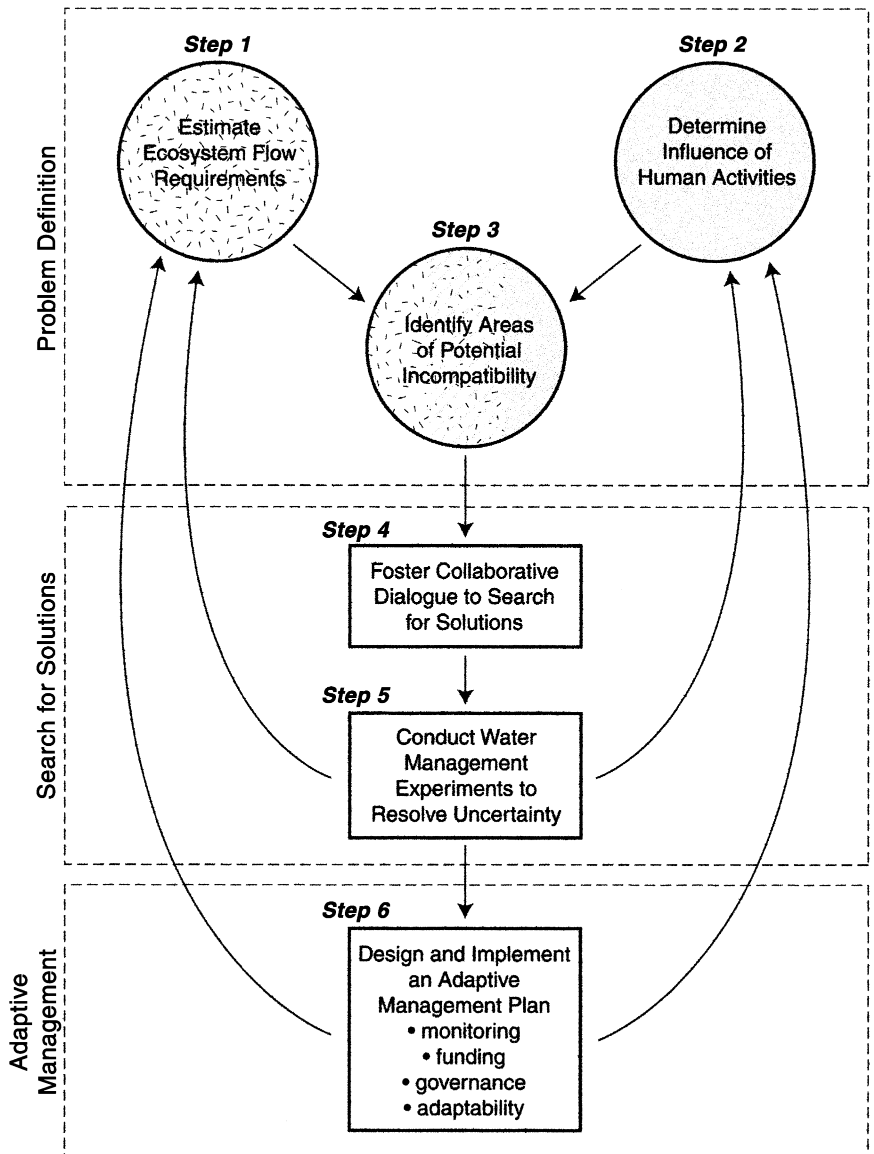

FIG. 2. A framework for ecologically sustainable water management.

do not occur every year; rates of flood rise and fall; and the interannual variability in each of these elements (Arthington and Zalucki 1998, King and Louw 1998, Trush et al. 2000). The particular flow components or statistics used to define flow requirements in different parts of the world necessarily vary to some degree, depending upon regional differences in annual hydrologic patterns. Ecosystem flow requirements can be specified as numerical ranges within which the flow component is to be maintained (e.g., Fig. 3; Richter et al. 1997*b*), or they can be expressed as threshold limits for specific flow characteristics (Table 1, Fig. 4) that should not be crossed (Rogers and Biggs 1999, Richter and Richter 2000).

Generally, the greater the number of flow characteristics used to describe ecosystem requirements, the better the chances of attaining the desired flow regime. On the other hand, the flow needs should be described using only as many characteristics as necessary. It is usually possible to identify a limited number of characteristics necessary to describe flow conditions of concern. For example, even though natural floods are essential in sustaining river ecosystems, their natural variability may not be constrained in a particular watershed in the absence of dams. Therefore, there may be no need to prescribe flood flow characteristics unless new dams are proposed in the future. This may help simplify the assessment of the ecological suitability of various water management alternatives. Primary attention should be given to flow characteristics that have been or may be altered by human influences (Rogers and Bestbier 1997, Rogers and Biggs 1999).

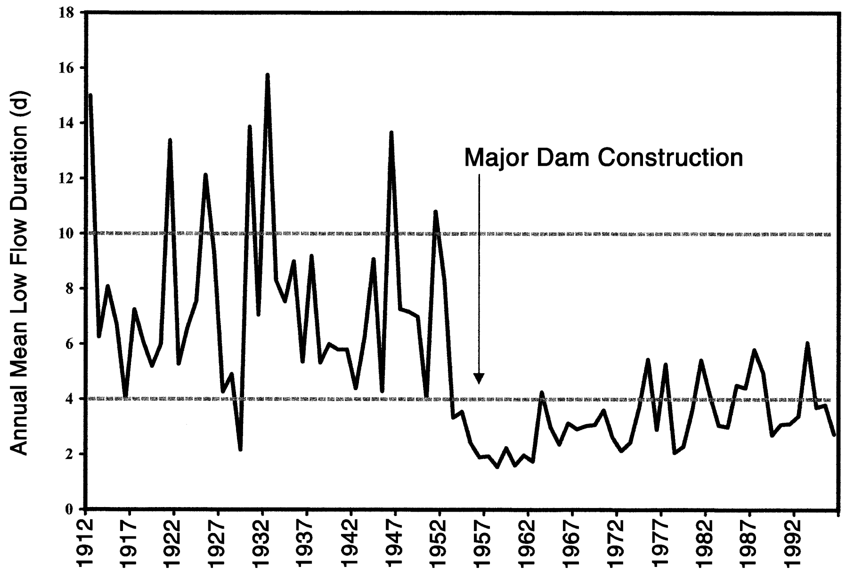

FIG. 3. Using long-term measurements of river flows for the Roanoke River in North Carolina, Richter et al. (1997*b*) applied their ''Range of Variability Approach'' method to assess changes associated with major dam construction in 1956. Initial ecosystem flow requirements for each of 32 parameters (such as annual low-flow duration, portrayed here) were then defined in terms of a range of values. For instance, one ecosystem flow target was to restore low-flow duration (defined as the cumulative number of days (d) during which flows are <96 m^3/s) to correspond more closely to its historical range of variability. This target specified that 50% of mean annual low-flow durations would fall within the range shown here with horizontal dashed bars; 25% would fall below this range, and 25% would fall above this range. Low-flow conditions are needed to dry out floodplain soils to enable reproduction and growth of plants.

Estimating ecosystem flow requirements requires input from an interdisciplinary group of scientists familiar with the habitat requirements of native biota (i.e., species, communities) and the hydrologic, geomorphic, and biogeochemical processes that influence those habitats and support primary productivity and nutrient cycling (Swales and Harris 1995, King and Louw 1998; Instream Flow Council [available online; see footnote 6]). In South Africa, expert assessment workshops are being convened for the purpose of defining necessary flows to support desired future conditions of riverine ecosystems (King et al. 2000). During these workshops, interdisciplinary participants draw upon existing data, research results, ecological and hydrological models, and professional judgment in developing initial targets for ecosystem flow requirements (King and Louw 1998). A wide variety of tools and methods is being used worldwide to prescribe ecosystem flow requirements, and these approaches are evolving rapidly (Tharme 1996, Arthington and Zalucki 1998, Bragg and Black 1999, Railsback 2001, Tharme, *in press*; Instream Flow Council [available online; see footnote 6]).

Defining ecosystem flow requirements presents many difficult challenges for scientists. For instance, the link between flows and the viability of a native species population may not be well understood, and certainly not known for all populations of native riverine species. Population viability also depends upon a number of other ecosystem conditions that are also influenced by, or unrelated to, flow variations, thereby obfuscating relationships between flow variables and population viability. Assessments of ecosystem flow requirements should not be limited to consideration of species needs, however. The flow needs of individual species provide only a very limited perspective of the broader range of flows needed to conserve healthy river ecosystems. Of great importance is evaluating the flow conditions (and particularly, disturbance events associated with droughts and floods) that structure river and floodplain ecosystems (Hill et al. 1991, Richter and Richter 2000, Trush et al. 2000). A river's natural flow regime is a cornerstone for determining ecosystem flow requirements; ecosystem flow prescriptions should always mimic natural flow characteristics to the extent possible (Poff et al. 1997, Tharme and King 1998).

It is very important that assumptions and hypotheses about flow–biota relationships, other nonflow related variables that affect biota, or the influence of flow on other ecosystem conditions such as water quality or physical habitat, be made explicit when defining initial estimates of ecosystem flow requirements. Developing conceptual ecological models that depict presumed relationships is an excellent way of communicating hypotheses (Richter and Richter 2000). Hypotheses should be formulated in a manner that allows them to be tested through carefully designed water management experiments (Step 5). These hypotheses should also, to the extent possible, express the range of variation in selected ecosystem indicators that is expected under

TABLE 1. Federal environmental agencies have defined ecosystem flow requirements thought necessary to sustain viable populations of endangered species in the Apalachicola–Chattahoochee–Flint River basin in Alabama, Florida, and Georgia.

Flow parameter	Guidelines based on pre-dam flows
Monthly 1-day minima	exceed the minimum in all years exceed the 25th percentile in 3 out of 4 years exceed the median in half of the years
Annual low-flow duration	do not exceed the maximum in all years do not exceed the 75th percentile in 3 out of 4 years do not exceed the median in half of the years
Monthly average flow	maintain the monthly mean flow within the range of the 25th and 75th percentile values in half of the years
Annual 1-day maxima	exceed the minimum in all years exceed the 25th percentile in 3 out of 4 years exceed the median in half of the years
Annual high-flow duration	exceed the minimum in all years exceed the 25th percentile in 3 out of 4 years exceed the median in half of the years

the influence of the prescribed flow characteristics (e.g., Table 2). These ecosystem indicators become part of the monitoring program (Step 6) that tracks the success of the water management plan in achieving ecological sustainability.

Initial estimates of ecosystem flow requirements should be defined without regard to the perceived feasibility of attaining them through near-term changes in water management. We reiterate our assertion that ecological sustainability should be presumed to be attainable over the long run, until conclusive evidence suggests otherwise. We have been involved in numerous water management conflicts in which initial perceptions of unfeasibility were overcome through creativity and deeper analysis, or a change in the socioeconomic or political landscapes that made possible what had seemed impossible a decade or two earlier.

Inviting water managers and other interested parties to observe the process of defining ecosystem flow requirements can have important benefits (J. King, *personal communication*). Water managers can help scientists understand how to prescribe flow targets in a manner that can be implemented. Water managers can learn a lot about the possible effects of water management on river ecosystems, thereby increasing their ecological literacy. Perhaps more important, water managers will gain insight into the nature of the *uncertainties in this knowledge*, thereby helping them understand the need for experiments and flexibility in water management. It is important for water managers, conservationists, and water users to understand that scientists will not be able to provide comprehensive and exact estimates of the flows required by particular species, aquatic and riparian communities, or the whole

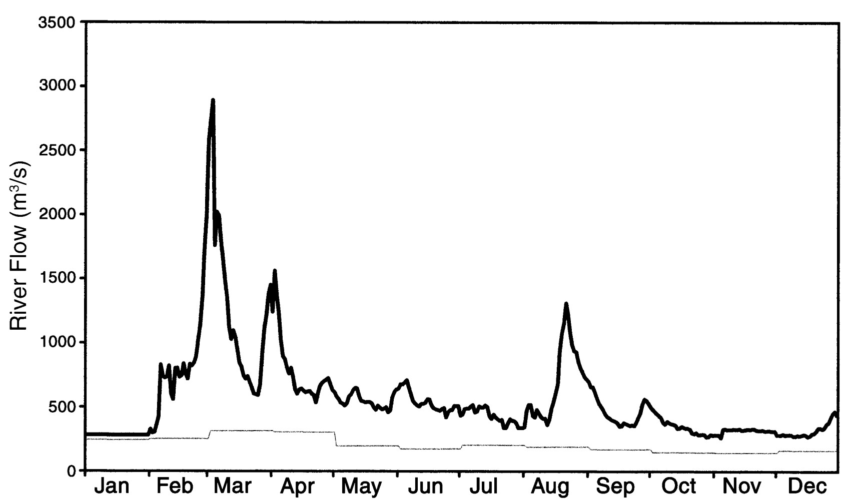

FIG. 4. One of the ecosystem flow requirements identified for the Apalachicola River in Florida is to maintain daily flows above targeted minimum levels during each month of the year. Ecosystem flow requirements (thin line) are compared with model simulated daily flows (thick line) for the drought year of 1985. River flow is in cubic meters per second (m^3/s).

TABLE 2. Examples of ecosystem indicators being used in managing river ecosystems within Kruger National Park in South Africa.

Ecosystem attribute	Unit of measurement	Measurement frequency	Measurement area	Sampling method	Threshold of possible concern (m^3/s)
River flow					
Baseflow in Sabie River during drought	cubic meters per second (m^3/s)	continuous	specified river reaches	streamflow gauge	2.0–4.0
Higher flows in Sabie River during drought	cubic meters per second (m^3/s)	continuous	specified river reaches	streamflow gauge	5.0–8.0
Geomorphic					
Channel types	proportion of channel type found in reach	every 5 years and after 25+ year floods	100–1000 m of river reach	aerial photos	depends on channel type†
Vegetation					
Population structure of key species	size class frequency distribution	every 3 years and after 25+ year floods	representative stream reaches	transects: stem diameter of individuals	must show recruitment of riparian species every 10 years or less
Fish					
Distribution of individual species	percentage of sites occupied by each species	3–5 year intervals	6 sites/river	seine netting or electroshocking	50% loss of range of individual species
Frequency of fish length	unitless	3–5 year intervals	6 sites/river	measure a minimum of 150 individuals per species	occurrence of a range of sizes, including both juveniles and adults
Invertebrates	total number of invertebrates contribution per taxon to total number	twice/year (March and April)	5 sites/river	bottom-layered agitation and sweep netting (mud, gravel); kick and sweep netting (stones) and net sweeps of river margin vegetation	50% change in abundance in each taxa
Birds					
By habitat types (reed beds, mud flats, and others)	presence or absence of a representative species	every summer	20 × 100 m transects walked along river bank	auditory and visual	when any category is no longer represented
By functional representatives (e.g., frugivore, granivore, and others)	presence or absence of a representative species	every summer	20 × 100 m transects walked along river bank	auditory and visual	when any category is no longer represented
Water quality					
Ammonium		every two weeks	at specific sampling points	collect water samples; phenate hypochlorite method	0.1 mg/L
pH		every two weeks	at specific sampling points	collect water samples; pH meter	6.5–8.1
Water temperature		every two weeks	at specific sampling points	in situ over 24-h period using thermometer	8–25°C

Note: This is only a partial listing of indicators being used by park managers; for full list see Rogers and Bestbier (1997).
† In pool–rapid channel types, lateral and point bars must be 20%, and pools need to be 15% or more of total area. In anastamosing channel types, bedrock core bars must be 50% or more; other key units must be 2–10% of area.

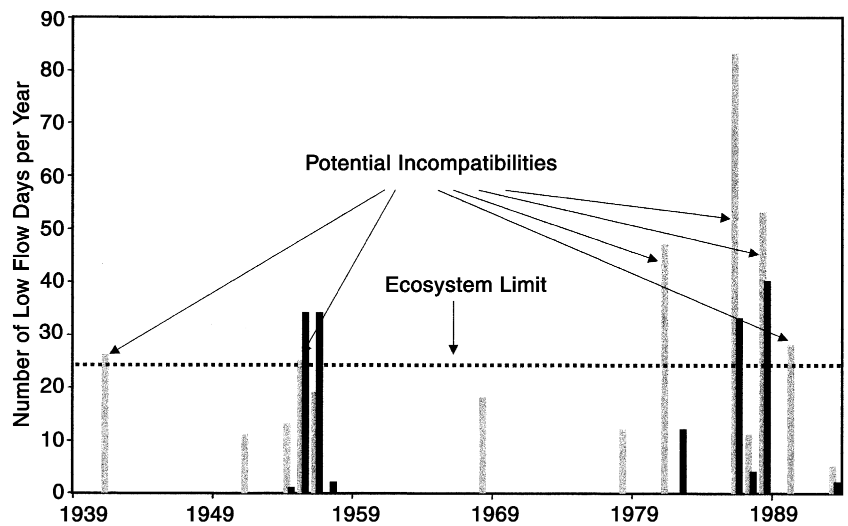

FIG. 5. A hydrologic simulation model developed for the Apalachicola–Chattahoochee–Flint (ACF) River basin enabled negotiators to assess the influence of projected increases in human water uses and proposed dam operations on the flow regime of the Apalachicola River in Florida. Fifty-five years of simulated daily flows were generated. One of the ecosystem flow requirements for the Apalachicola River specifies that critically low flows (<155 m^3/s) should not occur more than 24 d in any year. Modeling results suggest that incompatibilities between human demands and this ecosystem flow requirement would occur in 6 of the 55 yr under the January 2002 Florida proposal (gray bars). This ecosystem flow requirement was exceeded in four years under historical flow conditions (black bars).

river ecosystem. Rather, scientists should be able to provide initial estimates of ecosystem flow requirements that need to be subsequently tested and refined, as described later.

STEP 2: DETERMINING HUMAN INFLUENCES ON THE FLOW REGIME

Humans use water for myriad purposes including municipal and industrial water supply, agricultural irrigation, hydroelectric power generation, waste assimilation, navigation, and recreation. These human uses necessarily modify the natural flow of rivers. Assessments of the nature, degree, and location of human influences on natural flow regimes should be performed for both current and projected levels of human use, and expressed in spatial and temporal terms that are consistent with the definition of ecosystem flow requirements.

Hydrologic simulation modeling has advanced rapidly and computerized models have become essential tools for understanding human influences on river flows and designing ecologically sustainable water management approaches. Such models are capable of performing simultaneous calculations of all the many influences on water flows, even in complex river systems. They can be used to evaluate river flow changes expected under proposed water management approaches, such as increased future human demands and associated operation of water infrastructure. Because short-term hydrologic conditions such as extreme low flows or floods can have tremendous ecological influence, it is highly desirable and increasingly feasible to develop hydrologic simulation models that operate on daily (or shorter) time steps. Daily flow hydrographs resulting from various levels and types of human use can be generated for particular locations, enabling both visual and statistical comparisons between flows required for ecosystem support and human-altered flows (Figs. 5 and 6).

STEP 3: IDENTIFYING INCOMPATIBILITIES BETWEEN HUMAN AND ECOSYSTEM NEEDS

Areas of potential incompatibility in water management can be identified by comparing ecosystem flow requirements (Step 1) with the flow regime resulting from meeting human needs (Step 2). These areas of incompatibility become the point of origin for discussions in Step 4 (e.g., Figs. 5 and 6). When these incompatibilities between human needs and ecosystem requirements are well defined, efforts can be most effectively focused toward resolving them.

Areas of potential incompatibility must be examined both within and among years. Within-year evaluations will reveal the specific months or seasons during which ecosystem flow requirements are likely not to be met. Evaluations of multiple years will facilitate understanding of the frequency with which ecosystem requirements could be violated (Fig. 5). Areas of potential incompatibility between human and ecosystem needs should also be evaluated for each river reach of concern, as the nature and degree of conflict can vary widely from upstream to downstream, or across a watershed. Using models to explore water management alternatives can identify discrete pinch points and highlight the marginal differences between alternatives, thereby constraining the scope of the conflict (Carver

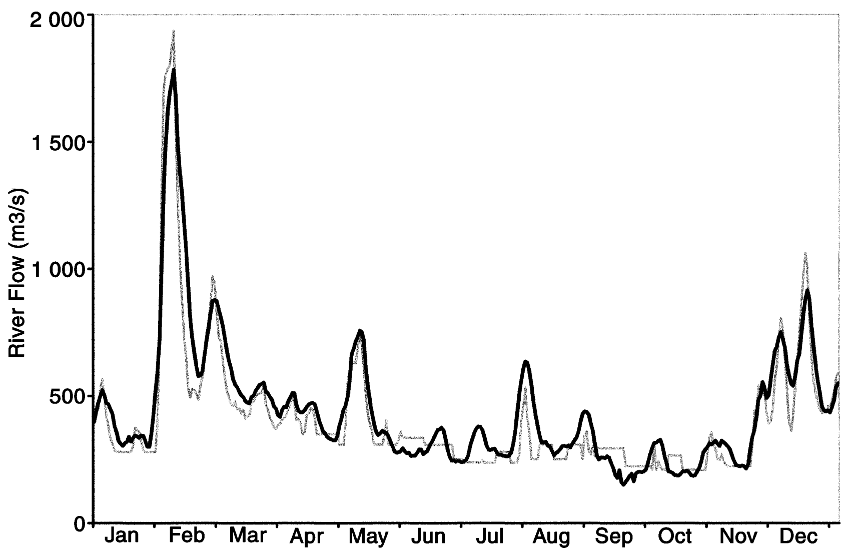

FIG. 6. Simulated natural flows during 1985 (black line) for the Apalachicola River are compared with flows that would occur under proposed future (2030) human demands and dam operations (gray line), as prescribed in the January 2002 Florida proposal. This comparison suggests that the river's natural flow variability can be protected to a high degree under projected development conditions.

et al. 1996). Statistical assessment of the differences between human-influenced flow conditions and ecosystem requirements can help quantify the magnitude of potential conflicts (Richter et al. 1996).

When human-influenced flow regimes are found to be incompatible with ecosystem flow requirements (either presently or in the future), water managers, scientists, water users, and conservationists will need to seek ways of alleviating the conflicts, as discussed in the next step.

STEP 4: COLLABORATIVELY SEARCHING FOR SOLUTIONS

Once the areas of potential incompatibility have been well defined and bounded in space and time as described previously, options for reducing or eliminating conflicts between human and ecosystem needs can be explored in an open dialogue among stakeholders. Fostering a collaborative dialogue among those affected by water management decisions will help clarify values, share information, and build trust between participants, making it far easier to build the consensus needed to develop and implement ecologically sustainable water management (Bingham 1986, Howitt 1992, Axelrod 1994, Rogers and Bestbier 1997).

Human needs, desires, and preferences, including those pertaining to river ecosystem protection or restoration, should be expressed as a set of goals that collectively represent stakeholder interests. This set of goals represents the desired integration of human and ecosystem needs. Rogers and Bestbier (1997) suggest a framework called an ''objectives hierarchy'' for such goal setting. This objectives hierarchy begins with formulation of a broad management vision, includes more specific management goals that give better definition to the vision, and is ultimately underpinned by a set of specific, quantified objectives (expressed as ''thresholds of possible concern'' in Table 2), which provide managers with management targets. Quantified objectives can include proposed levels of hydropower generation, delivery of water supplies, management of reservoir lake levels, and other human interests as well as ecosystem targets.

In this step of our framework, stakeholders negotiate to have their desires or needs expressed in the set of mutually agreeable goals that will drive water management activities. We believe that ecologically sustainable water management ultimately depends upon mutual commitment to a basic philosophy that no one wins unless everyone wins; conservationists must strive to meet human needs while water managers commit to meeting ecosystem requirements. When all parties are engaged in working toward ecologically sustainable water management, the power of human ingenuity can be optimally directed.

During the formulation of mutually agreeable goals, some of the incompatibilities identified in Step 3 will likely be resolved. For instance, certain water users may decide that they can achieve adequately satisfying benefits while modifying their current water use or future expectations. On the Roanoke River in North Carolina, The Nature Conservancy has proposed modifications to hydropower dam operations to alleviate unnaturally long floods during the growing season that impact floodplain ecosystems. The proposed modifications are expected to result in hydropower generation losses of only ~2–5%. The dam operators have indicated that this level of reduction is probably acceptable.

Box 1. Green River, Kentucky

Scientists from The Nature Conservancy are now working with the U.S. Army Corps of Engineers to design modifications to dam operations on the Green River in Kentucky to reduce their impact on natural flow conditions and aquatic species. One of the richest assemblages of native fish and mussels in North America is located downstream of the Green River Dam, operated by the Corps since 1963 to provide flood control and reservoir-based recreational benefits. Substantial alterations to the river's natural flow regime occur each year in the fall, when the Corps switches from recreation lake management to flood control operations. Reservoir levels are maintained at a high level during summer to accommodate recreational uses. During September and October, the water level in the reservoir is quickly lowered by >3 m to restore storage capacity needed to capture winter floods. Releasing this large volume of water in a short period of time produces greatly elevated flows that extend far downstream from the dam and disrupt native biota. Aquatic scientists hypothesize that steady low flows are needed in the fall season to concentrate certain prey species, enabling their predators to feed more efficiently. Certain mussels are believed to release larvae during the autumn season, which may be disrupted by high flows. Other aquatic organisms likely depend upon naturally quiescent, low-flow periods for conserving energy prior to winter.

The collaborative efforts between the Corps and the Conservancy are focused on shifting the timing of lake level lowering (and associated increases in downstream river flows) from September–October to late November, when river flows would be naturally higher during the onset of the winter rainy season. Because the lowering of reservoir levels will also be conducted over an extended period, the daily reservoir releases can be lessened. In addition to shifting the timing and increasing the duration of the reservoir draw-down, the dam releases will be pulsed to coincide with storm events rather than releasing at a constant rate, thereby mimicking some of the river's natural patterns of variability.

The basic ideas behind these operational changes were identified during an initial two-hour discussion between the scientists and engineers. This dialogue moved quickly toward possible solutions because the areas of potential incompatibility had been well described by Conservancy scientists; Corps engineers shared the Conservancy's goal of maintaining the river ecosystem in a healthy condition; and they both sought to restore ecological integrity while continuing to meet the operational purposes of the dam.

Equipped with adequate data and shared means for assessing them, water managers, scientists, conservationists, and water users should carefully examine each area of potential incompatibility identified in Step 3 and consider whether each ecosystem requirement and human use might be met in alternative ways that would remove or reduce the conflict. Some of the most powerful means of resolving these conflicts involve changing the timing or location of human uses toward greater compatibility with natural hydrologic cycles or the seasonal or life cycle needs of native species. For instance, can water be captured for human use during a time of the year that minimizes the relative change to the natural hydrograph and its ecological consequences? Can the location of a water diversion be relocated downstream of critical fish spawning areas?

A growing number of innovative strategies are now being tested and put to use for the purpose of eliminating conflicts between human and ecosystem needs for water (see Boxes 1 and 2 for Green River, Kentucky and San Pedro River, Arizona). Dam operations are being modified to reshape human-influenced hydrographs into something more compatible with ecosystem requirements while still meeting the human needs for which they were originally designed (Natural Resources Law Center 1996). New technologies for water conservation in cities, industries, and agriculture are reducing the volume of water needed to support human endeavors, or eliminating the need to build additional storage reservoirs that might further impair natural hydrologic regimes (Maddaus 1987, Postel 1999, Gleick 2000, Vickers 2001). Many governmental entities are adopting demand management strategies that place limits on the amount of allowable water withdrawals from certain freshwater sources. Water market transactions, including the purchase of irrigation water rights and their conversion to ''instream flow rights'' that allow the water to remain in the river (Gillilan and Brown 1997), or paying farmers not to irrigate fields during drought periods, hold promise for keeping river flows from dropping to critically low levels (Michelsen and Young 1993, Wigington 2000). As new strategies succeed and begin to be more widely communicated to water managers and conservationists, we expect the probabilities for attaining ecologically sustainable water management in the world's river basins to improve considerably.

Step 5: Conducting Water Management Experiments

During each of the preceding steps, a number of uncertainties about ecosystem flow requirements or hu-

Box 2. San Pedro River, Arizona

In the upper San Pedro River basin of southern Arizona, water managers and conservationists argued for more than a decade about the causes of measured declines in river base flows and the degree to which continued groundwater pumping for municipal and agricultural use might affect the river in the future (Commission on Environmental Cooperation 1999). In 1998, under the leadership of the Arizona Department of Water Resources, representatives from federal and state agencies, municipal governments, and conservation organizations agreed to step back from this debate and work together on a plan to meet both human and ecosystem water demands over the long run (Upper San Pedro River Partnership 1998). They formed the Upper San Pedro Partnership to seek consensus-based ideas for reducing human impacts, for organizing ecological research to examine more rigorously the water needs of the riparian ecosystem along the river, and for reassessing the groundwater models that have been developed by various parties.

The partnership has collaborated on an ambitious work plan including a variety of water conservation activities, recharge of treated wastewater effluent, and retirement of water-consumptive agriculture. The partnership committed more than $\$18 \times 10^6$ (U.S. dollars) to the effort during the first two years. In this case, Step 4 of the framework (Fig. 2) was predicated on reiteration of Steps 1–3, and the Upper San Pedro Partnership is an important example of revisiting and possibly modifying ecosystem flow requirements. The willingness of the major stakeholders to reexamine both human water needs and ecosystem flow requirements in a collaborative setting was an important breakthrough.

This example illustrates the fact that the time frames required for developing an ecologically sustainable water management plan can take decades. The example from the Green River in Kentucky (see Box 1) suggests that quick progress is sometimes possible and always desirable, but hardly assured.

man uses will likely have arisen. Even when attempts to resolve incompatibilities are pursued collaboratively and earnestly, water managers may remain uncertain about the feasibility of specific proposed modifications to water management, or river scientists will be uncertain about expected ecological responses.

Unfortunately, these uncertainties commonly cause a breakdown in collaborative dialogue. When water managers, scientists, water users, and conservationists are asked to ''cut a deal'' in the presence of substantial uncertainty, one or more parties may balk, thus delaying or terminating the search for compatible solutions. However, by instead framing critical uncertainties as hypotheses that can be tested and resolved through water management experiments, paralysis may be avoided.

Water management experiments must be carefully designed and executed if they are to yield the desired reduction of uncertainty, however. It is essential that scientifically credible experimental designs be employed to the extent feasible. If the experiment is not intended to last for many years, the selected response variables should be adequately sensitive to enable detection of response during the term of the experiment. Most important is the formulation of testable hypotheses based upon conceptual models of the expected response of the hydrologic and ecological systems to the water management experiments (Richter and Richter 2000). These experiments must be carefully measured or monitored. And of course, adequate financial support must be provided. Without appropriate design, evaluation, and funding, such water management experiments can backfire by introducing additional confusion about cause and effect, and result in increased frustration that can badly damage collaborative efforts.

The action plan developed by the Upper San Pedro Partnership (see Box 2 for San Pedro River, Arizona) includes a number of water management experiments designed to reduce human impacts on groundwater flows. For instance, wastewater from the City of Sierra Vista will now be injected back into the groundwater aquifer rather than continuing to release it into evaporative ponds. Also, water conservation measures are being implemented by various municipalities and a military base. The hydrologic improvements associated with these water management experiments have been modeled using groundwater simulation models, but verifying their actual benefits will require careful monitoring. If these experiments suggest that less actual benefit is attained than expected, the partnership will need to identify additional measures or broader application of their measures to realize success.

Step 6: Designing and Implementing an Adaptive Water Management Plan

The last step of our framework should never be completed; to be ecologically sustainable, water management should be perpetually informed by monitoring, carefully targeted research, and further experimentation to address new uncertainties or surprises, and management approaches must be continually modified in light of increased understanding or changes in human and ecosystem conditions. While much has been written about adaptive ecosystem management, we want to emphasize a few elements particularly relevant to water management.

Monitoring program

During the initial determination of ecosystem flow requirements, a number of hypotheses will be generated concerning the expected responses of various ecosystem conditions to the ecosystem flow prescription. For example, it might be hypothesized that under the prescribed flood conditions, the population of a target fish species will fluctuate within an estimated range. Some of the most important hypotheses will be tested during the water management experimentation described for Step 5 of our framework. Other hypotheses should be tested through the collection and analysis of monitoring data over longer time frames. Monitoring data should be collected for a suite of ecosystem indicators that reflect ecological integrity as a whole (Noss 1990), in a manner that allows for testing hypotheses developed in earlier steps.

In Kruger National Park in South Africa, ecosystem flow requirements and targeted ranges for other ecosystem indicators have been defined for geomorphic conditions, vegetation, fish, invertebrates, birds, and water quality (Table 2; Rogers and Bestbier 1997). For each ecosystem attribute, scientists have specified the frequency, scale, and methods for measurement, as well as an associated threshold of possible concern. These thresholds are expressed as upper or lower values, providing bounds within which an ecosystem attribute is expected to fluctuate, or thresholds that should not be crossed.

Selecting a suite of indicators and defining targeted ranges of variation or critical thresholds for each attribute requires a high level of understanding of the interaction among river flows, human activities, and ecosystem response. As results from the monitoring program clarify these relationships, new ecosystem indicators or target ranges may need to be selected.

Adaptability

As described in Step 4, adaptive management should always begin with defining mutually acceptable goals for water management (Rogers and Bestbier 1997). Definition of mutually acceptable goals related to ecosystem health, economic benefits, and other societal needs and preferences should be an explicit product of the collaboration we encourage in Step 4. Water management activities can then be directed at trying to fully attain these goals. This may require numerous iterations or trials, such as making modifications to dam operating rules or water withdrawal schedules. It may also become necessary to revisit mutually agreed upon goals if the full suite cannot be realistically attained.

Unfortunately, traditional water management plans have commonly been formulated in ways that make them difficult, if not impossible, to modify frequently or quickly. For example, specific requirements for provision of instream flows below private hydropower dams in the United States are commonly specified in 40-yr dam operating licenses, making modifications to these flow requirements costly, time-consuming, or legally problematic. The design of water infrastructure, such as water release structures at dams, or pipes and pumps used to divert water from a river, can place serious constraints on management flexibility if these structures are not designed to pass variable volumes of water.

It is absolutely essential that an ecologically sustainable water management plan preserves the ability to respond to new information gained from water management experiments or a long-term monitoring program, and to alter the plan and related infrastructure operations accordingly. This ultimately depends on the flexibility of water management infrastructure, regulatory or legal mechanisms controlling water use, and the political will to stay with an ever-evolving process.

Over the long term, managing adaptively to meet the goal of ecologically sustainable water management will increase certainty as the most troublesome uncertainties are resolved, infrastructure operations are refined for greater efficiency and compatibility, and ecological degradation halted. As adjustments in the status quo are required, parties may need to seriously explore ways to share and minimize the financial and economic impacts, including the possibility of indemnification agreements that cover some of the costs associated with these changes. If it is impossible to implement new or modified water management strategies over time, the options for attaining ecologically sustainable water management will be diminished greatly.

Governance

Water managers will need to continually respond to new information by modifying their ecologically sustainable water management plan. The process and authorities for such decision-making must be clearly articulated in the plan. We strongly recommend that this governance include the formation of a scientific peer review committee, chartered with responsibility for reviewing the design and results of water management experiments and monitoring and making recommendations to a river basin commission or other local or regional management agency with ultimate decision-making authority.

Secure funding

The management plan should also identify funding needs and sources, with an emphasis on sources that can provide for long-term security. Even short-term breaks in funding support can severely impact water management experiments and monitoring programs. The success of monitoring programs relies upon continuous, consistent measurements adequate to capture short-term and interannual fluctuations in flow and ecosystem conditions. Multiple-year congressional appro-

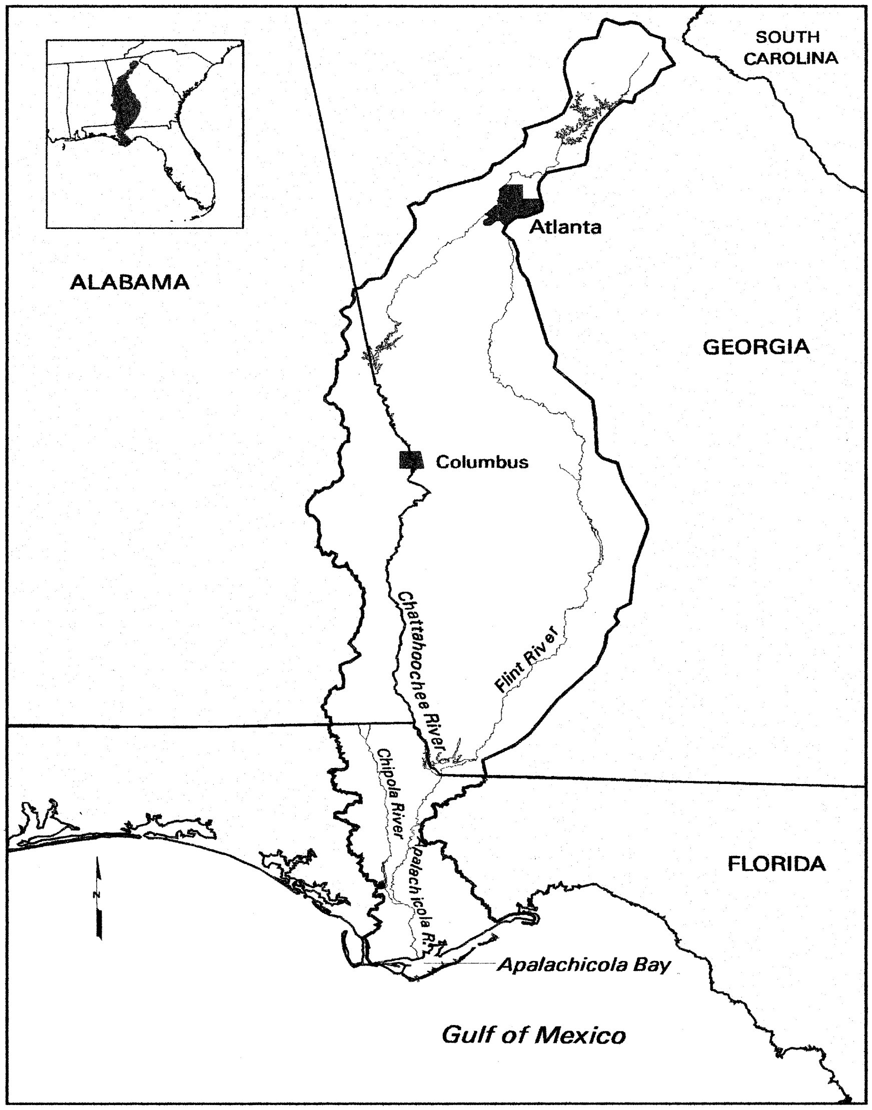

FIG. 7. The Apalachicola–Chattahoochee–Flint (ACF) River basin.

priations, such as those presently supporting the Long Term Resource Monitoring Program in the Upper Mississippi River basin can provide some degree of financial assurance. Tying funding sources to reliable revenues such as water user fees or hydropower revenues generated at public facilities may provide greater dependability.

Both the Grand Canyon Monitoring and Research Center and the monitoring element for the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin are supported by hydropower revenues generated at the main dams of the Colorado River Storage Project. This annual funding is capped but is authorized to continue as long as the monitoring is scientifically and politically justified.

APALACHICOLA RIVER CASE STUDY

Lying within the states of Georgia, Alabama, and Florida, the Chattahoochee, Flint, and Apalachicola Rivers and their tributaries drain an area of >50 000 km^2, reaching from the southern Blue Ridge Mountains to the Gulf of Mexico (Fig. 7). The Chattahoochee River begins north of Atlanta, passes through the city and then forms the border between Georgia and Alabama. It meets the Flint River, which begins just south of Atlanta and flows through southwest Georgia, at the Florida border. From this confluence, the Apalachicola River meanders 150 km through the Florida panhandle, emptying into the Gulf of Mexico at Apalachicola Bay.

The Apalachicola–Chattahoochee–Flint (ACF) River basin has long been noted for its freshwater biodiversity, including aquatic communities of endemic and imperiled species, anadromous and sport fish. The Apalachicola River and surrounding lands in the heart of the Florida panhandle was reported in Stein et al. (2000) as home of one of the nation's highest concentrations of imperiled species. The State of Florida has acquired much of the river's broad floodplain and manages it for conservation purposes. The Apalachicola Bay is considered to be one of the most productive estuaries in North America and is valued for its oysters, shrimp, blue crabs, and fish species including striped bass, sturgeon, grouper, drum, and flounder.

The water resources of the ACF basin were substantially developed in the 20th century for human uses. Sixteen dams were built on the Chattahoochee and Flint Rivers. Five of these dams are federal projects operated by the Army Corps of Engineers for hydroelectric power, navigation, recreation, fish and wildlife, water supply, and flood control. Surface and groundwater withdrawals are made for municipal and industrial (M and I) water supply and for irrigated agriculture. Dramatic increases in water use have resulted from extreme population growth in the metropolitan Atlanta area, a mid-century population of 500 000 grew to >4 million (4×10^6) by 2000, and increased reliance on irrigation for agriculture in southwest Georgia. From 1970 to 1990 surface water withdrawals increased by 29% and groundwater withdrawals, primarily for agriculture, increased by 240% (ACOE 1998).

To address the Atlanta region's growing water needs, the state of Georgia asked the Corps to reallocate water storage in the upstream federal reservoir (Lake Lanier) from hydropower generation purposes to provision of water supply, to which the Corps consented. In 1990, Alabama's concern about the potential downstream impacts of this reallocation led them to file a lawsuit against the Corps. When Florida and Georgia filed to intervene in the suit, the states made an important decision to seek a negotiated settlement that would avoid litigation. Importantly, they agreed that water allocation in the whole ACF basin should be negotiated rather than to argue about the use of any single reservoir. They agreed to conduct a Comprehensive Study to provide factual information on water availability, forecast water needs, and explore options to meet them. Continued discussions between the states led to the signing of the interstate Apalachicola–Chattahoochee–Flint River Basin Compact in 1997.

The compact provides a framework for the states, with the approval of the federal government, ''to develop a water allocation formula for equitably apportioning the surface waters of the ACF Basin among the states while protecting the water quality, ecology and biodiversity of the ACF'' (U.S. Congress 1997). The compact formed an ACF Commission made up of the governors of the three states and a federal commissioner appointed by the President of the United States. Once the three governors agree upon an allocation formula, the federal commissioner must concur or not concur, based on compliance with federal laws. Negotiations over the water allocation formula began in 1998 and continue as of April 2002. This compact is the first in the ''water rich'' southeastern United States. It represents an historical opportunity to establish a precedent for the future of water management in the eastern United States and to coordinate river basin management among the three states.

Discussions during the water allocation negotiations revealed the interests of each of the states. Simply stated, Georgia's primary concerns are to secure adequate water supply for M and I and agricultural uses such that economic growth is not constrained, and maintain high reservoir levels for recreational use. Alabama primarily wishes to protect sufficient quantity and quality of water for water supply and waste assimilation in the mid-Chattahoochee, and Florida desires to sustain a flow regime that will maintain the biological diversity and productivity of the Apalachicola River and Bay. Other stakeholders reinforced these values, and added hydropower, navigation, maintenance of stable lake levels, recreation, endangered, sport, and commercial species, and water quality protection to the list of concerns.

While negotiations continue as of this writing, we have used the states' proposals of January 2002 as the basis for our case study assessment. Many of the key elements of our framework for ecologically sustainable water management are addressed by these proposals. In particular, we focus on the Florida proposal, which we feel best addresses our key elements.

Ecosystem flow requirements

Several studies were conducted as part of the Comprehensive Study to develop a better understanding of relationships between flow levels and habitat conditions in the ACF basin (Chanton 1997, Freeman et al. 1997, Huang and Jones 1997, Iverson et al. 1997, Lewis 1997*a*, *b*, Light et al. 1998). Subsequent to these studies, two federal agencies reviewed historical records of river flow and native species surveys to develop a set of ''instream flow guidelines'' (Table 1) (USFWS and USEPA 1999). These guidelines address intra- and interannual flow variability by setting threshold limits for the monthly one-day minimum, annual low-flow duration, annual one-day maximum, and annual high-flow duration that must be met in all years, in three out of four years or in two out of four years; and as a range of values for the monthly average flows. Numerical values for the specified parameters have been defined for specific locations on each of the three rivers.

In essence, these guidelines represent an initial articulation of ecosystem flow requirements to support biodiversity in the basin and have enabled federal environmental agencies and others to assess the possible impact of any proposed water allocation formula on the ecological integrity of the ACF basin. The guidelines focus on a small subset of ecologically relevant hydrologic parameters that could be substantially affected by water management in the ACF basin, and thus have been useful in drawing attention to some key hydrologic parameters in the negotiations. However, these flow guidelines have not received much attention from the states and their proposals have not addressed them in any explicit way. This neglect can be largely explained by the reluctance of the negotiators to use flow targets that they felt had not been adequately linked to desired floodplain or channel conditions and ecological responses. While the federal flow guidelines were supported with a narrative that described the general importance of the specified flow conditions for sustaining species and ecosystem health, the numerical targets were based primarily on statistical characterization of the historical flow regime because the federal agencies hoped to preserve as much of the historical flow conditions as possible. The negotiators wanted to better understand how a flow of a particular level would fill the channel, inundate the floodplain, or otherwise affect biota in particular reaches.

Fortunately, work conducted during the Comprehensive Study did provide information about instream habitat availability in the Apalachicola River at various low-flow levels, and identified high-flow levels at which fish gain access to secondary channels and backwater areas in the floodplain (Freeman et al. 1997, Light et al. 1998). The Florida negotiators relied heavily upon these limited studies in framing their water allocation proposal, while also trying to protect as much of the natural flow regime as possible (S. Leitman, *personal communication*).

We believe the lack of adoption of any form of consensus-derived ecosystem flow requirements greatly hindered the ACF basin negotiations. Before any set of flow guidelines can be fully employed in the fashion suggested by Steps 1–3 of our framework, the states and federal agencies must reach consensus on ecosystem flow requirements. One way to facilitate such consensus might be to convene a more formal and rigorous scientific assessment of ecosystem flow requirements, engaging multidisciplinary academic and agency scientists from each of the three states and beyond. An excellent model for such structured assessment is the Building Block Methodology being employed in South Africa (King and Louw 1998).

Evaluating human influences

The Comprehensive Study produced estimates of existing and projected water demands for M and I, agricultural, and other uses. Subsequently, hydrologic simulation models were developed to enable assessment of daily flow regimes at 14 different locations in the basin. Alternate water management scenarios can be explored by modifying projected water demands and reservoir operations in the models.

Each of the three states has used these hydrologic models in developing their water allocation proposals for consideration by the other states and federal representatives. Each state has modified the model(s) to reflect key elements of their respective proposals, e.g., projected growth in water consumption, proposed reservoir operations, and other water management issues. In turn, the output of these model runs by the states has been analyzed by the federal environmental agencies to assess incompatibilities with their instream flow guidelines.

There has been disagreement over some of the key inputs to these models, including the relationship between groundwater pumping and river flows, irrigation demands, and other water use projections. Tremendous effort was expended in assembling a common set of input data for the hydrologic models, but some key inputs such as irrigation water consumption during droughts was very difficult to estimate due to lack of monitoring data. The lack of agreement on model input has been an obstacle in the negotiations, because it has made comparisons of the states' proposals difficult.

Areas of incompatibility

While the ACF basin lies within the comparatively water-rich Southeast, periodic episodes of drought, often lasting for multiple years, do occur. During a drought from 1999 to 2001 the annual flows in the river were only 40% of average. Such periods of drought have become the nexus of conflict between human and ecosystem needs for water. For example, maintaining high reservoir levels for recreation and preserving water storage during droughts conflicts with needed releases for water quality, hydropower, navigation, and ecosystem flows. These conflicts are most acute during the summer, when naturally low river flows are depleted by various human uses. In the negotiations, suggestions were made to curtail or constrain certain uses to enable other uses to be met adequately.

The federal instream flow guidelines include two low-flow parameters (Table 1): a limit on the one-day minimum flow in each month and a limit on the maximum number of days in each year that flows can be below a certain threshold. The water allocation agreement fails to meet these low-flow guidelines in some years (Fig. 5). Therefore, the ecological sustainability of this water allocation remains in question.

The search for solutions

The original deadline for arriving at an acceptable allocation formula was set by the Compact for 31 December 1998, but the deadline was extended more than 10 times. The states are highly motivated to achieve a negotiated agreement; the alternative is to resolve the issue in the U.S. Supreme Court. The water allocation proposals submitted by each of the states have provided the basis for the negotiations. The hydrologic models and analyses of their outputs have proved to be valuable tools for developing, communicating, and assessing a variety of water management alternatives. Stakeholder meetings, technical meetings, and workshops and other private meetings have been conducted both inside and outside of the formal negotiations. Each of these venues offered an opportunity to share information, present concerns or preferences, and collaborate in a search for solutions.

Steps 1 and 2 of our framework directly address two of the biggest obstacles encountered in the ACF basin negotiations: lack of agreement on ecosystem flow requirements and the implied limits on human uses resulting from these, and lack of agreement on current and projected water uses. Without well-defined, agreed upon quantification of ecosystem flow requirements and human uses, each party evaluated the potential incompatibilities differently. This limited the ability to focus a creative search for solutions.

In the absence of agreement on ecosystem flow requirements and water use projections, the states constructed proposals that focused on the desired net flows (and associated recurrence intervals) at selected places in the basin. For instance, the Florida negotiators focused on framing the water allocation formula in a manner that would minimally impair the natural flow regime of the Apalachicola River, and in this effort they were quite successful (Fig. 6). Their proposal includes a cap on total water withdrawals from the Chattahoochee River in the Atlanta area, and it dictates how much water must be released from the reservoirs for downstream ecosystem support according to weekly reservoir storage levels. The Florida proposal also includes some important commitments to adaptive management (see *Apalachicola River: Adaptive management*).

Water management experiments

While millions of dollars and many years of effort have gone into developing a set of data and tools for building the water allocation formula, there remain some areas of uncertainty that have frustrated the states' efforts to reach agreement. These uncertainties include the amount of water presently being used as well as projected water uses; the effects of alternative reservoir operating plans on lake levels, hydropower generation, fisheries, and navigation; potential responses of the river ecosystem and individual species of concern to alterations in the flow regime; and physical relationships between groundwater levels, agricultural pumping, and river flows in the Flint River basin, which strongly affects Georgia's ability to meet flow targets in the Apalachicola River at the Florida state line during droughts.

Some of these uncertainties can be addressed with additional investment in data gathering or short-term research. For example, the Georgia Environmental Protection Department (EPD) is conducting a ''Sound Science Study'' in the Flint River basin to further understanding of the groundwater/surface water relationships. Other uncertainties, including growth in future water demands and ecological responses to water management, are best addressed through design and implementation of an adaptive management plan, discussed next. Two major areas of uncertainty, reservoir operations and groundwater management in the Flint River basin, are ideally suited for experimentation.

The Army Corps of Engineers is beginning an assessment of needed modifications in its ''Water Control Plan'' for the major reservoirs in the ACF basin. Rather than attempting to develop a long-term plan of operations at this time, the Corps could instead design its operating plans as short-term (i.e., 5–10 yr) experiments. Such experiments would test the plan's ability to help meet ecosystem flow requirements while keeping other performance indicators, including lake level fluctuations and hydropower generation, within targeted ranges.

The Flint River Drought Protection Act of 2000 might offer a viable solution to reduce agricultural water use in certain years and thereby enable the ecosystem flow requirements to be met during droughts. This act authorizes payments from the state of Georgia to farmers that curtail irrigation on selected areas when the EPD declares a drought by 1 March. Each drought period can be viewed as an experiment to test the state's ability to reduce water use to the level that Flint River and state line flow requirements can be attained. If each such experiment is designed and evaluated carefully, water managers will be able to determine the amount of irrigation compatible with ecosystem flow requirements during drought.

Adaptive management

Because of uncertainties in both future water demands and ecosystem flow requirements, it is highly inadvisable to make any water allocation formula immutable. Numerous parties throughout the negotiations have advocated for managing the ACF basin adaptively and including provisions in the allocation formula agreement to address it. The states' proposals include some key elements of adaptive management.

1. *Governance*.—The Florida proposal calls for creating a Scientific Advisory Panel that will recommend a set of ecosystem performance indicators and a program for evaluating whether they are being maintained in satisfactory condition. The Scientific Advisory Panel will also be responsible for recommending modifications to the monitoring program as needed. Additionally, an ACF Committee will include representatives from the states and federal agencies. The committee will oversee monitoring of all ecosystem performance indicators, create an electronic database available to the public, and make recommendations for needed technical studies or additional data collection.

2. *Adaptability*.—The state proposals include no specific mechanism for modifying the interstate flow allocation formula or refining water management based on results of the monitoring program. However, the Florida proposal calls for the issuance of a performance report to the public before the 10th and 25th anniversaries of the agreement. After conducting public hearings on these reports, the ACF Commission is to pub-

lish a final report. Presumably, this formal public review process and annual reports and recommendations from the Scientific Advisory Panel could cause the ACF Commissioners to revise the allocation formula or water management practices as needed to meet the intent of the ACF compact.

3. *Secure funding for monitoring*.—While funding has not been addressed explicitly in the state proposals, the Florida proposal does firmly commit to monitoring the performance indicators. Success of the monitoring program will be dependent upon secure funding from state and federal governments or water users that will ensure long-term continuity.

The ACF basin is an important example of the progress being made around the world in ecologically sustainable water management. It is difficult work and many have given their best to finding a workable solution. The ACF story is offered here to commend these efforts and to illustrate that even in a complex, multistate, politically charged negotiation with diverse interests, a framework for ecologically sustainable water management can provide a pathway for meeting both human and ecosystem needs.

Conclusions

In this paper we have sketched what we believe to be a useful roadmap for finding ecological sustainability in water management. We are inspired by growing evidence proving that water management does not need to compromise freshwater ecosystems while providing for human needs.

Advocacy for ecological sustainability is mounting from different sectors of society as we are increasingly confronted with the side effects of historical water management practices. Society is becoming far less tolerant of the financial expense, technological complications, health problems, and aesthetic degradation associated with water quality deterioration, invasive species infestations, exacerbated flooding, loss of species and ecosystem productivity, and other changes caused by unsustainable water management. Whether water policy leaders share an appreciation for biodiversity or not, they are forced to pursue the concept of ecologically sustainable water management because of the inherently untenable objective of satisfying society's need for water in the midst of collapsing natural systems.

What will we need to do to move swiftly toward ecologically sustainable water management? We believe the answer lies in putting ecological considerations up front along with other goals for water management planning, rather than treating ecological criteria as compliance factors to be evaluated after a water development plan is completed. One of the most important lessons we learned from our involvement in the ACF discussions is that specification of ecosystem flow requirements should have been given much greater attention at the beginning of the negotiations, and much greater effort should have been expended in designing a way to meet both these ecological goals as well as other mutually agreed upon goals for meeting various human uses. This realization strongly shaped the framework we outline in this paper, in which the first step is estimating ecosystem flow requirements. This enables water planners and managers to give due consideration of ecological requirements throughout the planning or negotiating process.

Several existing water policies explicitly call for inclusion of ecological goals. Florida's Water Resources Act of 1972 called for the state to set ecosystem flow requirements, in the form of minimum flows and lake levels, within each of their water management districts. Permitting of water withdrawals is intended to avoid violating these requirements (SFWMD 2000). Similarly, the new South African National Water Act creates a reserve of water in each river basin containing two elements: an ecological flow regime and water needed to meet ''basic'' human needs of 26 L of water per person per day (Republic of South Africa 1998). Other human uses are not allowed to violate these reserves.

Experiences in both Florida and South Africa have shown that attaining ecological sustainability is much more feasible when ecosystem flow requirements are assessed and protected before a river basin's water supplies have been extensively developed. Good examples of water policy that facilitates better integration of existing human needs and ecosystem requirements in more heavily developed watersheds are badly needed.

Ultimately, the goal of ecologically sustainable water management will not be achieved until humans accept that there are limits to water use, and those limits are defined by what is needed by the natural systems that support us. This implies certain burdens. Scientists and conservationists must work hard to define ecosystem flow requirements that will protect the ecological integrity of the affected systems. Water managers and users must be willing to live within the limits posed by ecosystem flow requirements even as they undergo further refinement, to efficiently use available water supplies, and commit to long-term water planning and adaptive management. Together we must all search for innovative solutions, tap human creativity to address those areas where there is conflict, and keep working at it until we get it right.

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