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A COLLABORATIVE AND ADAPTIVE PROCESS FOR DEVELOPING ENVIRONMENTAL FLOW RECOMMENDATIONS

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ABSTRACT

Many river restoration projects are focusing on restoring environmental flow regimes to improve ecosystem health in rivers that have been developed for water supply, hydropower generation, flood control, navigation, and other purposes. In efforts to prevent future ecological damage, water supply planners in some parts of the world are beginning to address the water needs of river ecosystems proactively by reserving some portion of river flows for ecosystem support. These restorative and protective actions require development of scientifically credible estimates of environmental flow needs. This paper describes an adaptive, inter-disciplinary, science-based process for developing environmental flow recommendations. It has been designed for use in a variety of water management activities, including flow restoration projects, and can be tailored according to available time and resources for determining environmental flow needs. The five-step process includes: (1) an orientation meeting; (2) a literature review and summary of existing knowledge about flow-dependent biota and ecological processes of concern; (3) a workshop to develop ecological objectives and initial flow recommendations, and identify key information gaps; (4) implementation of the flow recommendations on a trial basis to test hypotheses and reduce uncertainties; and (5) monitoring system response and conducting further research as warranted. A range of recommended flows are developed for the low flows in each month, high flow pulses throughout the year, and floods with targeted inter-annual frequencies. We describe an application of this process to the Savannah River, in which the resultant flow recommendations were incorporated into a comprehensive river basin planning process conducted by the Corps of Engineers, and used to initiate the adaptive management of Thurmond Dam.

KEY WORDS: river restoration; environmental flow; instream flow; adaptive management; dam operations; water resource management; river ecology; river science; sustainability

INTRODUCTION

During the past century, the global human population quadrupled, the area of irrigated agricultural land multiplied more than six-fold, and water withdrawals from freshwater ecosystems increased eight-fold (Gleick, 1998; Postel, 1999). Natural river systems around the world were heavily modified to serve a variety of human purposes, including supplying water to cities and farms, generating electric power, facilitating navigation, and controlling floods.

Dams have facilitated human utilization and control of rivers by enabling water managers to convert natural flow variability into water releases governed by human needs. By capturing high river flows and releasing the water in a carefully controlled manner, dam managers can deliver steady and dependable water supplies to downstream areas, protect settlements from floods, or generate power. As a consequence of this water control, river flows below dams commonly bear little resemblance to their natural variability.

Human control of river flows is now ubiquitous in the developed world, and growing rapidly in developing countries. More than 800 000 dams block the flow of the world's rivers (Rosenberg *et al.*, 2000); an average of two large dams (15 m height or greater) were constructed each day for the last 50 years (World Commission on Dams, 2000). Nearly two-thirds of the planet's largest rivers are now fragmented by dams and diversions; in the contiguous USA,

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less than 2% of all rivers remain free-flowing and relatively undeveloped (Revenga *et al.*, 2000; Benke, 1990). Human impacts on rivers are expected to intensify during coming decades, particularly in developing regions, as human populations swell, per capita rates of water consumption rise, and a growing portion of arable lands is irrigated to meet the food demands of the future.

While human manipulation of the planet's river flows has provided many societal benefits, it has also caused considerable ecological damage and the loss of important ecosystem services valued by society (Baron *et al*., 2002; Postel and Richter, 2003; Fitzhugh and Richter, 2004). River ecosystem health deteriorates when natural flows of water, sediments and organic materials through a river system are substantially disrupted or modified by human activities (Poff *et al*., 1997; Richter *et al.*, 2003). River damming and associated alteration of natural flow and sediment transport patterns and water temperature are now widely recognized as a leading cause of declines in freshwater biodiversity globally (Richter *et al.*, 1998; Revenga *et al.*, 2000; Pringle *et al.*, 2000; Bunn and Arthington, 2002). Dams have also been implicated in the loss of commercial fisheries in many estuaries and coastal areas, and in the degradation of other natural ecosystem products and services worldwide (World Commission on Dams, 2000).

Growing attention to environmental flow needs

Fortunately, societal interest in river ecosystem restoration is growing rapidly around the world. Much of this activity is focusing on restoring or protecting some semblance of the natural river flow conditions necessary to support ecosystem health. More than 850 river flow restoration projects are now underway in at least 50 different countries (The Nature Conservancy, 2005). Much of this restoration activity has been stimulated by regulatory mandates or policy decisions that are forcing re-examination of dam operations or calling for better protection of river health. For example, at least 177 hydropower dams in the USA are scheduled for re-licensing by the Federal Energy Regulatory Commission during 2000–2010, providing many opportunities to negotiate new licence conditions that reduce impacts to river health.

The water needs of river ecosystems are receiving increasing attention in water supply planning as well, offering hope that many rivers can be protected before their health is seriously compromised by water development. For example, the South African National Water Act (1998) calls for the creation of a reserve of water in each river basin to meet both basic human needs and protect river ecosystem health. Similarly, other national directives and international agreements such as the Water Framework Directive of the European Union are providing mechanisms for river protection, including the provision of adequate environmental flows (Postel and Richter, 2003).

These restorative and protective actions require development of scientifically credible estimates of environmental flow needs. By providing water managers with environmental flow recommendations, scientists can help managers understand what will be required to support a sustainable river ecosystem and enable them to integrate these needs with other human demands on the river. Because the protection or restoration of environmental flows necessarily entails trade-offs with other potential uses of water, it is very important that the water needs of a river ecosystem be defined using current, best-available scientific information and knowledge.

Unfortunately, ecological science is not yet being adequately integrated into water decision-making in most parts of the world—most water management decisions or plans continue to be made on the basis of engineering considerations alone, with little or no scientific input concerning the water needs of freshwater ecosystems. There are many socio-political and economic reasons that might explain this lack of science integration in water decision-making, but we suggest that one major impediment has been the lack of a 'generic' process for engaging scientists. To be useful in a variety of water management contexts, such a process for integrating scientific input must be adaptable to a variety of applications ranging from water supply planning to the issuance of water withdrawal permits to the licensing of dam operations, and must be practical under a broad range of resource availability. This paper describes a flexible, adaptable process that can be used for engaging scientists in developing environmental flow recommendations to support a variety of water management decisions.

However, simply applying science to the challenge of determining environmental flow needs is unlikely to succeed over the long term if science is viewed as a one-time assessment or contribution. Because of the inherent complexity of ecosystem responses to variable flow regimes, water managers or stakeholders should not expect scientists to be 'perfectly right' about environmental flow needs on their first attempt. Being wrong about environmental flow needs has two potentially large societal consequences. Either the ecosystem will not get what it needs and degrade—with associated loss of socially valued ecosystem services—or other potential human uses of the water will be unnecessarily curtailed or limited, with attendant social and economic disruption.

Therefore, the process of determining environmental flow needs should be viewed as an iterative process, in which each water management action such as flow restoration is viewed as an experiment that must be monitored and evaluated carefully, enabling scientific refinement of environmental flow recommendations over time. This process of deliberate learning through testing, evaluation, and modifying management actions is called adaptive management (Holling, 1978; Walters, 1986; Gunderson *et al*., 1995).

Adaptive management of environmental flows

Environmental flow restoration or protection is ideally suited to an adaptive management approach. Water managers can often exert a high degree of control of water flows through their operations of dams or water diversions, and many of their management actions can be treated as experiments that can be monitored to evaluate their influence on river ecosystem health (Ward and Stanford, 1993; Poff *et al*., 2003). When designed properly, these experiments can be a powerful means for reducing the uncertainties in scientific understanding of the linkages between specific flow conditions and ecological responses, by testing various hypotheses in a carefully structured and scientifically credible manner. Because of their potential for reducing uncertainties and helping to better manage a variety of socio-economic risks, the science community has long advocated adaptive approaches in water management (Ward and Stanford, 1993; Castleberry *et al*., 1996; Stanford *et al*., 1996; Poff *et al*., 1997, 2003; Walters, 1997; Richter *et al*., 1997, 2003; Johnson, 1999; NRC, 2002, 2004a,b).

To date, the application of adaptive management principles has been extremely limited in environmental flow restoration and protection efforts, with only a tiny fraction of restoration projects being conducted in an adaptive management context. One major reason for the slow adoption of adaptive management in flow restoration is that it appears to be quite daunting to many water managers and scientists. Adaptive management has to a large degree been defined by, or equated with, a handful of well-publicized but complicated examples (Johnson, 1999). Each of the well-known adaptive management programmes (e.g. the Columbia River basin, the Colorado River in the Grand Canyon, the Everglades, the Sacramento–San Joaquin river basin and delta in California) has been supported with large sums of public funding. These programmes are each structured into complex, multi-layered institutional arrangements with executive, management and technical committees and peer-review panels (Marmorek and Peters, 2001; Walters *et al*., 2000). Each of these restoration efforts has also been encumbered by considerable socio-political controversy because of the magnitude of economic trade-offs inherent in the restoration actions being proposed. If water managers think that adaptive management necessarily entails great expense, complex institutional process, and many years to reach management decisions, they will be quite reluctant to invoke it (Walters, 1997).

There are many water management decisions being made every day that would benefit greatly from knowledge that can be gained from an adaptive flow management programme. Adaptive management can be effectively applied for a purpose as simple as determining the ecologically compatible withdrawal rate and timing for a single water diversion on a small stream. If the conceptual underpinning of adaptive management can be distilled down to its essence it might become more widely applied in water management. In its simplest essential form, adaptive water management includes the following elements (drawing from Holling, 1978; Walters, 1986, 1997; Castleberry *et al*., 1996; Stanford and Poole, 1996; Lee, 1999; Rogers and Biggs, 1999; NRC, 2002, 2004a,b; Irwin and Freeman, 2002; Richter *et al.*, 2003).

- *Sound science*. A vision or mental model is constructed for the ecosystem that is being managed. New information and insights help to increase knowledge and refine the model, thereby improving understanding of the system. A monitoring programme is developed, based upon the model, in which key indicators of ecosystem response to water management actions ('experiments') are tracked and evaluated so that the outcomes of management decisions can be evaluated.
- *Management commitment and flexibility.* Management objectives are explicitly defined, regularly revisited and accordingly revised. The uncertainties in current understanding of the system are recognized and managers and

stakeholders commit themselves to reduce those uncertainties. Managers and stakeholders recognize that a range of management options exist, and mutually create flexibility to test alternative management approaches. Because adaptive management is a process and not a final answer, managers must be willing to make changes in response to new learning.

- *Learning by doing*. Adaptive management does not postpone management actions until 'enough' information is available; instead, strategic, incremental actions are implemented to reduce uncertainties and enhance learning.
- *Public participation*. A collaborative structure provides for stakeholder participation in developing and revising management objectives.

There is great need for real-world examples of alternative models of adaptive water management that retain scientific rigour while requiring less technological sophistication and simpler institutional structure than those widely publicized to date. The process described in the remainder of this paper will enable water managers and scientists to implement adaptive flow management when financial resources, political controversy, and socio-economic risk are substantially more limited than is the case in the Everglades or the Grand Canyon.

DESCRIPTION OF THE PROCESS

We designed a simple, generic process for developing environmental flow recommendations that embodies the essential aspects of adaptive management discussed above, yet is flexible enough to be applied across a broad spectrum of resource availability. Our process comprises five steps (Figure 1): (1) convene an orientation meeting to custom-tailor the process to the needs and limitations of the particular project to which it will be applied; (2) prepare a literature review and summary of existing knowledge about the flow-dependent biota and ecological processes of concern; (3) convene a workshop to develop ecological objectives, initial flow recommendations, and key information gaps; (4) implement the flow recommendations on a trial basis to test hypotheses and reduce uncertainties; and (5) monitor system response and conduct further research as warranted.

This process emphasizes learning by doing. We place heavy emphasis on getting adaptive management underway in the shortest possible time at least expense, while retaining scientific rigour. As Lee (1999) emphasized, the focus should be on learning, not on getting ready to learn. The primary purpose of steps 1–3 is to gain broad, interdisciplinary input in defining ecological objectives and a starting point (i.e. environmental flow targets) to begin adaptive water management. The details and extent of study in steps 1–3 should be tailored to available time and

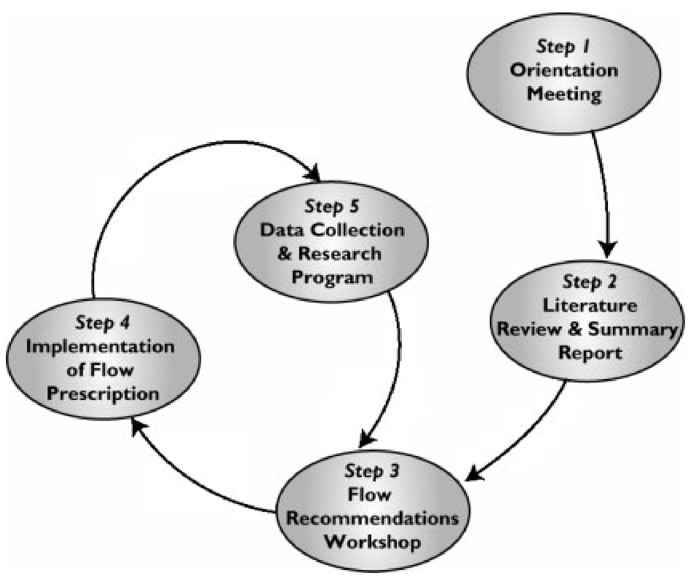

Figure 1. The scientific process for developing environmental flow recommendations comprises five steps. Steps 3–5 are repeated indefinitely to enable iterative refinement of the flow recommendations over time

resources, and governed by an assessment of the key issues that must be addressed before steps 4 and 5 can be initiated.

When applied successfully, the latter three steps are repeated indefinitely, thereby always fostering new learning and improving the environmental flow recommendations over time. We view the first iteration of this cycle as being a 'pump-priming' exercise that gets an adaptive flow restoration programme up and running. In each iteration of steps 3–5, new or refined flow recommendations are being generated and a prioritized list of critical uncertainties and associated research needs is being updated.

We intentionally avoid making any recommendations or specifications about the scientific tools, environmental flow methods, or analyses that should be employed in this process. The 'state-of-the-science' in environmental flow determination continues to mature rapidly, and a large and diverse toolbox is already available for this purpose (for comprehensive reviews of tools and methods being applied for the purpose of developing environmental flow recommendations see Tharme, 1996; Arthington and Zalucki, 1998; Bragg and Black, 1999; Railsback, 2001; Annear *et al*., 2002).

In developing a general process that meets the objectives above, we have drawn heavily from other environmental flow methodologies and processes, particularly the 'holistic' methodologies being applied in South Africa and Australia (Arthington and Zalucki, 1998; Tharme, 2003). Common to these methodologies is the formulation of flow recommendations that address the health of river, floodplain and estuarine ecosystems holistically, rather than focusing only on individual species or specific ecosystem service benefits. Additionally, holistic methodologies consider the full range of hydrologic conditions and events needed to sustain ecosystem health, rather than focusing only on low or minimum flows. Holistic methodologies typically engage scientists from an array of disciplines including hydrology, fluvial geomorphology, water quality, aquatic and riparian ecology, fish biology, and estuarine ecology where appropriate, along with specialists in particular taxa such as macroinvertebrates, mussels, amphibians, and mammals or birds.

Before describing our five-step process in greater detail, one additional aspect of the process deserves emphasis: sponsorship of the scientific process. Ideally, the water management agency that will be responsible for implementing the flow restoration programme (or making some other type of water management decision) initiates the process of developing environmental flow recommendations. If a different agency or a non-governmental organization sponsors the process, it is very important to obtain explicit endorsement from the water management agency from the start. This endorsement is a critical element in creating a supportive context for the scientific work, and for integrating science with management decision-making. It also sends a signal to the scientists that their work will be used to influence water management decisions.

Step 1: orientation meeting

The primary purpose of the orientation meeting is to inform and engage interested parties—including scientists, water managers, agency (federal, state and local) executives, political leaders and stakeholders—in the process of developing environmental flow recommendations. The first orientation meeting provides an important opportunity to tailor the generalized flow prescription process described in this paper for application to the river of interest.

We use an informal procedure to identify individuals, organizations or agencies that should be invited to the orientation meeting. We build our invitation list by contacting individuals in resource agencies, academic institutions, businesses, interest groups and landowners likely to be interested in any proposed flow changes in the river. The resultant invitation list, which commonly exceeds 50 individuals, needs to encompass the range of agencies and organizations responsible for or interested in the river, as well as the full spectrum of scientific disciplines mentioned earlier.

The orientation meeting provides an opportunity for participants to express their values and concerns for the river through the act of responding to the proposed process for developing flow recommendations. However, it needs to be emphasized early in the orientation meeting that the purpose of the process is to develop flow recommendations for *maintaining or restoring the health of the whole river–floodplain–estuary system*. Understandably, each participant will be more concerned with certain aspects of the ecosystem than others, but it is important that all participants maintain the perspective that by keeping the whole system healthy, each part of the system should benefit. It is also important to acknowledge that ecosystem water needs is only one of the issues that water managers will need to address in their decision-making process. Defining (quantifying) environmental flow requirements through this process will allow them to be balanced with other human demands such as power generation, navigation, municipal or agricultural water supplies, and flood control. It is also important to acknowledge that restoring flows may be only one component of a more comprehensive river restoration programme, in which other forms of ecological degradation—such as water quality problems or physical alterations such as channelization—will be addressed.

It should be possible to complete the orientation meeting in a single day. At the beginning of the meeting, participants are given an overview of how water resource decisions are made in the basin, including a clear description of how and when the flow recommendations are to be implemented. Participants are also provided with an overview of the basic process described in this paper as a proposed roadmap (e.g. who, when) that will be used in developing the flow recommendations. During a series of 'breakout' sessions during the day, participants: (1) discuss the details of the process and suggest refinements; (2) identify additional scientists not in attendance at the meeting that should be invited to participate in the flow prescription process; and (3) identify sources of data and written materials (agency reports, journal papers, newspaper stories, etc.) that might be useful in developing flow recommendations.

At the close of the meeting, the process to be used for developing flow recommendations—as refined during the day's discussions—is summarized for the participants, including next steps, who is to be responsible for these steps, and a timeline for completing them.

Step 2: preparation of literature review and summary report

During the orientation meeting, participants are also asked to nominate a specific academic institution, agency or organization that can compile a literature review and prepare a summary report describing existing data and knowledge of the river–floodplain–estuary system, native species, and their flow dependencies. An important qualification of the nominated entity or group of entities is its ability to provide an inter-disciplinary group of scientists to work on these written products; these disciplines usually include, at a minimum, hydrology, fluvial geomorphology, fisheries biology, riparian ecology and, where appropriate, estuarine ecology. Based on the nominations received, one or multiple entities are contracted to produce a literature review and summary report.

The primary purpose of these written products is to identify key aspects of flow regimes that are important in sustaining the health of the river–floodplain–estuary ecosystem. This is accomplished by capturing existing information and knowledge and presenting it in a fashion that will best support the exercise of developing flow recommendations in step 3. The content of these written products will depend upon the degree to which the river ecosystem has been studied, the nature and volume of data collected, and the amount of relevant information that can reliably be drawn from similar river systems. Data and knowledge may be entirely lacking for some rivers, particularly in less-developed countries with limited resources for monitoring and research, and in smaller streams everywhere. In these data-poor situations, scientists may decide that some minimal amount of field data, such as river flow measurements and channel cross-sectional surveys, simply must be performed before proceeding.

The literature review should examine all references identified during the orientation meeting, as well as other pertinent sources of information identified by the contractor in the course of the review. Each document included in the literature review should be assessed for its likely relevance in formulating flow recommendations, noting in particular any statements that specifically link aspects of the flow regime with biota or key ecological processes.

We have found it very helpful to structure the literature review, summary report and flow recommendations using a simple classification of river flow conditions into three 'environmental flow components': low flows, high flow pulses, and floods. Under natural conditions, low flows (also known as base flows) occur during periods between storm runoff or snowmelt, when groundwater contributions are the primary source of river flow. High flow pulses occur when a rainstorm or snow melt causes a rise in river levels, but the magnitudes of these high flow pulses are less than the river's bank-full level. Flood levels can be defined as anything greater than the bank-full level. In the literature review, information about hydro-ecological relationships is categorized according to whether the information applies to low flows, high flow pulses or floods.

When reviewing pertinent literature, it is very important to note the time of year at which the flow condition needs to occur, such as the occurrence of floods during a spawning season. It is also helpful to distinguish whether the relationship being described needs or tends to occur every year, or only during unusually wet or dry years. The summary report (described below) and flow recommendations developed in step 3 are formulated using this same simple categorization of flow components, their seasonal timing, and water year types.

In performing the literature review, the contractor should look for both direct and indirect connections between the components of a flow regime and a variety of biota (see examples of these connections in Table I). Species-specific information can be extremely useful in developing initial flow recommendations, particularly if the species is known to be a keystone species, or if its flow needs are representative of a habitat guild, or if some phase(s) of its life cycle is strongly tied to specific flow conditions. Many of these flow–biota relationships will reflect direct connections, such as the flow levels needed to enable fish spawning migrations. However, other relationships will be indirect, such as the influence of freshwater flows on salinity distributions in estuaries that affect estuarine organisms. Because flows of various levels influence physical habitats, water chemistry, energy supplies, connectivity among different habitats, and species interactions, any information describing the inter-relationship of flow with

Table I. Ecological functions performed by different river flow levels (adapted from Postel and Richter, 2003)

Flow component	Ecological roles
Low (base) flows	Normal level • Provide adequate habitat space for aquatic organisms • Maintain suitable water temperatures, dissolved oxygen, and water chemistry • Maintain water table levels in floodplain, soil moisture for plants • Provide drinking water for terrestrial animals • Keep fish and amphibian eggs suspended • Enable fish to move to feeding and spawning areas • Support hyporheic organisms (living in saturated sediments) Drought level • Enable recruitment of certain floodplain plants • Purge invasive, introduced species from aquatic and riparian communities • Concentrate prey into limited areas to benefit predators
High pulse flows	• Shape physical character of river channel including pools, riffles • Determine size of stream bed substrates (sand, gravel, cobble) • Prevent riparian vegetation from encroaching into channel • Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants • Aerate eggs in spawning gravels, prevent siltation • Maintain suitable salinity conditions in estuaries
Floods	• Provide migration and spawning cues for fish • Trigger new phase in life cycle (e.g., insects) • Enable fish to spawn on floodplain, provide nursery area for juvenile fish • Provide new feeding opportunities for fish, waterfowl • Recharge floodplain water table • Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances) • Control distribution and abundance of plants on floodplain • Deposit nutrients on floodplain • Maintain balance of species in aquatic and riparian communities • Create sites for recruitment of colonizing plants • Shape physical habitats of floodplain • Deposit gravel and cobbles in spawning areas • Flush organic materials (food) and woody debris (habitat structures) into channel • Purge invasive, introduced species from aquatic and riparian communities • Disburse seeds and fruits of riparian plants • Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes) • Provide plant seedlings with prolonged access to soil moisture

these other ecosystem variables could be useful in developing flow restoration recommendations. Attention also should be paid to the necessary intra- and inter-annual variability in each of the three flow conditions. For example, sustaining a population of fish may require large floods that enable access to floodplain spawning areas during the spring season, but the fish may not need such access every year. Table II summarizes some of the questions that should be addressed in the summary report.

The inter-relationships between flow components and biotic responses or ecological processes should be portrayed in conceptual ecological models (Figure 2). Conceptual models are an excellent way to portray ecological knowledge and show hypothesized linkages between flow and various aspects of ecosystem health, or a species' dependence upon certain flow conditions to complete a particular life history stage. The process of conceptual modelling usually results in identification of key uncertainties and information gaps in eco-hydrological relationships. When possible, statistical correlations between flow conditions and various ecosystem or species variables should be explored to provide a cursory test of the strength of these relationships, but we recognize that appropriate data for such analyses are seldom available at the onset of a flow restoration project or other water management activity.

We acknowledge that the type of conceptual, qualitative modelling that we are suggesting here differs markedly from the quantitative ecological simulation models that have been developed in some of the well-publicized adaptive management programmes discussed previously. We are certainly not suggesting that technologically sophisticated simulation models are not useful in addressing eco-hydrological phenomena—in fact, they may be essential in developing adequate scientific understanding to enable formulation of environmental flow recommendations in large, complex ecosystems. However, these simulation models can become prohibitively expensive, and to suggest that adaptive management cannot be implemented without such quantitative tools would in many instances kill the prospect of applying adaptive management practices to support water resources decision-making. The decision of whether to use qualitative versus quantitative models during the planning phase of an adaptive management programme should be based on funding availability and an assessment of the level of certainty that must be attained before water managers and stakeholders will allow experimentation and 'learning by doing' to begin. This assessment will hinge largely upon the management flexibility available in the system, and the potential controversy that any change in management might engender. Our experience suggests that sufficient flexibility usually exists to enable water managers to implement experiments within a fairly broad range of flow variability, even though implementation of some flow experiments (such as re-instating large floods) may require considerable additional scrutiny, modelling analysis, and investment in water infrastructure. Therefore, adaptive management can often proceed within a certain range of flow variability while further analysis is focused on more challenging aspects of the flow management programme. In general, when financial resources are constraining but management flexibility exists, we would much prefer to spend available money on learning from real-world experiments than those conducted in cyberspace.

It is important for the summary report to identify other sources of ecological degradation that may affect ecosystem health even if target flows are restored or protected. In a flow restoration programme, this will help to clarify how much restoration should be anticipated from improving the flow regime, and keep managers focused on other concerns that require attention as well.

Once completed, the literature review and summary report is sent to all individuals invited to participate in the 'flow recommendations workshop' (described below; see Figure 1). These written materials are distributed well in advance of the workshop, to enable all workshop participants to familiarize themselves with relevant knowledge that will inform their deliberations. Workshop participants are also asked to provide review comments on the summary report. Reviews should identify points needing clarification, disagreements on data interpretation, and species or ecosystem components that should have been considered but were not.

Step 3: flow recommendations workshop

The primary purpose of the literature review and summary analysis in step 2 is to describe qualitatively the annual and inter-annual hydrograph patterns necessary to restore or sustain ecosystem health. As discussed above, these patterns can be described using as few as three flow components and noting the desired timing of their occurrence in an annual or inter-annual hydrograph. In step 3, scientists work together in a workshop setting to

Table II. Key questions to be addressed in the summary report

Hydrology
1. Do stream gauges exist along the river, and if so, where are they located, who maintains them, and how long have they been in operation?
2. What are/were the typical seasonal patterns of natural river flow variation (e.g. when do higher flows tend to occur, when do the lowest flows occur)?
3. To what extent have the low, high pulse, and flood flows in the river changed over time in response to human influences? Have extreme low flows become more frequent or extreme? How do hydrographs from recent years compare to pre-development hydrographs?
4. What are the primary human influences on the flow regime, and where do these impacts occur? Do certain human impacts appear to dominate over other human influences?
5. What types of water development activities are planned for the future, and how might those developments influence river flows?
6. How important are ground water contributions to base flows? What is the nature of hydraulic connections between river stage and alluvial water table levels? How might these connections be altered by future water developments?

Hydraulics
1. Has any hydraulic modelling been performed for the river? Has any flood hazard mapping been undertaken?
2. How well are relationships between river stages (water elevations) and river flow levels understood?
3. How well are relationships between river flow and the distribution of velocities and depths in the river channel understood?
4. Is there longitudinal (upstream to downstream) connectivity in flow or are there major discontinuities (i.e. diversion dams), and if so where?
5. Has the lateral connectivity between the river and its floodplain been altered in any way?

Geomorphology
1. Have any topographical surveys been conducted of the river channel or floodplain (including any surveying for bridges, roads, floodplain mapping, etc.)?
2. Is the channel and floodplain system in dynamic equilibrium or disequilibrium? Is the sediment input to each segment in equilibrium with the capacity of the channel to transport it through the segment? Are there detectable trends in the elevation of the river bed or lake bottom, indicating degradation or aggradation? Has the river's longitudinal profile changed over time?
3. Has the channel or floodplain width changed over time?
4. Has the channel's planform changed over time, such as between meandering and braided forms?
5. Has the size distribution of stream bed sediments changed over time?
6. Has the availability of in-stream physical habitats changed over time (e.g. changes in availability of pools or riffles)?
7. Is lateral channel migration or bar formation important ecologically (e.g. to support riparian plant communities)?
8. Has human activity and land use significantly altered the stream channel and floodplain morphology and processes?

Water quality
1. Have water quality data been collected for the river, and if so, by whom, where, for how long, and of what type?
2. How do water quality conditions vary spatially in the river?
3. What is known about water quality problems in the river?
4. Is wastewater discharged into the river? Where, and how much? What proportion of the low flows in the river arises from upstream wastewater discharges?
5. What is known about daily, seasonal, annual fluctuations in key parameters such as dissolved oxygen or temperature in the river?
6. How do human activities affect water chemistry, temperature or dissolved oxygen in the river?
7. What water quality components are of greatest concern to the target organisms, life stages or riverine processes (e.g. dissolved oxygen, suspended sediment, temperature, chemical elements, nutrients)? Are species distributions or abundances thought to be affected by water pollution?
8. Is large woody debris an important component of the aquatic ecosystem?
9. Are any invasive plant species an issue of concern?

Freshwater ecology
1. What type of biological data have been collected for the river? Who collected these data, over what time frame, and how often?
2. Has the abundance or distribution of certain species changed over time? Are these changes thought to be linked to changes in river flow or water quality? Are data available to document these trends?

Continues

Table II. Continued

3. What species (fish, birds, mammals, invertebrates, aquatic plants or riparian vegetation) are of greatest concern from either ecological or socio-economic or recreational standpoints?
4. What is known about the linkages between river flow and life histories of aquatic species? What times of year are most critical for indicator species, life stages or species assemblages?
5. Can the flow needs of certain indicator species be used to represent the flow needs of assemblages of organisms (e.g. fish communities, riparian vegetation)?
6. If the river flow regime has been altered by human influences, are necessary flow conditions still properly sequenced to enable successful life cycle completion for indicator species?
7. Which habitats are most limiting, and what is the importance of drought, flooding and intermediate flow conditions for developing and maintaining these habitats?
8. Are aquatic floodplain habitats critical for maintaining fish populations in rivers?
9. Is the aquatic ecosystem dependent upon energy subsidies (e.g. detrital matter) that are brought into the river from the floodplain during floods?
10. Do certain species require particular flow levels to facilitate movements in the river?
11. If reservoir releases are proposed in order to provide recommended flows, could there be effects on the ecology and fisheries in the reservoir?
Riparian ecology
1. Have the riparian plant communities or distributions of riparian plant or animal species been surveyed or characterized? Have they changed over time?
2. What is known about relationships between river flows, alluvial water table levels, floodplain inundation patterns, and the influence of these hydrologic conditions on riparian plants or animals?
3. Do certain riparian plants or animals depend upon physical habitat conditions that are shaped by river flows? Is lateral channel migration or bar formation important in forming these physical habitats?

quantitatively define the necessary dimensions of the flow component patterns. They must determine appropriate ranges for low flow, high pulse and flood levels, how long they should last, how often they should occur within the year or among years, and how rapidly flows can change from one condition to another. When defining low flow needs, we typically ask the scientists to specify ranges for each month of the year (Table III). We also ask them to differentiate among dry, average and wet years in developing their recommendations for each of the three flow components. This differentiation among wet, average and dry years should be assessed for each river individually.

The list of scientists invited to participate in the flow recommendations workshop should include those identified during the orientation meeting, as well as any others identified during step 2. The workshop, which typically lasts three days, needs to begin with a clear statement of purpose, such as 'to develop consensus for environmental flow recommendations to be used in modifying the operations of the Heartbreak Dam on the Big Hearted River to restore the health of the river–floodplain–estuary system'.

At the start of the workshop, it is critically important to communicate the expectation that quantitative flow recommendations will be developed during the workshop, and the need for the flow recommendations to be as spatially and temporally explicit as possible. While flow recommendations need to address the whole river ecosystem, and floodplain and estuary systems where relevant, they will usually be expressed as a range of magnitudes (e.g. 30–35 m^3/s) for each flow component at specific locations, at specific times during the year, and with a specified frequency of occurrence among years (e.g. a prescribed flood may need to occur only once in three years, or once every ten years). Each specification of a desired flow magnitude and its associated timing and location will become a management target for water managers. Flow recommendations are typically expressed as desired flow conditions at one or more flow measurement gauges located downstream of the water management activities that are to be modified, such as below a dam or diversion point. By tying the flow recommendations to specific measurement points, flow data can be collected at those locations to assess whether flow recommendations are being met. These flow data can also be used in evaluating ecosystem responses to the implementation of the flow recommendations.

The agenda for the workshop will depend upon many factors, but we have found it useful to begin by separating the workshop participants according to their familiarity with the different ecological systems or river sections to be considered. For example, we might have one sub-group focused on a canyon-bound section of river with unique

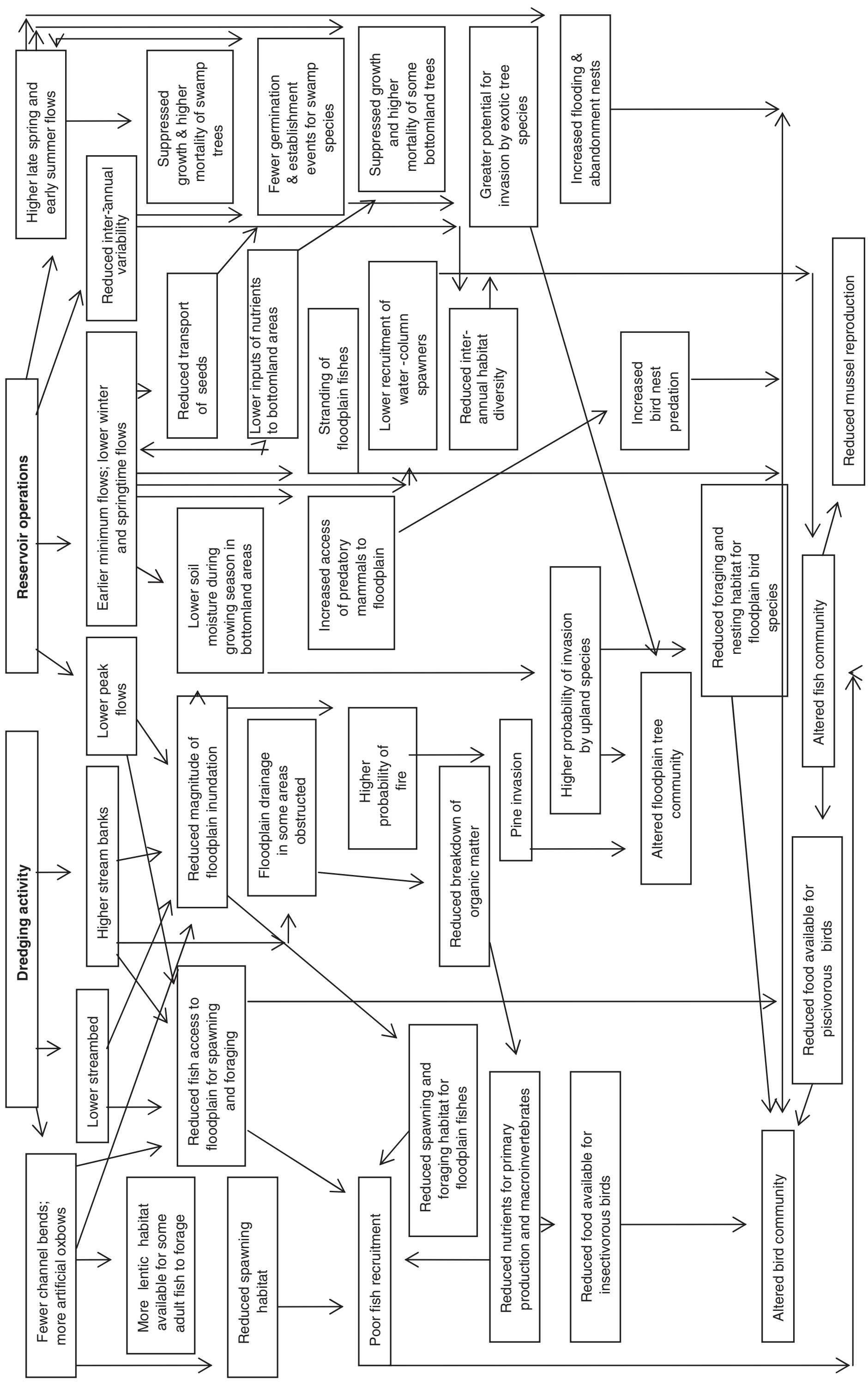

Figure 2. Conceptual ecological model portraying key linkages between river flows and ecological conditions or responses. This model was developed for the Savannah River in Georgia and South Carolina

Table III. Recommended flows in the Savannah River (all flows in m^3/s)

Month	Low flows			High Flow Pulses			Floods
	Dry year	Average year	Wet year	Dry year	Average year	Wet year	
Augusta Shoals flow recommendations, as measured at the Augusta stream gauge							
January	114	170	241		469–1037	753	
February	114	213	284		469–1037	753	
March	114	241	284	355–412	469–1037	753	
April	114	185	284	355–412	469–1037	753	
May	77	128	284				
June	77	128	142				
July	77	114	142				
August	57	114	142				
September	57	114	142				
October	57	114	156			469	
November	77	114	156				
December	77	114	156				
Floodplain flow recommendations, as measured at the Burtons Ferry stream gauge							
January	213	270	341		568–1136	852	
February	213	313	384		568–1136	852	1420
March	213	341	384	455–511	568–1136	852	
April	213	284	384	455–511	568–1136	852	
May	176	227	384				
June	176	227	241				
July	176	213	241				
August	156	213	241				
September	156	213	241				
October	156	213	256			568	
November	176	213	256				
December	176	213	256				
Estuary flow recommendations, as measured at the Clyo stream gauge							
January	227	270	341		568–1236	852	
February	227	313	384		568–1236	852	1420
March	227	341	384	455–511	568–1236	852	
April	227	284	384	455–511	568–1236	852	
May	176	227	384				
June	176	227	256				
July	176	227	256				
August	170	227	256				
September	170	227	256				
October	170	227	256			568	
November	176	227	256				
December	176	227	256				

aquatic habitats, another focused on a wide section of river that is associated with floodplain forests, and another focused on a downstream estuary. Ideally, each sub-group will comprise scientists from a variety of disciplines (e.g. hydrologists, hydraulic engineers, geomorphologists, fisheries biologists, riparian ecologists, water quality specialists, etc.) so that each ecological system or section of river is being assessed through inter-disciplinary perspectives.

In all cases, we strongly encourage workshop participants to consider use of historic or simulated flow records from a time period in which the river was relatively unaltered (e.g. pre-dam) as they develop their recommendations. Such unaltered flow conditions can provide important insight into the necessary shape of flow component patterns and the range of variability in those patterns that sustained the ecosystem's health prior to significant human development (Poff *et al.*, 1997; Richter *et al.*, 2003). It is also useful to compare the emerging flow recommendations against recent hydrographs to ensure that the proposed flow conditions will have the effect of moving the flow characteristics in the direction of the undeveloped flow regime.

Each sub-group carefully documents their justifications for each flow target. For instance, they may have recommended a specific low flow in the summer to prevent water temperatures from becoming too high and thereby causing fish mortality. At the same time, each sub-group describes the uncertainties associated with their recommendations, and data collection or research needed to address these uncertainties.

We then re-mix the workshop participants into new sub-groups representing low flows, high flow pulses and floods. The purpose of this new arrangement is to facilitate an examination of the compatibility of flow recommendations across different sections of the river, or between different ecological systems such as in-channel aquatic habitats, the floodplain and the estuary. Any inconsistencies are discussed and a new, integrated set of recommendations is generated. The component driving the integrated recommendation is identified (e.g. floodplain ecosystems require these flows in this month; the estuary is not harmed by this flow, but could get by with less). Again, if any new data gaps or uncertainties arise during these discussions, they are noted by each of the sub-groups.

In the final phase of the workshop, the participants assess the recommendations for low flows, high flow pulses and floods as a whole group, addressing any remaining problems or inconsistencies in the recommendations. Each piece of the flow recommendation, along with the ecological functions or outcomes it is intended to support, is thoroughly documented. Before concluding, the workshop participants produce a prioritized list of data gaps and research needs.

Step 4: implementing the flow recommendations

From a scientific perspective, implementing flow recommendations provides a valuable opportunity for improving scientific understanding of the flow conditions necessary to effect desired ecological changes or processes (Poff *et al.*, 2003). By carefully tracking the response of an ecosystem to flow management, the recommendations can be further refined, thus helping to ensure that river management is accomplishing its objectives. Therefore, it is critically important that this step be implemented with considerable forethought and careful design so that trial implementation of flow recommendations will optimize learning potential (Castleberry *et al.*, 1996; Irwin and Freeman, 2002).

In virtually all cases, a new monitoring programme will need to be initiated or modifications to an existing programme will need to be made such that the ecological effects of implementing the flow recommendations can be evaluated adequately. This typically requires installation of new monitoring equipment, such as construction of new streamflow, ground water, or water quality monitoring gauges. New ecological indicators may need to be monitored and assessed to gain a better understanding of biotic responses to flows. Additionally, some period of baseline monitoring may need to be completed prior to imposition of the new flow regime so that existing conditions can be better defined, thereby providing benchmarks against which the benefits of the flow restoration programme can be compared.

A key issue in the design of monitoring programmes to track the response of the system to new management actions is to identify ecosystem indicators that are sufficiently representative of the health of the river ecosystem, directly address ecological goals, and are sufficiently responsive to flow management to enable evaluation of the success of the programme on relatively short time frames (Dixon *et al.*, 1998; Rogers and Biggs, 1999; Richter *et al*., 2003; Parrish *et al*., 2003). In assessing the efficacy of environmental flow management, scientists must explicitly address the temporal and spatial scale of the response indicator variables with respect to the influence of the flow conditions to be imposed. We place great emphasis on the selection of indicators that will respond immediately, or within subsequent months, to the adjustment of flow conditions. For example, in the Savannah River case study described below, we monitored the movement of target fish species during the imposition of a high flow pulse release from a dam to verify that the fish were able to move upstream past a lock-and-dam structure that had previously impeded their spawning migrations. We are also monitoring the recruitment of floodplain tree species by tracking seedling establishment during growing seasons in which flows are adjusted for this purpose.

There are many non-scientific considerations that can delay implementation of flow recommendations, and these issues need to be considered and understood by scientists in their design of the flow prescription process described in this paper. In an ideal situation, water managers would be willing and able to implement the flow recommendations resulting from step 3 immediately. For instance, a dam operator may be able to implement the new flow recommendations simply by modifying the dam operating rules to produce desired flow releases. However, even in this ideal situation, water managers will usually need to conduct modelling simulations or economic evaluations to assess the impacts of the new operating plan on other water-related values and concerns such as flood control capabilities or recreational use of a reservoir, or the reliability of water supplies during drought periods.

It is quite common to find that flow recommendations simply cannot be implemented all at once, for various political or economic reasons. Restoring low flow conditions in a stream may require implementing a number of water conservation measures to improve agricultural irrigation efficiency, for example, or water rights or permits may need to be purchased from existing water users so that more water will flow downstream during low flow periods. Restoring more natural levels of high flow pulses or floods may require modifications to reservoir release structures, time-consuming changes in land use such as restoring wetland areas in agricultural catchment areas, or constructing stormwater management infrastructure in an urbanized area.

Too often, delays in implementation have discouraged both scientists and water managers from pursuing a flow restoration programme. However, we advocate strongly for completing steps 1–3 in all river basins needing flow restoration, at the earliest time possible. As we have stated previously, sufficient flexibility will exist to implement some aspects of the flow recommendations in most instances. Defining an ecosystem's flow requirements can provide considerable stimulus for implementing needed restoration actions because it provides managers with an excellent first estimate of how much restoration may be required, thereby stimulating innovation in achieving the targeted flows. In the San Pedro River basin of southeastern Arizona, scientific assessment of environmental flow requirements and human impacts on the hydrologic system catalysed the formation of the Upper San Pedro Partnership, a consortium of 21 different agencies that have together identified at least 57 flow restoration measures that can be implemented (Postel and Richter, 2003; Davis, 2004). These agencies have already committed US$46 million to the restoration effort since 1999. Each of the incremental restoration measures and water-dependent ecological conditions is being monitored carefully so that the flow recommendations for the San Pedro River can be refined on the basis of new information and understanding.

Step 5: additional data collection and research

Another notable benefit of completing steps 1–3 is the fact that identification of data and research needs will galvanize attention from the science community to fill critical knowledge gaps. During the flow recommendations workshop, priorities for additional data collection and ecological research are explicitly defined. The pursuit of this information should begin as part of step 4, and continue as step 5, in which the results of on-going and previous flow restoration experiments are evaluated and priorities for data collection and research are refined or updated.

On the Roanoke River in North Carolina, a diagnosis of dam-induced flow alteration (Richter *et al.*, 1996) generated many questions about the ecological impacts associated with this flow alteration. More than US$4 million has been invested in ecological research since 1992 in trying to answer these questions.

CASE STUDY: SAVANNAH RIVER

Beginning in the Blue Ridge Mountains of north Georgia at the confluence of the Seneca and Tugaloo rivers, the Savannah River traverses more than 500 km in its path to the Atlantic Ocean (Figure 3). The Savannah River divides the states of South Carolina and Georgia and crosses three geographically distinct ecoregions: the Blue Ridge, the Piedmont and the Atlantic Coastal Plain. A rich variety of ecological systems can be found in the 27 000 km^2 basin, including aquatic shoals, bottomland hardwood forests, tidal wetlands, longleaf pine forests, Carolina bays, granite outcrops and bluff forests.

The waters of the Savannah River provide habitat for approximately 100 species of fish—one of the most diverse fish assemblages in the southeast USA. Many of these fish species are widely known to anglers, such as largemouth bass, striped bass, chain pickerel and redbreast. Several rare fishes are also found in the Savannah, including the robust redhorse (*Moxostoma robustum*). Freshwater mussels are also abundant in the river system, with nine rare species documented in the basin.

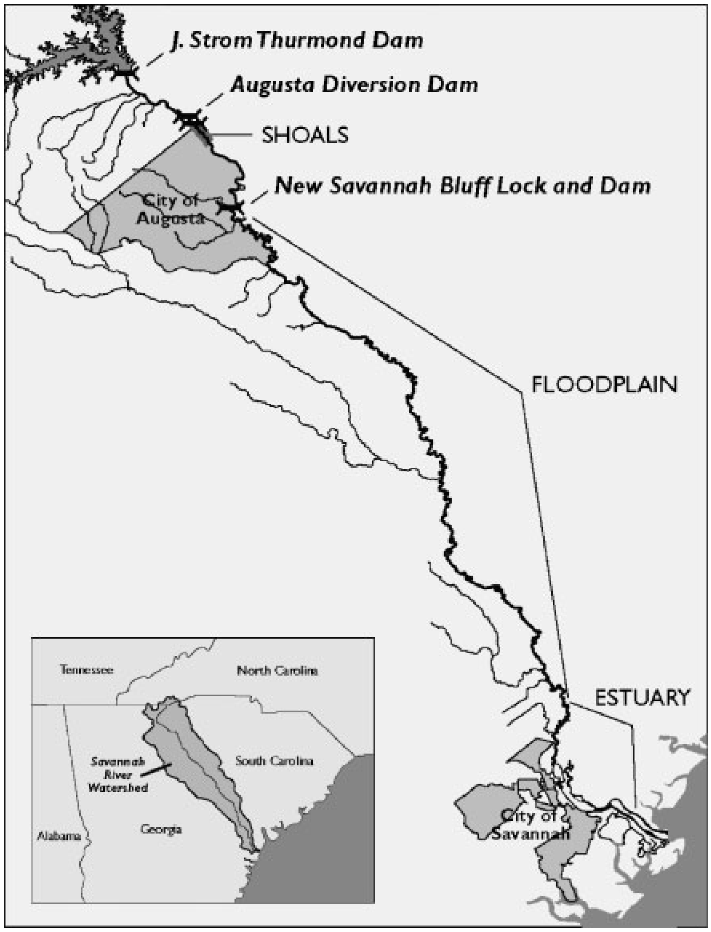

Figure 3. The Savannah River basin

The US Army Corps of Engineers (hereafter, 'Corps') operates three large dams on the river—Hartwell, Russell and Thurmond dams—all located upstream of Augusta, Georgia (Figure 3). These three facilities are multi-purpose dams authorized for hydropower generation, flood control, recreation, water supply, and fish and wildlife habitat. Thurmond Dam, completed in 1954, was the first of the three dams to be constructed, and is located furthest downstream. Hartwell Dam was constructed in 1962, followed by Russell Dam in 1984.

Partnership between the Corps and the Nature Conservancy

In July 2002, the Nature Conservancy—a non-governmental conservation organization—and the Corps announced a collaborative effort to improve water management on rivers across the country. Under this Sustainable Rivers Project, the two organizations agreed to work together in a number of ways to restore river health. The primary restoration strategy is modifying dam operations to improve downstream river health and associated ecosystem services while continuing to meet other human uses of water such as power generation, recreation, and flood control.

As the two organizations were launching their Sustainable Rivers Project, the Corps' Savannah District was in the start-up phase of a new Comprehensive Plan for the Savannah River Basin. The purpose of this plan, co-sponsored by the states of Georgia and South Carolina, is to assess the existing authorized uses of the river and reservoirs to determine if water management practices are adequately addressing the needs of all stakeholders on the river. When the Nature Conservancy met with the Corps to discuss their hopes for the river, the Corps and the Nature Conservancy agreed to enroll the Savannah River in the Sustainable Rivers Project. The Corps also invited the Nature Conservancy to participate in the comprehensive plan by helping to facilitate the development of environmental flow recommendations. The Nature Conservancy then began facilitating the scientific process for flow recommendations described in this paper.

Orientation meeting

More than 50 individuals, representing many different federal, state and local agencies and academic institutions, attended an orientation meeting in May 2002 to initiate the process for developing environmental flow recommendations. During the meeting, the participants reviewed and commented on the general scientific approach described in this paper, then identified key science contributors and sources of relevant information for developing the flow recommendations.

Several key messages were distilled from workshop participants: (1) a considerable amount of relevant information existed, which could be used in developing draft environmental flow recommendations; (2) existing data and other information could best be summarized by a small team of researchers, with review and input from a larger group of scientists; and (3) developing environmental flow recommendations as part of the Corps' Savannah River Basin Comprehensive Plan would be critically important in ensuring that ecological needs are adequately considered as part of the overall water management for the river.

The Nature Conservancy subsequently developed a scope of work for a literature review and summary report, addressing the ideas and sources of information generated during the orientation meeting. The scope of work outlined the specific products and scientific process necessary to develop environmental flow recommendations for the Savannah River within a one-year time frame. This time frame was designed to align with the timing of other analyses and decision-making in the comprehensive plan. The scope of work was subsequently funded by the Corps and the states of Georgia and South Carolina.

Preparation of literature review and summary report

After consulting with a number of the scientists that participated in the orientation meeting, the Nature Conservancy determined that the best group to develop a summary report and literature review was the University of Georgia's (UGA) River Basin Science and Policy Center, located in Athens, Georgia. It was further decided that the UGA research team should be composed of researchers with expertise in floodplain systems, diadromous and resident fishes, estuaries, and hydrology/geomorphology. Four lead researchers, representing each of these disciplines, and a team of graduate assistants developed an annotated literature review of information sources to be used in developing environmental flow recommendations. This review included, but was not limited to, information sources identified during the orientation meeting. More than 375 sources were reviewed by the UGA research team. This annotated bibliography was then sent to all participants in the orientation meeting and their review comments were solicited. Specifically, these reviewers were asked whether important information sources had been missed and whether the species chosen as representative or critical were appropriate.

Using both the literature review and their own professional knowledge and familiarity with the Savannah River ecosystem, the UGA research team then developed a summary report that included: (a) a description of key linkages between specific ecological flow components and biotic tolerances or dependencies; (b) pictorial models illustrating connections between natural hydrographs and life cycles of representative species; and (c) box-and-arrow diagrams expressing relationships between ecological flow components and biotic responses or dynamics. The literature review and summary report was then peer-reviewed by a larger scientific group selected for participation in the flow recommendations workshop as discussed below (the literature review and summary report are available online: www.rivercenter.uga.edu/pdfs/summaryreport.pdf). This larger group of scientists comprised individuals identified at the orientation meeting and in subsequent discussions with regional scientists.

Flow recommendations workshop

A three-day ecosystem flow workshop was held in Augusta, Georgia, in April 2003. The workshop brought together 47 scientists and other technical experts from a variety of disciplines. The participants were asked to develop quantitative flow recommendations for the Savannah River that would sustain the river, floodplain and estuarine ecosystems. The resulting recommendations were based upon information provided in the literature review and summary report, but a good deal of professional judgement was also required to develop an adequately complete flow recommendation. At the start and throughout the workshop, participants were reminded that their recommendations would be used to inform ecological needs to be considered in the Corps' comprehensive plan. They were also told that their recommendations would be considered to be a first approximation, and that these recommendations would mark the beginning of a long-term adaptive management programme during which the flow recommendations would be continually refined. During the discussion of environmental flow needs, the scientists also identified numerous data collection and research needs.

The first day of the workshop included an overview of the comprehensive study provided by Corps staff and presentations by the UGA research team which provided a synthesis of the major findings from the summary report. Workshop participants were then divided into three working groups. Each group was challenged to provide flow recommendations that would sustain or restore ecosystem health in one of three reaches of the river: the Augusta Shoals reach, a floodplain reach, and the estuary.

Recommendations were developed through discussion of three components of the flow regime: low flow, high flow pulses, and flood events with a recurrence interval greater than two years. Five ecologically critical aspects of the natural flow regime (magnitude, frequency, timing, duration, and rate of change) were incorporated into the recommendations. Recommendations were provided for each of these flow components for dry, average and wet years (Table III). Average flow years were defined as occurring 50% of the time, while dry and wet years were defined as those falling below the 25th percentile and above the 75th percentile, respectively. Recommendations from each 'reach working group' were presented to all workshop participants.

The reach working group participants were then re-assigned to one of three different working groups and asked to combine the recommendations from each river reach into a unified flow recommendation for low flows, high flow pulses and floods. The unified flow recommendations were then discussed by the entire group of workshop participants until consensus was reached on a final set. The group's flow recommendations are summarized in Figure 4 and Table III.

At the end of the workshop, each of the three reach-specific working groups re-assembled to summarize critical data gaps and to prioritize the most critical research needs for each section of the river (Table IV). The working group recommendations were then discussed by the entire workshop group until consensus was reached on a final set of highest-priority needs. Key ecological objectives to be supported by the flow recommendations are presented in Figure 5.

Implementing the flow recommendations

Shortly after the flow recommendations workshop, Nature Conservancy staff met with the Corps to discuss the feasibility of implementing some key features of the recommendations so that the scientists could continue to refine their recommendations while the comprehensive planning process proceeded. The Corps expressed willingness to begin such implementation in 2004. In March 2004, the Corps released a controlled flow 450 m^3/s, in accordance with the high flow pulse recommendations, as an early test of their abilities to implement some key aspects of the flow recommendations. Another high pulse of 850 m^3/s was released in October 2004. The UGA research team, the Nature Conservancy, and others involved in the flow recommendations workshop have designed a monitoring and research programme to assess physical and biological conditions as elements of the flow recommendations are being implemented. During its comprehensive planning process, the Corps will more thoroughly assess the feasibility of implementing the whole suite of flow targets included in the environmental flow recommendations.

SUMMARY AND CONCLUSIONS

The application of our process for developing environmental flow recommendations in the Savannah River revealed some strong benefits of this inter-disciplinary, collaborative, adaptive approach. Most importantly, the probabilities for improving the ecological health of the river and estuary, and associated ecosystem service benefits

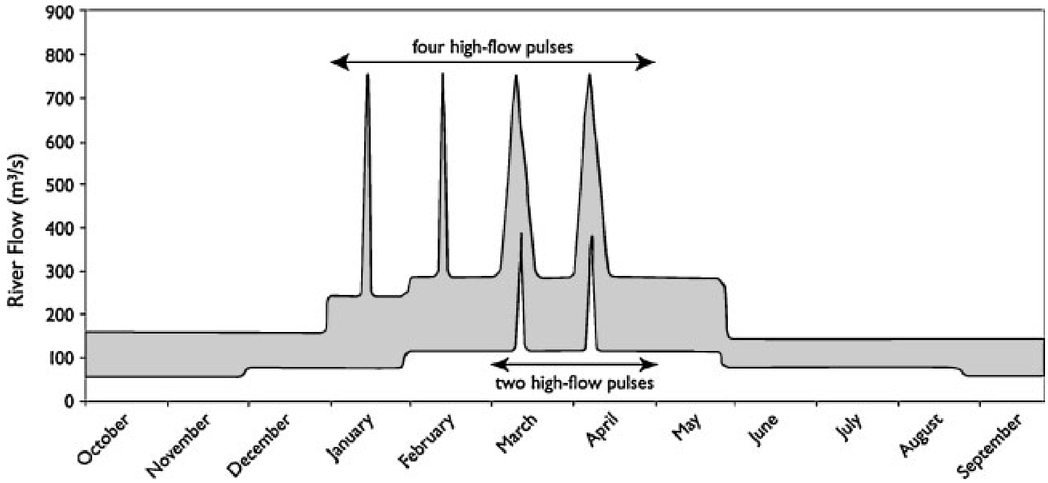

Figure 4. The flow recommendations developed during the Savannah River environmental flow workshop were specified for three different types of water years (dry, average, wet) and three different river reaches. The shaded band represents a synthesis of the flow recommendations across all three water year types for the Augusta Shoals reach. In dry years, water managers would follow the lower band range; during wet years, flows would be closer to the upper band limit. The shaded band reflects desired flow conditions during low flow periods as well as high flow pulses needed during the winter and spring (January–April)

Table IV. Summary of highest-priority data collection and research needed to help improve the Savannah River environmental flow recommendations

Shoals	Floodplain	Estuary
Conduct real-time streamflow gauging in Shoals along with temperature monitoring to enable development of a streamflow–temperature model	Develop cross-sectional and/or spatial topography at fine resolution in the floodplain	Relate flow at Clyo to salinity distribution in estuary
Characterize fish, plant and invertebrate distribution, community composition, and movement tied to flows over time	Characterize vegetation community distributions	Characterize fish community distributions and inter-tidal marsh conditions during high flow periods
Characterize physical dynamics during low and high flow extremes to inform sediment transport and deposition study	Conduct in-channel survey of physical structure (woody debris, sand and gravel bars, etc.)	Relate salinity conditions to inter-tidal/floodable habitat
Determine spider lily flow needs	Modify existing USGS stream gauges to include temperature, turbidity, dissolved oxygen measurements	Determine flow effects on spawning and recruitment success for estuary-dependent (including diadromous) fish species
Characterize robust redhorse spawning habitat	Determine duration of inundation in floodplain after flood events	Determine relationship between flow and dissolved oxygen
Assess Atlantic sturgeon spawning and passage needs as well as shortnose sturgeon passage needs in relation to flow	Determine location of gravel patches below New Savannah Bluff Lock and Dam and flow influences on those habitats	Analyse fish community data collected to date to assess impacts of flow regulation
Determine striped bass passage and thermal requirements as well as egg drift requirements for movement past New Savannah Bluff Lock and Dam	Determine level of flow at which oxbows and sloughs begin to exchange water with river, and assess the influences of these connections on water quality in these aquatic habitats	
	Revisit Corps of Engineers cut-off bend study to assess opportunities for further physical restoration of natural meanders	

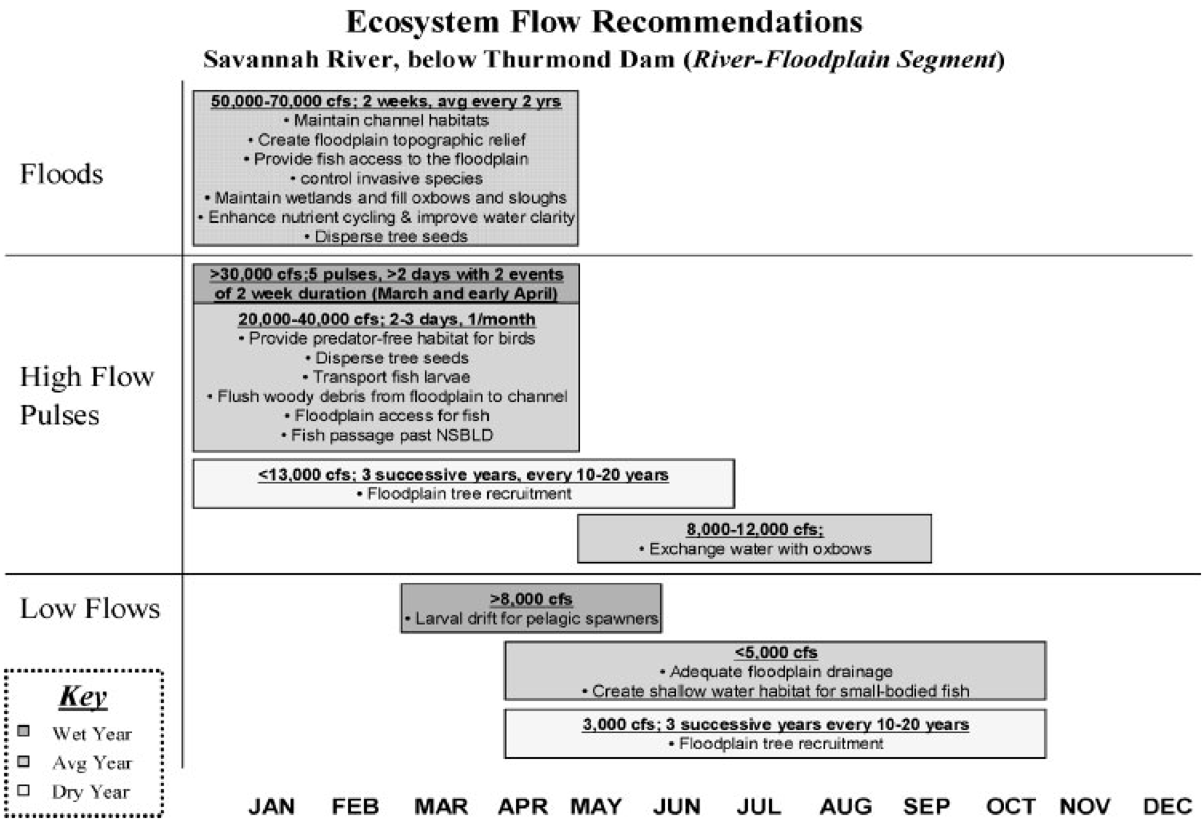

Figure 5. This diagram highlights some of the key ecological objectives to be supported by the flow recommendations developed for the Savannah River floodplain segment. These objectives pertain to specific flow components (low flows, high flow pulses and floods), time of year, and water year type (dry, average, wet)

to society, are likely to be optimized through this approach because of its use of a broad spectrum of scientific expertise. By involving inter-disciplinary scientists and multiple resource agencies in this process we captured diverse perspectives and insights on river management.

Our process helped to build a strong and influential constituency for flow recommendations by engaging a large number of scientists representing many different agencies and institutions. The inclusive nature of the process gave the flow recommendations a level of credibility that is highly desirable in a restoration programme. This credibility can be extremely important when, as part of a restoration programme, water managers propose changes in existing allocations or operations that might be controversial with some existing water users.

This process also helped to foster a coordinated and consistent vision for the protection and management of the river. In the Savannah River effort, we included scientists from various agencies that are responsible for regulatory activities associated with the river, ranging from water quality enforcement to endangered or migratory species protection. Because of their involvement in the flow recommendation process, these agencies became familiar with and supportive of the proposed flow recommendations. The agencies are now taking the flow recommendations into account as they make regulatory decisions. Their mutual adoption of the same set of flow recommendations helped to foster a consensus vision for the river.

Our experience on the Savannah River also highlighted some significant challenges for implementing this type of process. Initially, it was quite difficult to get the participants in the flow recommendations workshop to suggest any quantitative flow targets. We found it very important to remind them that their recommendations were a first approximation that would be refined over time through an adaptive management process. Rather than allowing uncertainties to paralyse their selection of flow targets, they recorded these uncertainties in the form of data collection and research needs that would be addressed in the future to enable refinement of the flow recommendations.

We realize that because our process involves many scientists and agencies it may seem onerous and time-consuming. However, the Savannah River application proved to be quite time- and cost-efficient. Most of the work burden fell on the UGA research team that was contracted for the literature review and summary report. Those products provided a considerable amount of relevant and useful information that greatly aided the ability of a larger group of scientists to reach consensus at the flow recommendations workshop. It took less than a year to progress from the orientation workshop to the conclusion of the flow recommendations workshop. Because all of the scientists other than the UGA research team contributed their time as part of their regular job duties, and because a considerable volume of relevant information already existed for the Savannah River, the total cost of completing steps 1–3 (see Figure 1) was approximately US$75 000.

In sum, implementing our process in the Savannah River basin enabled scientists to generate initial flow recommendations in a short time frame that aligned well with the Corps' river basin planning process, at a cost that compares quite favourably with similar exercises conducted for rivers of this size and complexity. Similar levels of scientific knowledge and data exist for many rivers in the United States and other developed countries, suggesting that this process could work equally well in many other settings. In fact, we are now applying this same process to the Bill Williams River in Arizona, Caddo Lake in Texas, and Rivanna River in Virginia. While some additional field data collection will be required to apply this process to less-studied rivers in the developing world, many of the elements of our process—such as its engagement of inter-disciplinary scientists in a flow recommendations workshop—will be quite applicable.

As stated earlier, one of our primary goals in developing our five-step process was to enable adaptive management to get underway as soon as possible, thereby providing opportunity to learn by doing. The fact that the Corps of Engineers moved forward almost immediately in implementing important aspects of the flow recommendations suggests that we met this goal on the Savannah River. We concur strongly with Irwin and Freeman (2002) that it is important to initiate aspects of a flow restoration programme even when full implementation may not yet be possible or desirable. By identifying aspects of our flow recommendation that were least problematic for the Corps and other stakeholders, we were able to launch the adaptive management programme while the comprehensive river planning process further examines the potential for implementing the full prescription. We are already learning much from these early experiments.

Many of the scientists involved in the Savannah River application expressed a sense of accomplishment for having generated flow recommendations that were ready for trial implementation by the Corps. Perhaps more importantly, they expressed enthusiasm for having effectively launched an adaptive management programme for the river that will enable their recommendations to be continually improved in the future.

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