Improving Reservoir Management from an Ecological Perspective

By

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Abstract

A growing human population is looking to an aging reservoir infrastructure to implement solutions to current and future water resource challenges. Water managers are asked that reservoir operations provide additional and increasingly diverse benefits to society, including lower flood risk, increased quantity, quality, and reliability of water supply, more electricity through renewable hydropower, more resilience to a changing climate, more effective ecological stewardship, reduced environmental impact, and greater recreation opportunities. These and other interests share reservoir reoperation as a common solution often integrated with other management actions.

Two fundamental and complementary approaches exist to understanding the effects of changes in reservoir operation. Changes can be made and the resulting effects monitored in the field or changes can be explored proactively through computer modeling and decision support systems. Most computer models used in water resources management were developed to support traditional engineering tasks like floodplain delineation and reservoir simulations for flood routing, hydropower and water supply. Such engineering software has much potential as an approach for environmental applications.

This dissertation examines and develops information technologies that align with and expand on traditional engineering software to help with the creation (HEC-RPT; Regime Prescription Tool) and testing (HEC-EFM; Ecosystem Functions Model) of water and ecosystem management alternatives for reservoir management. The work also explores programmatic opportunities to improve the management of reservoirs for environmental purposes.

Acknowledgements

This dissertation is the culmination of three interrelated efforts. Many contributed to its success.

The national reservoir survey was supported by the Institute for Water Resources, U.S. Army Corps of Engineers. Without the backing and endorsement of Jerry Webb, leader of the Corps' Hydrology, Hydraulics and Coastal Community of Practice, and Bob Pietrowsky, Director of the Institute for Water Resources, this effort likely would never have started. And without the continued support and patience of Ted Hillyer and Jeannette Baker, Institute for Water Resources, it likely would never have been completed. Along the way, Corps staff from 33 offices contributed to the database, which was greatly improved by the diligent data processing efforts of 13 interns.

Development of the Regime Prescription Tool (HEC-RPT) was initially partnered by The Nature Conservancy, and the Portland District and Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers. Mary Karen Scullion, Brad Bird, and Bruce Duffe, Portland District, were instrumental in commencing this project. Since then, HEC-RPT has been supported through a model maintenance program sponsored by a cooperative of Corps District offices. The Nature Conservancy (www.nature.org) contributed to design and led several applications of HEC-RPT. Software coding was performed by Resource Management Associates, Inc. (www.rmanet.com). The McKenzie River Environmental Flows workshop was led by Leslie Bach, The Nature Conservancy, Karl Morgenstern, Eugene Water and Electric Board, and John Risley, U.S Geological Survey. Application of HEC-RPT was prepared and conducted by John Risley.

Development of the Ecosystem Functions Model (EFM) was done initially in support of the Sacramento and San Joaquin River Basins Comprehensive Study, which was an ambitious effort to improve the flood risk management system and ecological health of the Central Valley of California. Since then, HEC-EFM has been advanced through a series of research and development programs, including the Corps' SMART - System-wide Modeling, Assessment, and Restoration Technologies, SWWRP - System-Wide Water Resources Program, and EMRRP - Ecosystem Management and Restoration Research Program.

The splittail minnow spawning relationship was analyzed as part of the Comprehensive Study. At the time of that study, Mike Welsh of the Sacramento District of USACE, and Jerry Ripperda, Gary Lemon, and Hongbing Yin of the California Department of Water Resources led the technical application of EFM. Scott Stonestreet of the Sacramento District led the hydraulic modeling. Cottonwoods dynamics have been investigated using HEC-EFM at several rivers in the United States, but the Bill Williams River application has been the most thorough, spanning simulations and verification of model results with field observations. This application was made possible by the rich history of field study performed by a cooperative of governmental, nongovernmental, and academic organizations that support the stewardship of the Bill Williams River (www.billwilliamsriver.org). Patrick Shafroth of the USGS, Andrew Hautzinger of the U.S. Fish and Wildlife Service, and Joe Evelyn, formerly of the Los Angeles District were instrumental in this application of HEC-EFM. Van Crisostomo of Los Angeles District developed the first version of the hydraulic model, which was later advanced by Woodrow Fields of HEC.

Software coding for HEC-EFM was performed by David Ford Consulting Engineers (http://ford-consulting.com). Coding for HEC-EFM Plotter was performed by Resource Management Associates. Coding for HEC-GeoEFM was performed by ESRI (www.esri.com). Many of the figures in this dissertation were prepared by Woodrow Fields and David Julian, HEC. The HEC-RPT and all components of HEC-EFM are available online, free of cost (www.hec.usace.army.mil).

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CHAPTER 1

Water and Ecosystem Management

Reservoirs provide a physical capacity to store water and change the magnitude and timing of river flows to benefit a range of purposes, including reduction of damaging flood flows, hydropower generation, reservoir-based recreation, water supply, water quality, and ecosystem support.

Ecosystems are communities of organisms that interact with each other and their environment. Reservoirs influence ecosystems by altering the physical, chemical, and thermal characteristics of the environment in which organisms interact and by interrupting the connectivity of habitat and fluxes of sediment and nutrients. Management decisions at dams affect aquatic conditions for long stretches of river and connected wetlands. The fact that reservoirs affect ecosystems implies that reservoirs can be used as tools in the restoration and management of ecosystems.

Changing the operations of a reservoir for environmental or other purposes is a social and often political process. There are two fundamental and complementary approaches to understanding the effects of a change in reservoir operation. Changes can be implemented and the resulting effects monitored in the field, or changes can be explored virtually through computer models and decision support systems. Both modes (i.e., actual and virtual experimentation) encourage adaptive management, which is made easier and more effective with computer modeling as a foundation (Holling 1978).

Experiences with reservoir reoperations at different river sites are helping to refine a technical approach for testing operational changes from many different ecological perspectives. These experiences have fostered the development of specific tools that provide information to help managers better understand the implications of reservoir operation decisions. Section 1.1 below is largely extracted from Hickey 2007.

1.1 Developing a technical roadmap

Technical support for environmentally sustainable water management typically begins with establishing a solid hydrologic understanding of how the river has been altered (Hughes 2001). This requires the preparation and analysis of hydrologic data sets that compare river flows for regulated (with reservoirs and other alterations of the flow regime) and unregulated conditions. These data can be prepared through a variety of mass-balance (Hickey et al. 2002), stochastic generation (Salas 1980), or simulation (Anderson et al. 2002; Johnson et al. 2003) approaches. Choice of method depends on the availability and condition of gage data as well as the budget and preferences of the study team investigating the river. Once completed, these data serve as a foundation for additional technical efforts, including processes for defining ecosystem flow recommendations. They also relate to the six linked models noted in figure 1.

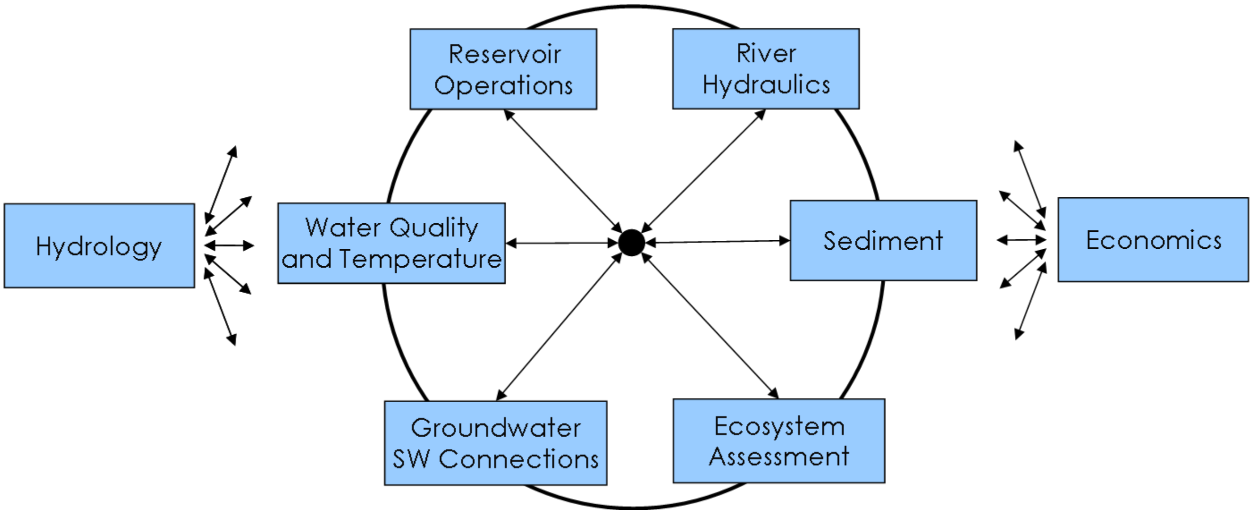


Figure 1. Connections between different types of models for ecological considerations in water management (as in Hickey 2007).

Generally, of the six linked models in the center of figure 1, reservoir operations, river hydraulics, and ecosystem assessment are at the core of technical support for ecological considerations in water management.

Reservoir operations models simulate the storage and release of waters in systems of reservoirs. These models are typically either rule-based simulation or goal-based optimization models, or a combination of the two (Rani and Moreira 2010). Simulated water releases in rule-based models are guided by rules specified by the modeler (e.g., a minimum flow rule might say “avoid releases less than 10-cfs”). Rules are created, prioritized, and modified to make simulated releases agree with how the reservoirs are actually operated. When the model is producing reasonable results, rule sets can be changed to test different management approaches (start with current operations and change from there). Optimization models take a different approach – they make decisions that optimize the net benefits of the water, subject to user defined constraints (Lund and Ferreira 1996; Labadie 1997). This is a nice complement to rule-based approaches because it encourages study teams to consider a different perspective about operations (start at an optimized operation and change from there).

River hydraulics models use channel topographies to translate flow rates to river depths, velocities, inundated areas, and a host of other output. Models are described by the number of dimensions (Horritt and Bates 2002) in which water velocities are computed (1-d means that velocities are computed in line with the river channel at any given cross section, the second dimension adds a velocity component from bank to bank, and the third adds a vertical velocity within the water column) and by whether the model performs steady (flow values are simulated independently) or unsteady state (time series of flow are simulated) calculations. River hydraulics models also may offer algorithms for computing stream temperatures (Jensen and Lowney 2004) and sediment transport (USACE 2010b). Hydraulic modeling is a critical aspect in understanding the physical connections between land and water (Hardy 1998), which enables a more detailed look at ecosystem dynamics.

Ecosystem assessment techniques and the software that support them run the gamut from simple regression equations that compute biomass based on variables like river flow and reservoir storage to complex models that simulate things like forest (Botkin 1993; Pacala et al. 1996; Busing and Mailly 2004; Scheller et al. 2007) or fish population dynamics (Bartholow et al. 2002). Three of the main categorical purposes of these tools are statistical assessments, habitat assessments, or population assessments (statistical and habitat assessments are discussed further in Chapter 3). As part of the progression of models, output from reservoir operations and river hydraulics models feed into the ecosystem assessment, which estimates how those changes affect different aspects of the ecosystem. Statistical and spatial results are generated to estimate the direction and magnitude of ecosystem changes.

By fostering dialogue between water managers and biologists about how to make water management more environmentally sustainable, efforts that examine reoperation of reservoirs to improve ecological condition are aided by methods and tools used in technical support of ecological considerations in water management. There is a growing awareness of the influence of water management activities on ecosystems. As awareness leads to improved scientific understanding (and vice versa), more strategies linking water and ecosystem management will be identified, which will in turn become new analytical challenges for software tools.

1.2 Setting a new course

This dissertation explores tools and ideas that have potential to improve the management of reservoirs from an ecological perspective. Current environmental operations for a collection of nationally significant reservoirs are reviewed. Two emerging, free, and publicly available software tools are introduced and their applications are illustrated via case studies. And finally, ideas for improving environmental operations at reservoirs are presented. These topics are organized in four additional chapters.

Chapter 2 details the national inventory of reservoirs with federal flood management responsibilities to be considered and the effort undertaken to compile a database that describes them. This chapter is not an exhaustive analysis of the database. Instead, select attributes are summarized to help 1) characterize the overall group (storage capacity, ownership, authorized purposes, and operational policies) and 2) define current environmental operating strategies and their potential for change (minimum flows, outflow release decisions, and past changes to operational policies).

Chapter 3 introduces the Regime Prescription Tool (HEC-RPT), a software to help groups of scientists, engineers, and water managers access hydrologic data and draft flow recommendations while they formulate different ways to manage rivers. It is a communications and discussion tool and contributes in the early stages of planning by formalizing ideas and expert knowledge into a structure easily visualized and considered in more detailed analytical tools. An RPT application used to help define environmental flows for the McKenzie River, Oregon, USA, is presented.

Chapter 4 introduces the Ecosystem Functions Model (HEC-EFM), which is designed to help study teams determine ecosystem responses to changes in the flow regime of a river or connected wetland. HEC-EFM analyses involve: 1) statistical analyses of relationships between hydrology and ecology, 2) hydraulic modeling, and 3) use of Geographic Information Systems (GIS) to display results and other relevant spatial data. Through this process, study teams can visualize and define existing ecologic conditions, highlight promising restoration sites, and assess and rank alternatives according to predicted changes in different aspects of the ecosystem. This chapter focuses on use of HEC-EFM for statistical analyses and habitat mapping. Two examples are provided: Provision of spawning habitat for the Sacramento splittail minnow, San Joaquin River, California, USA, and establishment of cottonwood seedlings, Bill Williams River, Arizona, USA.

Chapter 5 presents a series of ideas for improving reservoir operations from an environmental perspective that range from improving the information resources of water managers to creation of an environmental operating storage zone within reservoirs. Conclusions are drawn regarding the efficacy of the ideas in improving water and ecosystem management at reservoirs and the potential use of the previously introduced software to help formulate (HEC-RPT) and quantify the ecological benefits (HEC-EFM) of water and ecosystem management alternatives.

Chapter 6 concludes this dissertation with a brief summary of the national reservoir survey, review of ideas for improving reservoir operations from an environmental perspective, and the use and potential of HEC-RPT and HEC-EFM in water and ecosystem management.

CHAPTER 2

Federal Flood Management Reservoirs

Many years ago after a meeting about environmental operating strategies for a system of reservoirs, one of the attendees asked casually and rhetorically “why is this so complicated?” That question, which was a bit longer with its expletives, aptly summarized the mood of the moment. It also implies that an awareness of the factors that make managing water with reservoirs complicated is important for any effort seeking to affect it.

Surface water reservoirs, despite all being fundamentally comprised of an area to hold water and a structure to impound it, are amazingly diverse. In the United States, the most comprehensive database of reservoir information is less about the water and more about the structures. This National Inventory of Dams (NID) contains information for 84,134 structures that impound surface water in the United States, Puerto Rico, and the U.S. Virgin Islands (USACE 2011c).

Roughly 8,100 of these dams exceed 50 feet in height, impound a normal storage of 5,000 or more acre-feet (AF) of water, or have a maximum capacity of at least 25,000 AF. At 770’, Oroville Dam on the Feather River in California is the tallest listed. At more than 30 MAF, Hoover Dam on the Colorado River can store the most water, excluding Soo Compensating Works, a low head structure between Lakes Superior and Huron with a reported max storage of over 277 MAF. Most dams in the NID are small; the cumulative volume of the smallest 70,000 dams would only fill 40% of Hoover.

Operational purposes in NID are described succinctly. Oroville’s purposes, for instance, are simply noted as “CISHR”, which is short for flood control, irrigation, water supply, hydroelectric, and recreation. Purposes for Hoover, or more specifically for the biggest Hoover - there are 38 instances of “Hoover” in NID dam names, is recorded as “SHI”, even though it has a rarely exercised flood control purpose. All told, there are 103,317 purposes listed for the 80,735 dams that reported at least one of the 12 purposes tracked in the database. Recreation is a cited purpose for 43% of reporting dams, followed by flood control (20%), fire protection, stock, or small fish pond (20%), irrigation (12%), water supply (12%), other (8.9%), fish and wildlife pond (6.0%), hydroelectric (3.3%; 2,678 mentions), debris control (1.3%), tailings (1.2%), grade stabilization (0.8%), and navigation (0.5%). Just over 20% were multi-purpose, with as many as 8 purposes listed for a single structure.

Ownership is diffuse. A basic review (no screening for aliases) of NID data shows 48,502 owners for 79,633 dams, excluding the 4501 dams where ownership was unknown or not reported. Certainly the number of owners is inflated by typographical inconsistencies and inclusion of aliases for individual owners. The Corps, for example, which by almost any measure (e.g., number of reservoirs, storage, geographic distribution) is the largest water management organization in the United States, had 55 aliases. Most labeled the different Corps offices that manage reservoirs. While this might seem to make ownership slightly more uniform, it is actually symptomatic of another factor that complicates water management. For organizations that own and operate numerous reservoirs, management of different reservoir systems are typically divided organizationally such that the methods and technologies, even the terminology, used by water managers differ regionally to the extent that it is difficult to characterize water management at a corporate level.

This challenge becomes acute when working with operational databases. The NID is available online, but, apart from purpose, offers little detail on how the dams are operated without particulars on water management. Most operational data that describe reservoir management (e.g., inflows, outflows, storages, pool elevations, and other time series) are maintained in local databases, with little aggregated reporting. Some local data are available online, though inconsistently so and lacking standardization of units, data types, and quality assurance. These characteristics make it exceedingly difficult to quantitatively inform basic questions about collections of reservoirs, including: How is storage allocated among different operating purposes? How much water is managed? When water is released, what purpose or purposes does it serve? What environmental strategies are considered when release decisions are made? What policies guide operations? Are these subjects changing with time, and, if so, what drives that evolution?

2.1 National Database

In 2008, a national reservoir survey was initiated to: 1) compile a database to examine the status of water management from local, regional, and national perspectives; 2) provide an engineering and scientific foundation for a national adaptive management program; and 3) assemble baseline data for investigating the evolution of operational policies.

The survey consisted of three parts: water supply, water management, and sediment management. The water management portion asked a series of reservoir-specific questions designed to define status for many facets of the Corps' water management function. It was formulated at HEC in 2005, but unfunded until 2008. At that time, a separate effort called the National Portfolio Assessment for Reallocations (Portfolio Assessment) was initiated at the Corps' Institute for Water Resources through the Corps' Water Supply Business Line. The Portfolio Assessment focused on the potential for Corps reservoir storage to be reallocated to enhance water supply. Both intended to formally request reservoir data from all relevant Corps offices and so the efforts were combined into a single national data request. Shortly before the data request was officially distributed, a third portion regarding sediment concerns at reservoirs was added on behalf of the Corps Subcommittee on Sedimentation, a group of technical experts that provides guidance regarding sedimentation considerations for Corps studies and operations. Table 1 lists topics queried by each portion of the survey.

An initial list of reservoirs to be queried was proposed by the water supply portion of the survey. It mainly included reservoirs with a flood risk management purpose because, historically, most reallocations have shifted storage from the flood pool to another purpose. All 383 of the listed reservoirs were owned and operated by the Corps, who has no reason or authority to investigate reallocations at non-Corps reservoirs unless instructed to do so by Congress or requested to do so by other owners through planning assistance programs. This initial list was used by the water supply and sediment management portions.

Table 1. Portions and queries of the national reservoir survey. Data were collected for each topic for individual reservoirs.

Water Supply (n=383)	Water Management* (n=465)	Sediment Management (n=383)
Reservoir name	Reservoir name*	Reservoir name
Managing office	Managing office*	Managing office
Year of completion	Year of completion*	Basin hydrology (e.g., arid)
Drainage area (total)	Drainage areas (local and total)	Sediment contributing land use
Storage allocations	Storage allocations*	Percent storage infilled
Authorized purposes	Authorized purposes*	Impacts to authorized purposes
Operating purposes	Ownership*	Sediment management practices
Location (lat-long)	Minimum flow requirements*	Obstacles to sediment management
Watershed	Maximum power release*	Historical sediment surveys
River	Max release at min top of con	
Congressional district	Objective flow locations	
Dam Safety Classification	Objective flow levels	
Project Yield	Max non-damaging flows	
Reallocation Possibilities	Exceedances of objective levels	
	Fish passage presence	
	Fish passage effectiveness	
	Water temp management*	
	Infrastructure condition	
	Dam safety restrictions	
	Start/end electronic database	
	Start/end data in any format	
	Water control manuals*	
	Operational changes*	
	Motivation for changes*	
	Testing of alternative operations	
	Motivation for testing	
	Time series data (daily)*:	
	Inflows, outflows, storage, and top of conservation storage	

*Indicates survey material used in this dissertation.

The water management portion focused on these projects (excluding 27 that did not have a flood risk management purpose) and also non-Corps reservoirs that contain federally authorized flood space, which added 109 more for a total of 465 reservoirs in the database. This inclusion addressed a key component of the Corps' reservoir operation responsibilities for flood risk management and clearly defined the type of reservoir to be surveyed. Specifically, the water management portion set out to query all reservoirs in the United States with federally authorized flood storage.

The rest of this chapter, as well reservoir-oriented content in chapters 5 and 6, are based on reservoirs, data, and analyses associated with the water management portion of the survey.

2.1.1 Quality Assurance

Organizationally, the U.S. Army Corps of Engineers includes a headquarters, divisions, districts, and an assortment of laboratories and centers of expertise. Divisions and districts have specific geographical areas. Oroville and Hoover, for instance, are both within the boundaries of South Pacific Division. Oroville is within the Sacramento District, which encompasses the Central Valley of California, most of Nevada and Utah, and parts of Idaho, Wyoming, Colorado, and Arizona. Hoover is within Los Angeles District, which includes southern California, most of Arizona and the rest of Nevada.

The United States is split into 8 divisions, all of which have water management responsibilities, and 38 districts (figure 2), 32 of which manage reservoirs with federally authorized flood space. Geographically, the Northwestern Division (NWD) is one of the largest. Its water management staff are split into two primary groups, Columbia River Water Management in Portland, OR, and Missouri River Reservoir Control in Omaha, NE. These are the only division offices that directly manage reservoirs. Others provide oversight of reservoirs managed at the district level and coordination of system operations. The Northwestern Division office in Portland (NWD-CR) also oversees the reservoir operations of Portland, Seattle, and Walla Walla Districts; the division office in Omaha (NWD-MR) oversees Kansas City and Omaha Districts.

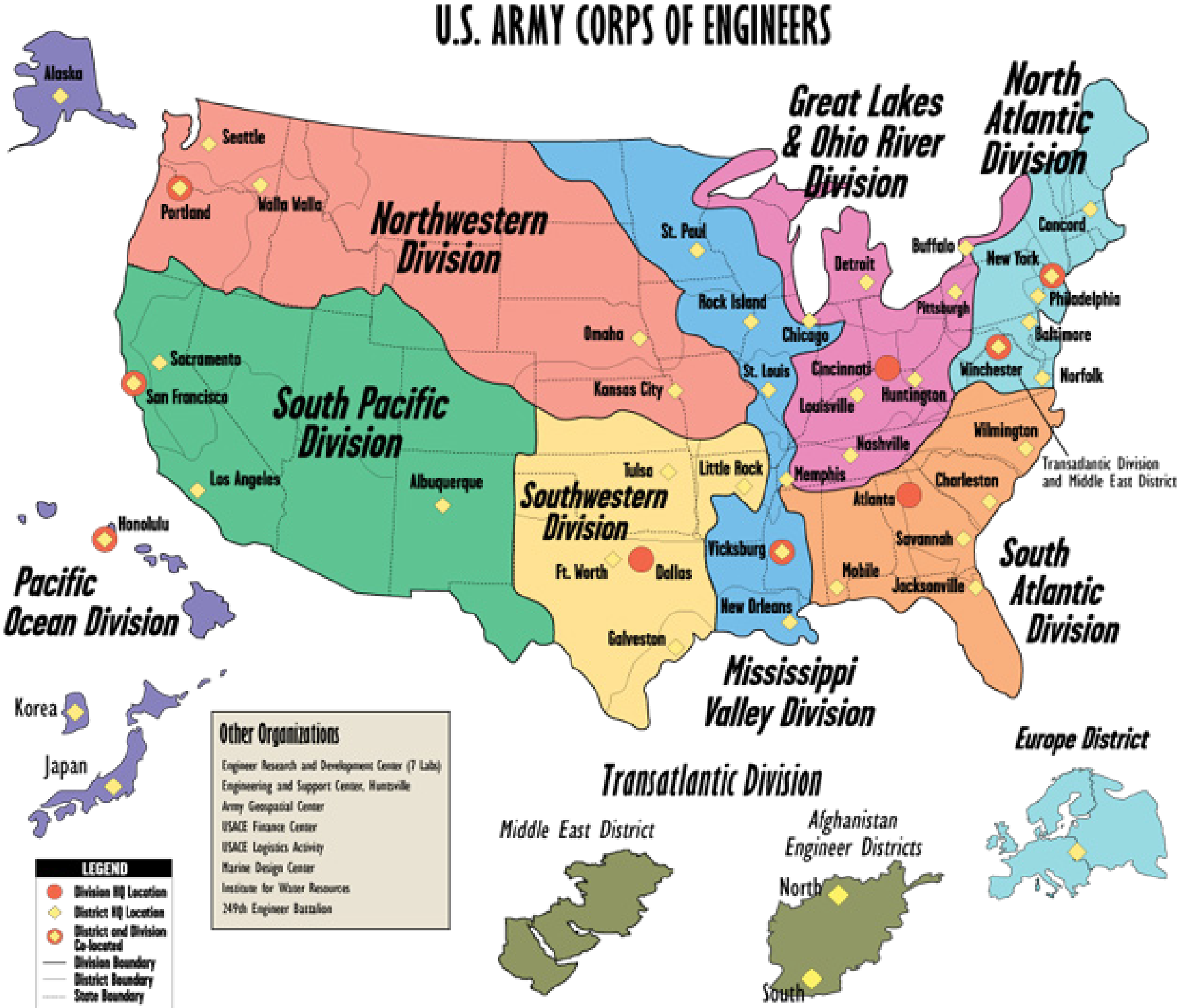


Figure 2. Divisions and districts of the U.S. Army Corps of Engineers (www.usace.army.mil/Locations.aspx).

Six Districts in the Great Lakes and Ohio River Division (LRD) operate flood management reservoirs: Buffalo, Detroit, Huntington, Louisville, Nashville, and Pittsburgh. Mississippi Valley Division (MVD), North Atlantic Division (NAD), South Atlantic Division (SAD), South Pacific Division (SPD), and Southwestern Division (SWD) each oversee the operations of four Districts. Pacific Ocean Division (POD) oversees one, Alaska District.

The correspondence announcing the survey was distributed primarily to divisions, who in turn notified their associated districts that had a water management function. All told, 41 Corps offices (2 Northwest Division offices, 7 other divisions, and 32 districts) had responsibilities relevant for the survey. 33 of these offices (2 Northwest Division Offices and 31 Districts) maintain local databases. San Francisco was the odd district. Its operational data are archived by Sacramento District, which with 45 reservoirs (not including the 3 in San Francisco District), has operational responsibilities for the most surveyed reservoirs of any office. Buffalo, Detroit, Norfolk, Jacksonville, and Alaska Districts each reported only one flood management reservoir.

Initially, the challenge believed to be facing the survey was to obtain responses from 41 and operational time series from 33 offices and compile this mass of data into formats that would facilitate analyses of reservoir management activities. In support of this effort, a website was created that allowed water managers to input, review, and edit their responses and arranged informational data into a spreadsheet format. Also, a common reference entitled “definition of terms” was written, appended to the survey announcement, and provided via the website to encourage consistency in responses. However, as early responses were received, it became clear that most effort would be spent working to assure that data submitted were of sufficient quality for anticipated analyses.

Review of informational responses. Data for most informational queries were readily available and simply required screening for missing or suspect responses. A few queries, such as those related to objective flow exceedances (i.e., instances where operational and hydrologic conditions led to high flows that exceeded target flows at locations, often cities or towns, located below the dam), water control manuals, and testing of alternatives, were more involved. However, the process for compiling data remained the same: Coordinate with responding offices, review submissions, and revisit with responders until all data were deemed complete and of sufficient quality and detail to be used in analyses without reservation. This cycle was repeated as many as 8 times per office. When all coordination and review were completed, the informational database included 465 reservoirs.

Review of operational data. Time series of reservoirs inflow, outflow, minimum flow requirements, storage, and target storage were also collected on behalf of the survey. Only electronic data, preferable daily values, were requested. Data were submitted in formats ranging from text files to custom database applications. The quality of data varied widely. Some were nearly complete for all data types with excellent data quality. Others had poor data for a smaller fraction of historical operations. Time series of target storage, which is also known as top of conservation storage, and minimum flow requirements were largely unavailable and had to be reconstructed based on informational responses and operational knowledge and guidance.

Raw data were reviewed for errors and missing values. Wherever possible errors were corrected and data gaps filled using a daily mass balance approach based on storage, inflow, and outflow:

$$Inflow_t = Outflow_t + (Storage_t - Storage_{t-1}) * 0.50417\left(\frac{cfs}{AF}\right)$$

Short data gaps of less than or equal to 5-days were filled with linear interpolation. Longer data gaps were filled with linear interpolation when hydrologic conditions were sufficiently consistent per the judgment of the data processor. Occasionally poor data that were not fixable through these screening methods were removed. Units were converted to cubic feet per second (cfs) for flow time series and acre-feet (AF) for storage time series as needed. Data from real-time operational databases, where values were relayed from gage equipment to databases, used to inform release decisions, and archived with no or limited review, required the most processing.

After screening, the resulting database contained 37.3 million daily values. When considered from the beginning of project operations, these data represent 81% of the operational history of surveyed reservoirs (figure 3).

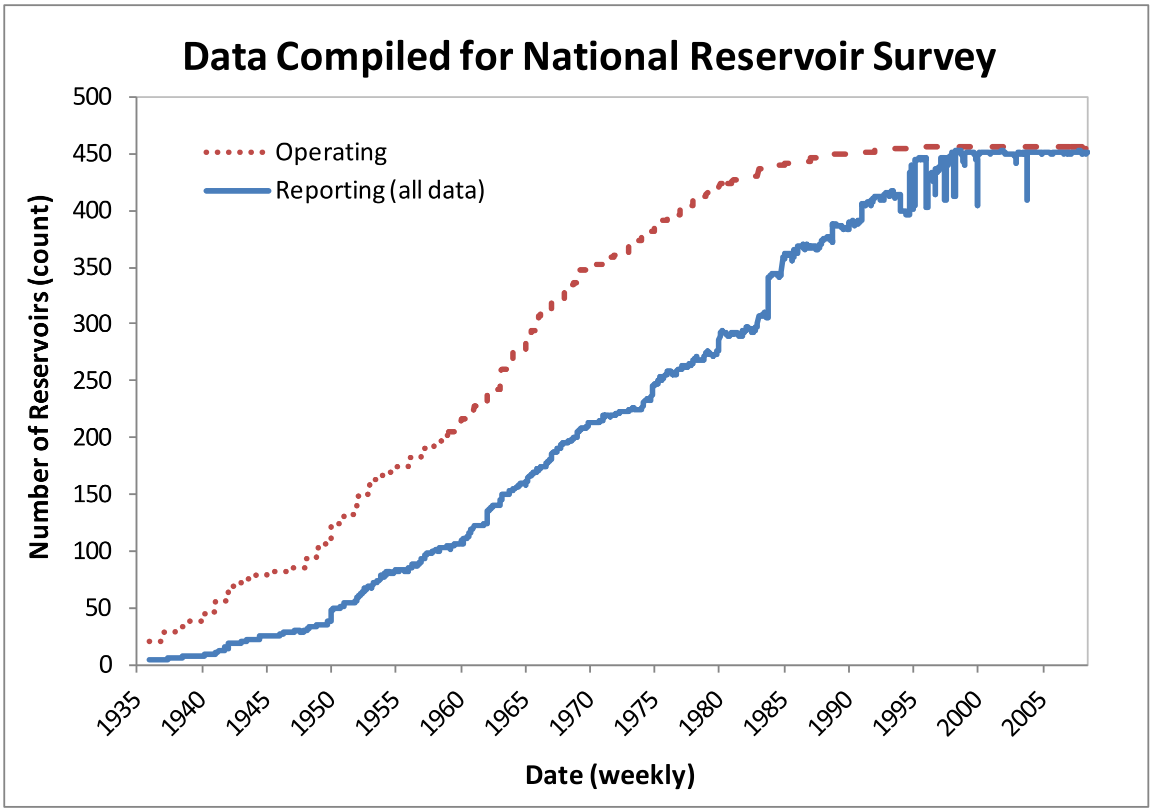


Figure 3. Time series data compiled via the national reservoir survey.

By the early 1990's, all local databases had transitioned to electronic formats. Nearly all missing data occurred between the beginning of reservoir operation and the beginning of available electronic data. Since then and apart from the occasional and typically short gap, data have been consistently available. Only 0.5% of data were missing after data were initially reported for a project. Of the 465 reservoirs surveyed, 457 had time series data (table 2).

Table 2. Summary of reservoirs and data in the operational database. Database statistics are based on inflow, outflow, storage, and top of conservation time series.

Category Region	**Reservoirs in database**	**Mean equivalent years of record**	**Percent missing w/in data record**	**Percent operational history**
All	457	40.1	0.5%	81.4%
LRD	78	46.2	0.2%	89.7%
MVD	32	49.7	0.5%	88.6%
NAD	54	35.2	0.6%	73.1%
SAD	14	41.6	0.0%	99.5%
SPD	83	41.1	0.3%	84.1%
SWD	83	30.6	1.4%	65.8%
NWD-MR	67	42.3	0.0%	89.4%
NWD-CR	46	40.9	0.8%	76.7%

2.1.2 Structure for Analyses

Even with the constant theme of federally authorized flood storage, surveyed reservoirs varied so widely in character that most analyses were more meaningful when performed for classifications and regional groupings of reservoirs. Three simple classifications were used: “Big river”, “dry dam”, and “general” reservoirs. Big river reservoirs are mainstem projects on the Colorado (Hoover Dam), Columbia (Grand Coulee and John Day Lock and Dam - Lake Umatilla), and Missouri (Fort Peck Dam and Lake, Garrison Dam - Lake Sakakawea, Oahe Dam - Lake Oahe, Big Bend Dam - Lake Sharpe, Fort Randall Dam - Lake Francis Case, and Gavins Point Dam - Lewis and Clark Lake) Rivers. Though only 9 in number, the large amount of water and drainage area regulated separate these reservoirs from the others.

Dry dams are typically smaller and more single-purpose than other surveyed reservoirs. Most were solely constructed for flood risk management and many release water passively, storing water only when inflows exceed the physical capacity of always open outlets. Reservoirs were included in the dry dam category if 1) their impoundments are dry (zero storage) under normal conditions or 2) specifically noted as dry dams in survey responses. Fifty-one reservoirs, nearly 11% of all surveyed reservoirs, were identified as dry dams.

The remaining 405 reservoirs comprised the “general” category. These reservoirs were split into regional groups based on Corps Divisions and then also separated into Corps and non-Corps ownership (table 3).

Three reservoirs, Tioga-Hammond in Baltimore District, Two Rivers Dam in Albuquerque District, and Whittier Narrows Dam in Los Angeles District, were unusual in that each regulated two streams, had separate dams capable of releasing water to those streams, and had impoundments that merged into a single water body at high water levels. These reservoirs were represented by a single entry in the informational database and two entries in time series analyses. Two Rivers and Whittier Narrows were dry dams.

Table 3. Classifications and associated characteristics of reservoirs in the informational database.

	Number of Reservoirs			Mean (per reservoir)		
Category Region	All	Corps Owned	Non-Corps Owned	Total D.A. (sq. mi.)	Total Storage (AF)	Max Normal Storage (AF)
All	465	356	109	5,964	776,031	514,010
Big river	9	7	2	193,613	12,457,258	11,336,373
SPD	1	0	1	167,740	27,377,000	25,877,000
NWD-MR	6	6	0	212,447	12,184,500	11,406,833
NWD-CR	2	1	1	150,050	5,815,661	3,854,678
Dry dam	51	44	7	*314	*78,966	*4
LRD	6	6	0	613	181,539	0
MVD	2	2	0	16	9,640	0
NAD	9	9	0	73	25,309	0
POD	1	1	0	1,496	200,000	0
SPD	26	23	3	*363	*75,391	*8
SWD	2	2	0	133	204,900	0
NWD-MR	4	0	4	19	2,787	3
NWD-CR	1	1	0	400	106,275	0
General	405	305	100	2,381	598,654	338,240
LRD	73	73	0	857	372,374	185,522
MVD	32	32	0	1,894	746,196	290,400
NAD	44	42	2	188	74,613	22,939
SAD	14	13	1	2,027	1,394,426	829,356
SPD	56	18	38	2,105	614,403	485,030
SWD	82	68	14	4,962	931,082	430,839
NWD-MR	61	39	22	2,371	504,646	446,858
NWD-CR	43	20	23	3,141	629,059	274,002

*Excludes Painted Rock, which is a dry dam in Los Angeles District, SPD, with a drainage area of 50,800 sq. mi., total storage capacity of 2.3 MAF, and max normal storage of 0 AF.

To summarize, 465 reservoirs were surveyed, which to the knowledge of the author represents every reservoir in the United States with federally authorized flood storage. The informational database describes all 465, comprised of 9 big river, 51 dry dam, and 405 general reservoirs. The time series database describes 457 (the 465 total, minus 11 that did not have data, plus 3 split dual reservoirs), comprised of 9 big river, 44 dry dams (lost 9 with no data and gained 2 splits), and 404 general reservoirs (lost 2 with no data and gained 1 split).

2.2 Understanding the Reservoirs

Based on number of reservoirs, comparison of the NID and the survey show that surveyed reservoirs comprise a small fraction (less than 1%) of all surface water reservoirs in the United States, but include increasing percentages of larger reservoirs - 29% of the nation's reservoirs greater than 50 TAF, 43% of those greater than 200 TAF, 52% of those greater than 500TAF, and 61% of those greater than 1MAF.

Before comparing storage volumes, the NID database needed to be screened for duplicate reservoirs because NID data describes dams and multiple dams often impound a single reservoir. For example, Folsom, a reservoir with flood storage in SPD near Sacramento, has 11 NID entries (Folsom, Folsom - Mormon Island Auxiliary Dam, Folsom Dikes 1-8, and Folsom Left Wing) each with a storage of 1.12 MAF, which is the total capacity of the reservoir. The following screenings were performed: 1) for projects greater than or equal to 10 TAF, entries with adjacent and duplicate storages were reviewed and deleted if storage was redundant – this removed 484 entries and 328 MAF of storage, 2) projects with duplicate database identifiers (NIDID values) were deleted if storage was redundant – this removed 283 entries and 11 MAF of storage and was only useful in 25 of 50 states, the other states had unique NIDID values for each entry, 3) for projects greater than or equal to 200 TAF, entries were reviewed manually and deleted if storage was redundant – this removed 20 entries and 40 MAF of storage, and 4) removal of redundant and suspect storage found when joining the NID and survey databases – this removed 4 entries and 288 MAF of storage, including Soo Compensating Works and its 277 MAF of storage.

The resulting combined storage of all of facilities in NID, after screening and based on "NID_STORAGE" values in the NID database, totaled to 793 MAF (n=83,343). Surveyed reservoirs (n=465) have a combined storage of 403 MAF (also based on NID_STORAGE). Surveyed reservoirs therefore have 51% of the nation's surface water reservoir storage capacity (figure 4). If the same comparison is done using normal reservoir storage (based on "NORMAL STORAGE" in the NID database), surveyed reservoirs comprise 46% of the nation's surface water reservoir storage capacity.

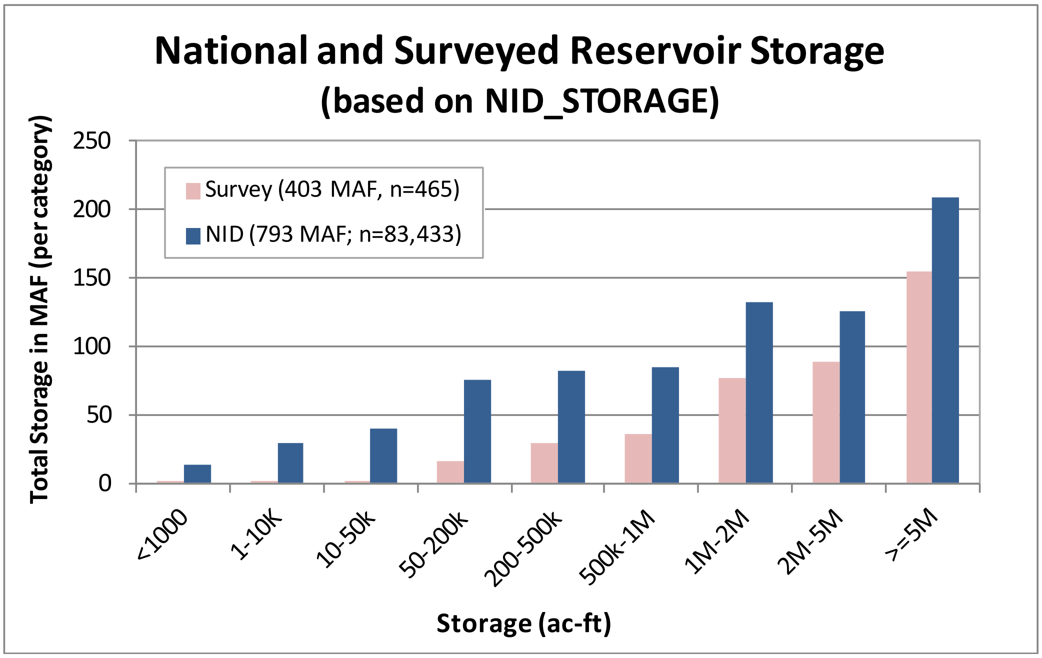


Figure 4. Comparison of surveyed reservoirs and the National Inventory of Dams, by storage volume, post-screening for redundant storage (USACE 2011c).

The U.S. Army Corps of Engineers (Corps) is the primary federal agency responsible for flood risk management. It is also the principal owner and operator of reservoirs with federally authorized flood storage. There are reservoirs owned and operated by entities other than the Corps that have federally authorized flood space. These reservoirs are often referred to as "Section 7" projects in reference to the section of the Flood Control Act of 1944 which authorized the Corps to prescribe regulations for use of this flood storage (Public Law 534, December 22, 1944, 78th Congress, 2nd Session; Hickey et al. 2003). Of the 465 surveyed reservoirs, 356 were owned and operated by the Corps and 109 were Section 7 projects, of which 78 were owned in full or in part by the U.S. Bureau of Reclamation, and 31 were owned by a variety of other federal agencies, states, county, municipalities, and utility and irrigation districts (figure 5).

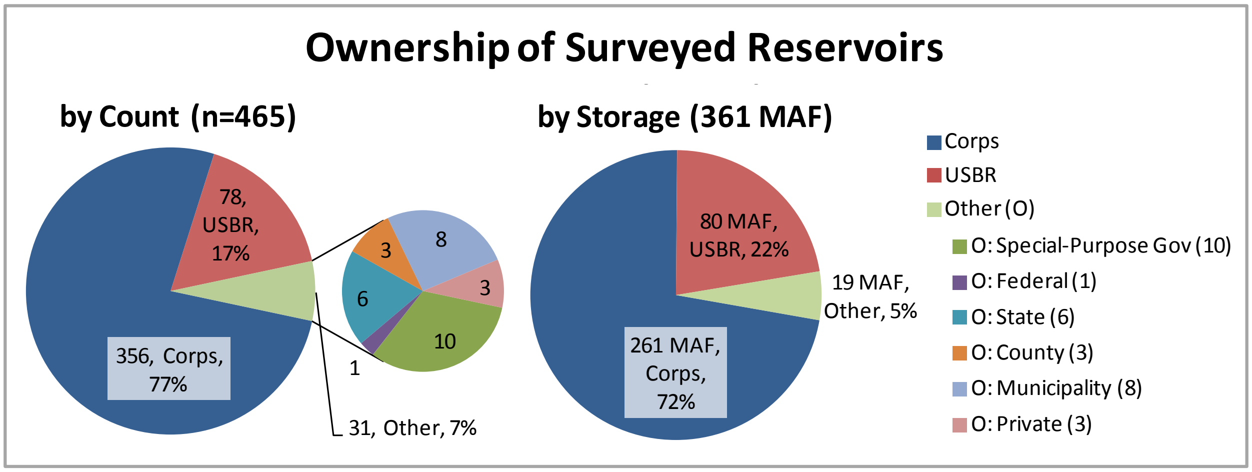
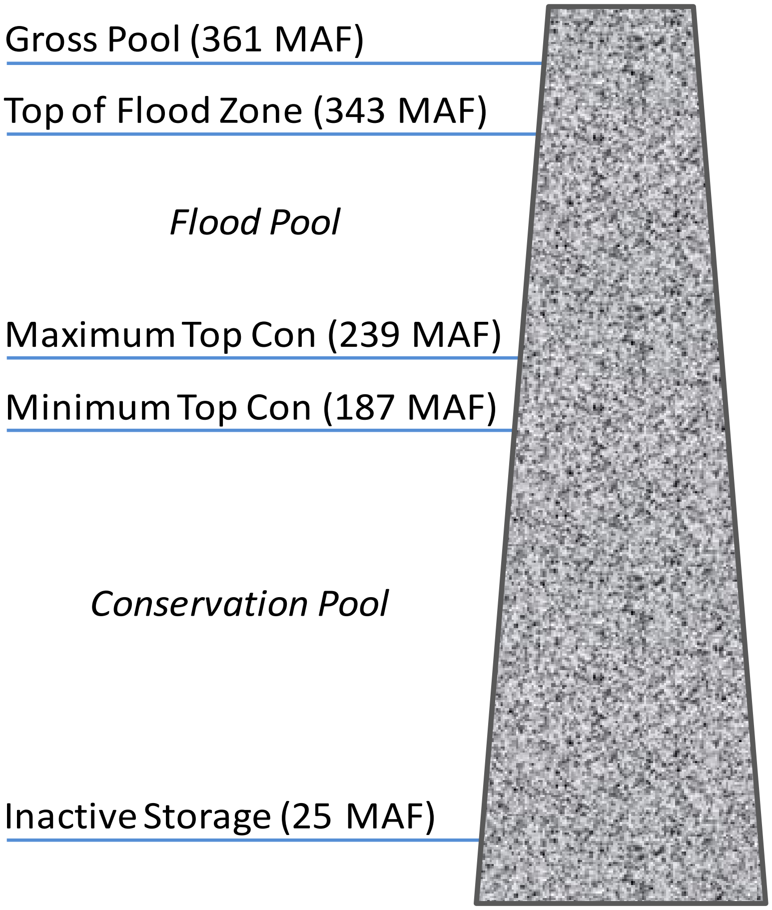


Figure 5. Ownership of reservoirs with federally authorized flood storage based on count and total (gross pool) storage.



Designation of flood storage is one mechanism that creates zones in reservoirs (figure 6). Flood storage is held as vacant as possible to attenuate potentially damaging high flows. Conservation storage is reserved for a variety of purposes including waters for irrigation, environment, municipal and industrial use, hydropower, and recreation. Inactive storage is water that is, physically, too low to be released through reservoir outlets. The boundary between conservation and flood zones is called the "top of conservation" and can fluctuate seasonally, as a function of the prevailing hydrologic conditions, and as a function of storage in other system reservoirs. Rules that guide reservoir outflows differ between zones (USACE 1982).

Figure 6. Combined storage allocations of surveyed reservoirs.

Reservoirs are operated for different purposes. Purposes for reservoirs with federal government involvement are specified by laws regulating each project's authorization and construction, project specific laws passed after the project was constructed, and laws that apply generally to all reservoirs with a federal interest (USACE 1992), such as the Clean Water Act (Public Law 92-500) or the Endangered Species Act (Public Law 93-205).

The complexity of operational decision-making is generally proportional to the number of authorized purposes. Balancing multiple purposes is a fundamental challenge for water managers and becomes increasingly difficult in times of water scarcity. As federally authorized flood storage was a prerequisite for inclusion, all surveyed reservoirs had flood risk management as an authorized project. Ten percent of these (n=46) were single purpose; 10% of surveyed reservoirs had flood risk management as the sole project purpose (figure 7). Multi-purpose reservoirs had a mean average of 4.0 purposes per project. Recreation was the second most common purpose (figure 7).

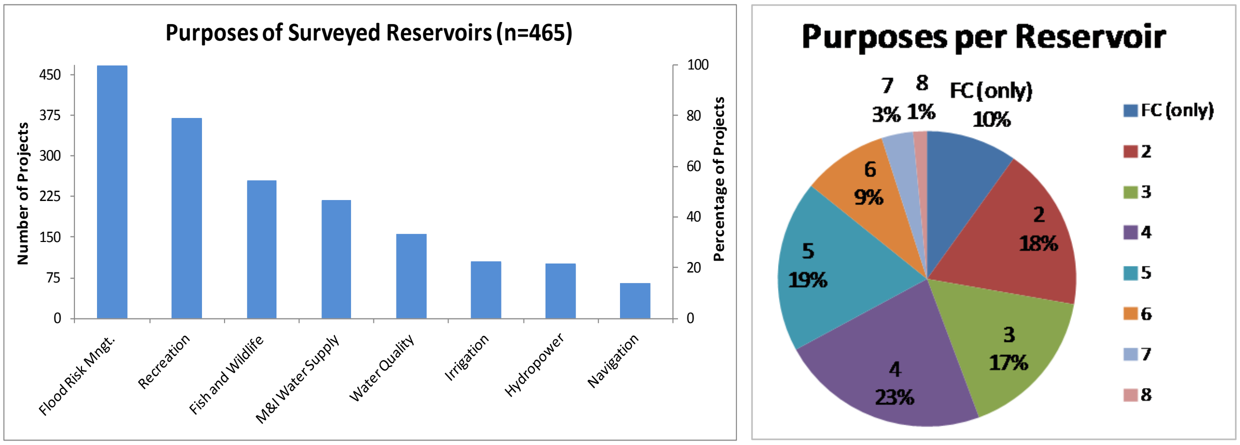


Figure 7. Purposes and purposes per project for reservoirs with federally authorized flood storage.

Operational guidance for reservoirs with flood storage is specified in documents called water control manuals. Publication of initial manuals typically lagged completion of the dam by several years. In the intervening period, water managers relied on a variety of initial guidance (Field Working Agreements, Preliminary or Draft Water Control Manuals, Interim Plans for Regulation of Storage, Design Operating Criteria, etc.) as operational references. Once issued, manuals are updated periodically as operations are adjusted for changing demands or watershed and hydrologic conditions.

The survey compiled information on the evolution of operational guidance. Specifically, operational changes for each edition of a reservoir's water control manual, as well as the purpose or purposes motivating each change, were requested. Changes were then categorized as minor or significant and associated with operational purposes.

Historically, most operational changes from initial guidance to water control manuals and then between subsequent manual editions were motivated by opportunities to improve flood risk management (41%). Water supply enhancements, for irrigation or municipal and industrial purposes, was the next most common motivation (19%) followed by operational changes for water quality and fish and wildlife management (14%; figure 8). The distribution of changes has changed over time, with environmental (water quality and fish and wildlife management) purposes becoming more common.

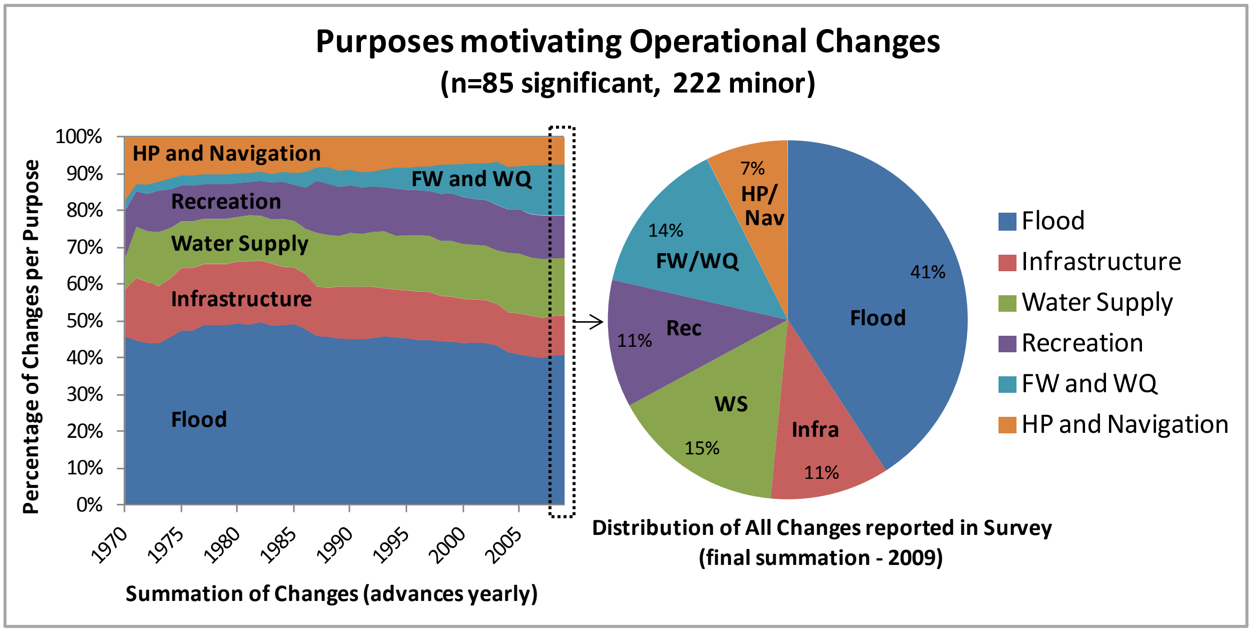


Figure 8. Purposes motivating operational changes for surveyed reservoirs.

2.3 Current Operations

Water release decisions from reservoirs are done according to operational guidance and purposes. Using storage allocations, storage time series, minimum flow requirements, and operational bands for hydropower generation, time series of reservoir outflows can be separated into purpose and plotted as a display that also shows outflows as a function of pool zone. The outflow separation process assumed outflows were used to meet minimum flow requirements ("environmental" category), generate "hydropower" (if released through turbines), and were otherwise ambiguous and categorized as "other". Outflows released to meet minimum flow requirements and to generate hydropower were categorized as "enviro and hydro".

Survey information allowed outflows to be separated only for environmental, hydropower, and "other" categories. For example, no information was collected about water supply deliveries or provision of water for navigation. Many releases overlap in purpose or are determined by others downstream. This limited the granularity of separation. Realistically, most reservoir outflows serve multiple purposes, which are not fully accounted for herein. Also, a comparison of reservoir inflows and outflows for all reservoirs showed that total outflow equaled 95% of total inflow, 1989-2008. The reasons for the difference are unknown though evaporation, seepage, and diversions from the pool or dam could all contribute to the gap.

Storage status was used to track where in the pool releases were made. Storage status was computed based on two main operational modes, flood and conservation, which are split at the top of conservation storage (ToC). Each reservoir was considered independently. Categorized outflows were aggregated in 10% intervals within the flood and conservation zones. The process for computing pool status used the following logic and equations:

If: $S_t >= ToC_t$; else $S_t < ToC_t$

$$Status = \left(\frac{S_t - ToC_t}{S_{\max} - ToC_t} \right); \qquad Status = \left(\frac{ToC_t - S_t}{ToC_t - S_{\min}} \right)$$

where S_{max} is the highest of the maximum historical storage, maximum historical top of conservation storage, or gross pool storage and S_{min} is the lowest of the minimum historical storage, minimum historical top of conservation storage, or inactive pool storage.

Figure 9 details the outflow separation process and use of storage status. The resulting displays show from which storage zone, reservoir outflows tend to occur and which purposes are served.

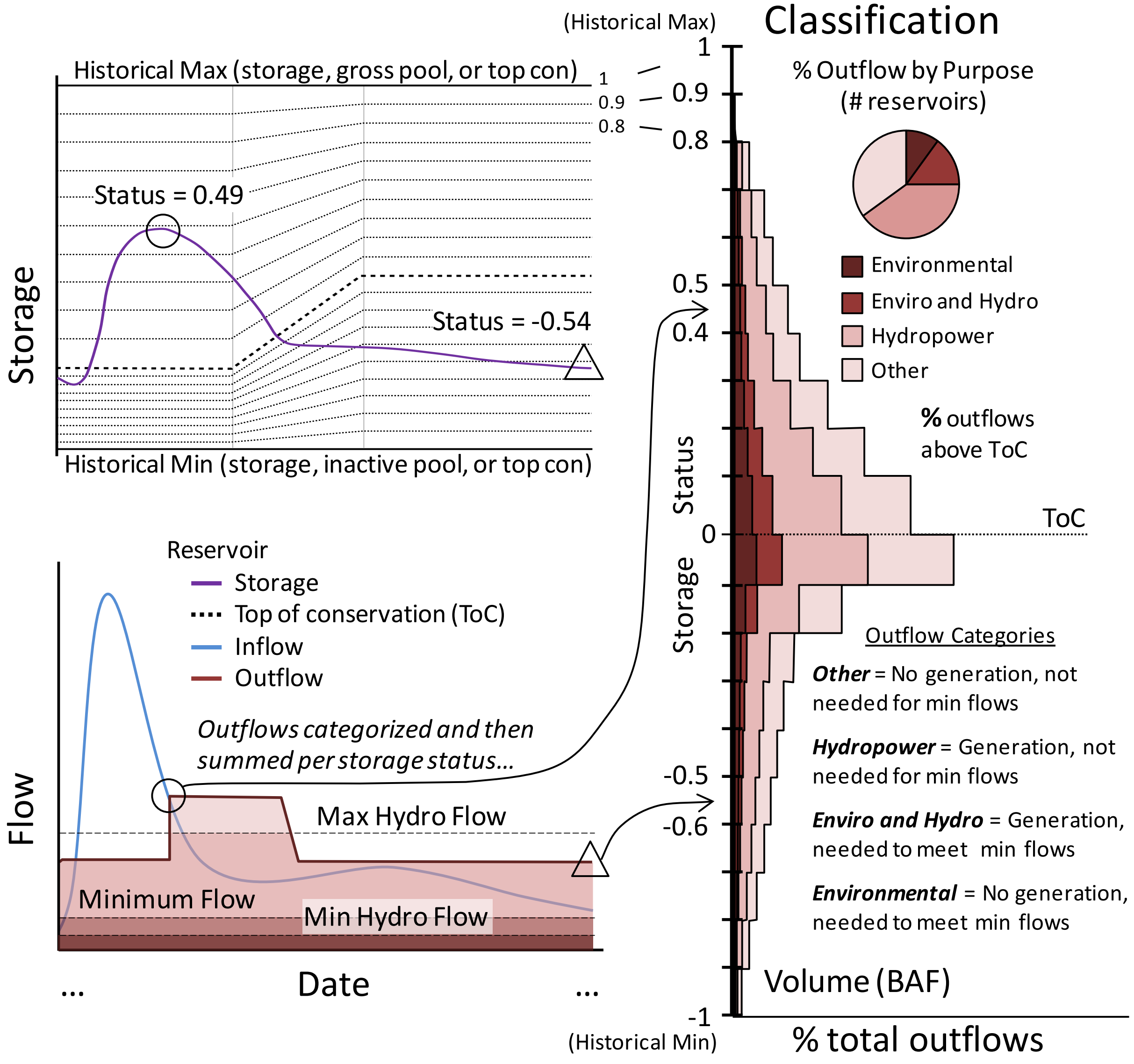


Figure 9. Outflow analysis method based on storage status and operational purposes.

When in the flood zone (above the top of conservation), the "other" category is comprised mainly of flood releases not routed through hydropower turbines. When in the conservation zone (below the top of conservation), the "other" category corresponds to releases that are not mandated by environmental requirements and are not used to generate hydropower. Since reservoirs typically store when possible (in the conservation zone), those "other" outflows are most likely water deliveries not routed through turbines.

The balance between outflows released above and below the top of conservation reflects operational flexibility. Reservoirs are generally managed to maintain storage as close to the top of conservation as possible. As stored waters are released to meet existing obligations such as water supply deliveries and minimum flow requirements, pools are drawn down and operational flexibilities are reduced.

Distributions, volumes, and purposes of outflows were assessed between 1989 and 2008. Results are summarized in table 4 and presented in a series of figures. Over that period, surveyed reservoirs released 12.6 BAF of water (figure 10, part a). Big river reservoirs, though only nine in number, accounted for nearly half of that volume (46%; figure 10, part b). Big river reservoirs were impressively efficient at generating hydropower; 98.4% of all waters released at those projects, 1989-2008, spun turbines (figure 10, part b).

Table 4. Outflow volumes and percent per category for surveyed reservoirs, 1989-2008.

	Reservoirs		**Outflow**	**Percent Outflow by Purpose**				
Category Region	Count	w/ Hydro	Volume (BAF)	Enviro and Hydro	Total* Enviro	Total* Hydro	Other - Con Zone	Other - Flood Zone
All	457	109	12.6	16.8	17.8	77.7	3.3	18.0
Big river	9	9	5.8	23.1	23.1	98.4	0.8	0.8
Dry dam	44	0	0.15	0.0	2.0	0.0	0.2	97.8
General	404	100	6.7	11.7	13.5	61.5	5.6	31.2
LRD	73	10	1.4	9.3	11.3	53.6	3.5	40.8
MVD	32	4	0.55	0.2	6.3	11.8	6.4	75.8
NAD	45	4	0.22	3.8	13.5	14.1	14.2	61.9
SAD	14	9	0.51	15.4	16.1	91.2	1.0	7.4
SPD	55	25	0.62	10.1	10.6	72.6	14.7	12.2
SWD	81	19	1.3	1.1	1.8	50.8	1.9	46.6
NWD-MR	61	6	0.41	19.0	21.4	67.5	8.5	21.5
NWD-CR	43	23	1.7	24.2	24.9	83.7	6.1	9.5

* "Total" columns correspond to the sum of two outflow categories (i.e., "total enviro" is equal to the sum of the environmental and environmental and hydropower categories). Tabulated percentages may not exactly equal the sum of percentages from figures due to rounding.

Dry dam reservoirs comprised nearly 10% of surveyed reservoirs (44 of 457), but regulated only 1% of total outflows (figure 11, part c). No dry dam had hydropower facilities. Two listed minimum flow requirements, though both were single purpose (flood risk management) reservoirs. A review of the time series data for these reservoirs showed that waters were not stored to meet minimum flows.

Within the "general" collection of reservoirs, Corps owned projects released a higher percentage of outflows above the top of conservation waters than non-Corps owned projects (figure 12, parts e and f), which suggests that the Corps owned projects have comparatively more operational flexibility. Some of this difference is likely related to environmental requirements. Corps owned projects released a lower percentage (11.1%) of outflows than corresponding Section 7 projects (20.4%) to meet environmental requirements (figure 12, parts e and f).

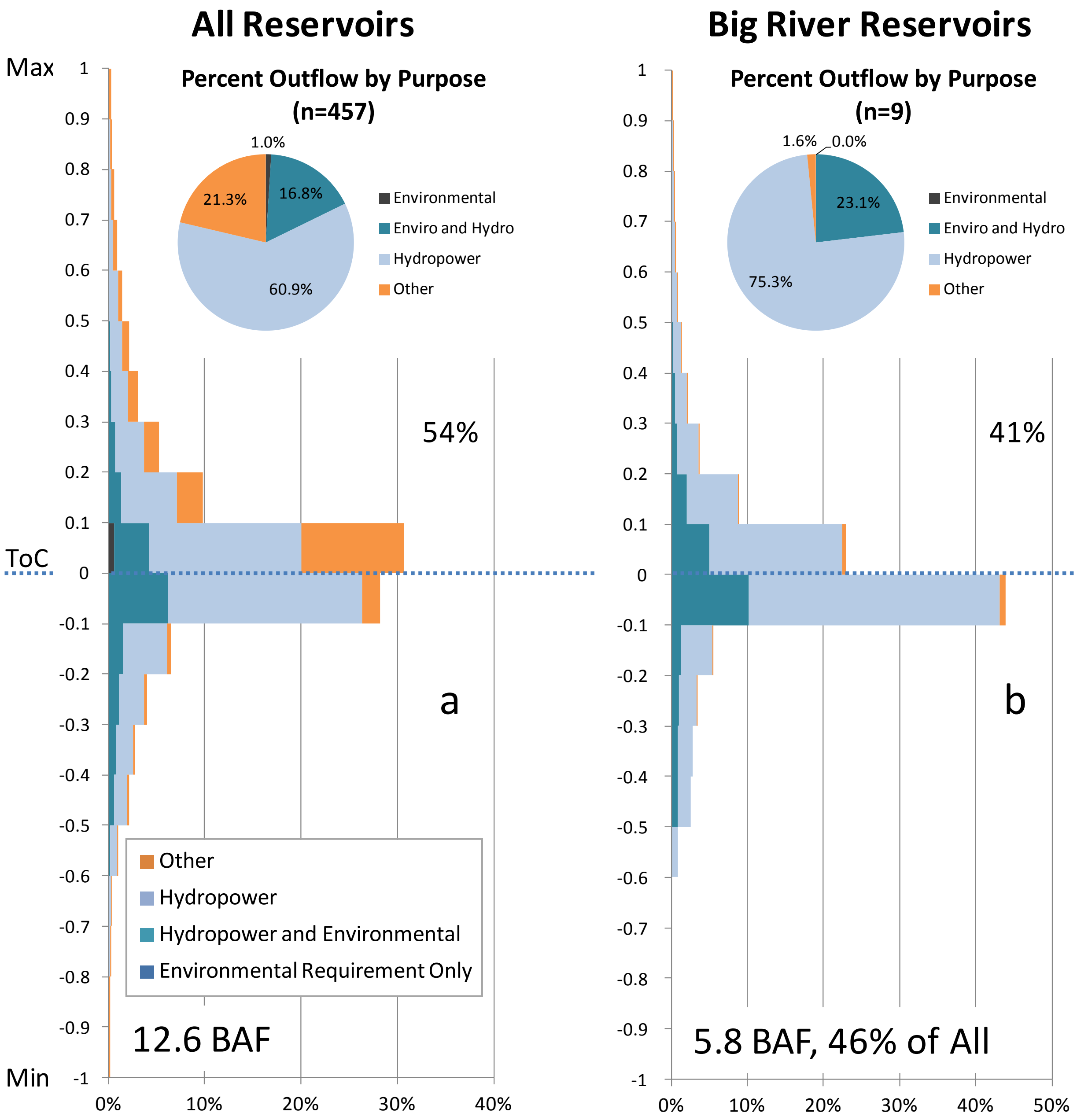


Figure 10. Comparison of outflow purpose and pool status, 1989-2008, for a) all surveyed reservoirs with available time series and b) surveyed "big river" reservoirs on the mainstems of the Missouri, Columbia, and Colorado Rivers.

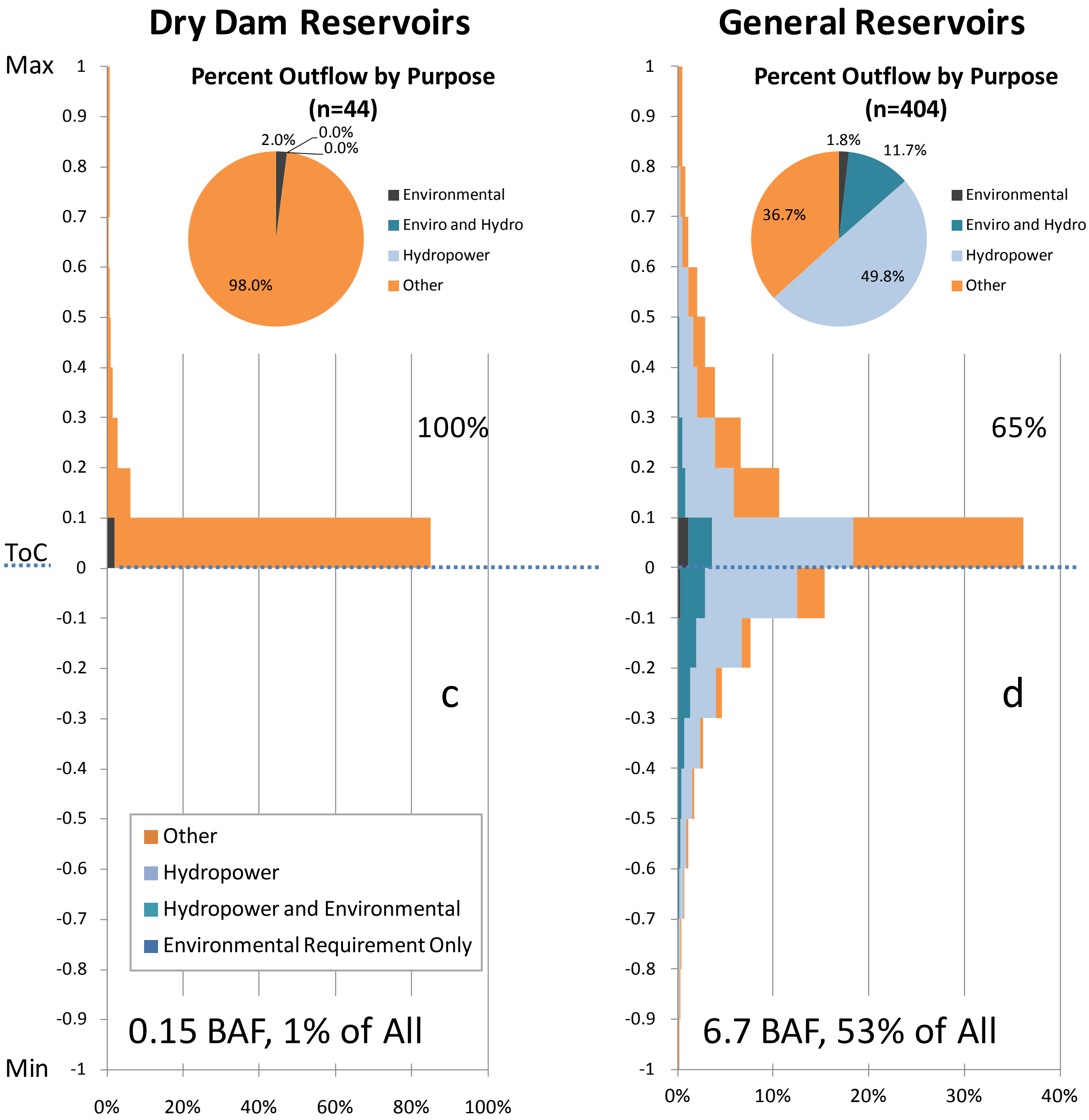


Figure 11. Comparison of outflow purpose and pool status, 1989-2008, for c) "dry dam" reservoirs that have zero conservation storage or were described in survey responses as dry dams and d) all surveyed reservoirs that were not "big river" or "dry dam" reservoirs. The sum of reservoirs in this figure and in figure 10, part b, is equal to the "all" collection displayed in figure 10, part a.

2.3.1 Environmental Strategies

While environmental strategies at reservoirs can involve management of physical, chemical, and thermal characteristics of in pool and downstream waters, as well as connectivity of habitats and fluxes of sediment and nutrients, most surveyed reservoirs were limited to flow (61%) or thermal (17%) management strategies. Environmental flow management strategies were formalized mostly in terms of minimum flow requirements.

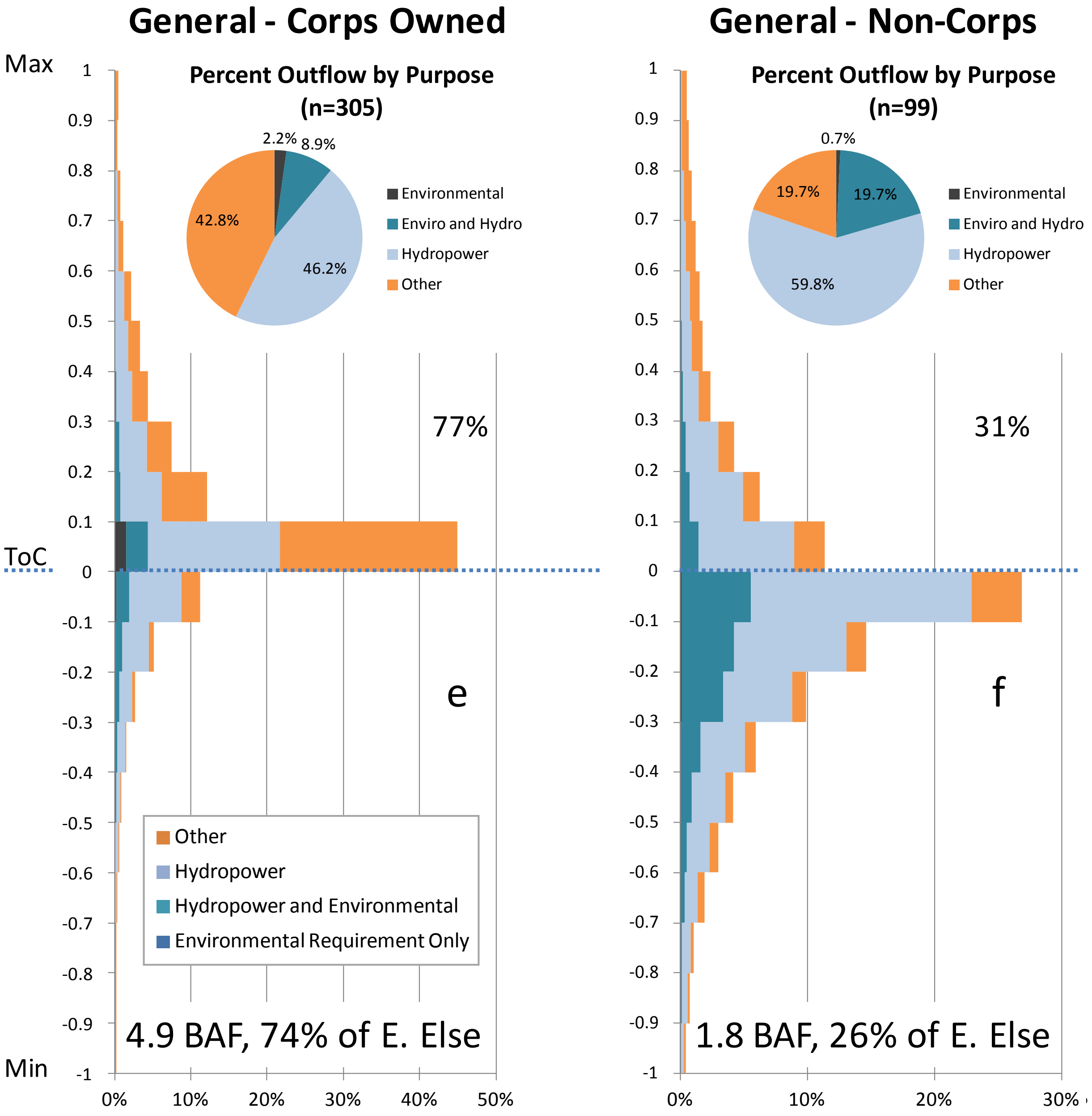


Figure 12. Comparison of outflow purpose and pool status, 1989-2008, for reservoirs with federally authorized flood storage that are e) owned and f) not owned by the U.S. Army Corps of Engineers. The sum of reservoirs in this figure is equal to the "general" collection (figure 11, part d), which includes all surveyed reservoirs that are not "big river" or "dry dam" reservoirs.

Surveyed reservoirs had minimum flow requirements that totaled to 17.8% and 13.5% of outflows for the "all" projects (figure 10, part a) and "general" (figure 11, part d) categories, respectively. Within the "general" category, reservoirs owned and operated by the Corps had minimum flow requirements totaling to 11.1% of outflows (figure 12, part e).

Minimum flow time series were aggregated for all surveyed reservoirs to investigate modes of requirements (table 5) and trends in pattern. Of all reservoirs with time series data, 39% had no requirement. The most common mode (45%) of requirement was a constant minimum flow. The remainder (16%) had a variable flow requirement that fluctuated either seasonally, as a function of condition, or both.

Table 5. Summary of minimum flow modes (none required, constant requirement, and variable requirement) for surveyed reservoirs.

		Reservoirs per Min Flow Mode			Percentage per Mode		
Category	Count	None	Constant	Variable	None	Constant	Variable
All	457	180	205	72	39%	45%	16%
Big river	9	4	4	1	44%	44%	11%
Dry dam	44	42	2	0	95%	5%	0%
General	404	134	199	71	33%	49%	18%

Between 1991 and 2008, minimum flow requirements were generally stable, though there is a visible trend, beginning in the 2000's, which shows flow requirements increasing in terms of magnitude and variability (figure 13).

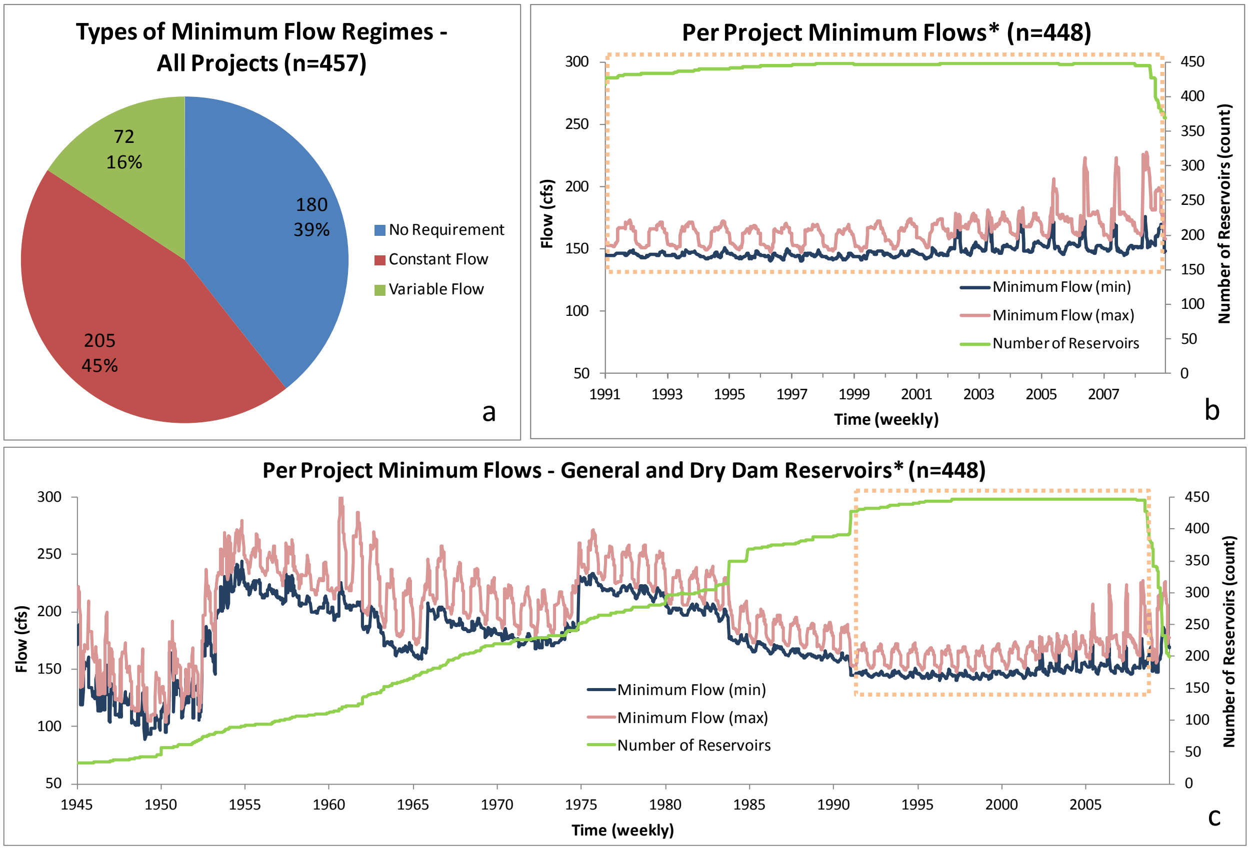


Figure 13. Required outflows for environmental purposes at surveyed reservoirs. Results are shown for the a) type of minimum flow requirement, b) patterns of minimum flow requirements between 1991 and 2008, and c) patterns of minimum requirements between 1945 and 2009. Reservoirs on the mainstem Missouri, Columbia, and Colorado Rivers are omitted.

2.4 Conclusions

This chapter details a national inventory of reservoirs with federal flood management responsibilities and the effort undertaken to compile a database that describes them. Select attributes of the database are summarized to help 1) characterize the overall group (storage capacity, ownership, authorized purposes, and operational policies) and 2) define current environmental operating strategies and their potential for change (minimum flows, outflow release decisions, and past changes to operational policies). Chapter 5 continues these themes and presents a series of ideas for improving reservoir operations from an environmental perspective.

Key points in this chapter include:

- Reservoirs have diverse physical characteristics, ownership, and operational purposes, which makes it difficult to characterize the management of water at regional and national scales.

- The NID is the most comprehensive source of information about dams in the United States, containing information for 84,134 structures that impound water, but offers little detail about how water is managed.

- A national reservoir survey compiled operational information (e.g., storage allocations, purposes, policies) and time series data (daily inflows, outflows, storages, and top of conservation storages) for reservoirs with federally authorized flood storage (table 1). The 465 surveyed reservoirs contain roughly 50% of the reservoir storage capacity in the U.S (figure 4).

- Time series were compiled, reviewed, and edited to fill missing data and correct errant values. The resulting database contained 37.3 million values, which represent 81% of the operational history of surveyed reservoirs for which time series data were available. Nearly all missing data occurred between the beginning of reservoir operation and the beginning of available electronic data.

- Surveyed reservoirs varied widely in character. Three categories were used during analyses: 1) “Big river” reservoirs are mainstem projects on the Colorado, Columbia, and Missouri Rivers - though only 9 in number, nearly half (46%) of all surveyed outflows were released from these projects, 1989-2008; 2) “Dry dams” are typically smaller and more single-purpose than other surveyed reservoirs. Most were constructed solely for flood risk management and do not store water under normal conditions. Fifty-one reservoirs were identified as dry dams; and 3) “General” reservoirs include the remaining 405 reservoirs. Though this group is still diverse, the General category is most representative of typical reservoirs with federally authorized flood storage.

- Improvements to flood risk management is the most common motivation for operational changes at surveyed reservoirs, though the percentage of changes for environmental enhancements (water quality and fish and wildlife) has been increasing since the 1980’s (figure 8).

- Environmental strategies at most surveyed reservoirs were limited to flow (61%) or water temperature (17%) management. Environmental flow strategies were formalized mostly in terms of minimum flow requirements, with 45% of reservoirs having a constant minimum flow and 16% having a variable requirement (table 5).

CHAPTER 3

HEC-RPT - Software for Facilitating Development of River Management Alternatives

River systems have diverse stakeholders that share an appreciation of the many services a river can provide. These interests vie for an allocation of waters advantageous to their position throughout a continuum of water development from initial planning and construction of water resource infrastructure to an optimization of existing facilities, and ultimately, to a sustainable state of management or alteration to the point where the river ceases to exist.

Voices wax and wane responding to historical circumstances and rhetorical and political opportunities. Some change from a competitive to a protective tone as the services they advocate for achieve acceptable and reliable performance. Others fade as their position fails in competition, perhaps to return when social opinion and economic value become more aligned with their uses in hopes of affecting the allocation of waters to restore services lost.

Maintaining open and clear communications where a diversity of perspectives can be heard and express their goals in a common manner is critical when trying to achieve a generally accepted balance among different uses of rivers. For water managers, decision-making that involves river conditions is often as much about managing conflict as it is about managing water.

This chapter is about a software developed to help a diverse group of interests develop a single set of river management recommendations that balance these interests.

The idea for the Regime Prescription Tool (RPT) was conceived during a workshop for the Savannah River, where nearly 50 scientists representing 13 organizations worked together to formulate a set of water management recommendations designed to sustain Savannah River ecosystems. During the workshop, recommendations were created independently for different ecotypes of particular importance in the Savannah Basin and then merged into a single set of recommendations.

Throughout this process, many hydrographs were created, discarded, and modified. Facilitators were pressed to track all of the recommendations and lacked an easy way to present results electronically. It was noted that a tool capable of rapidly displaying, adjusting, and documenting hydrographs would aid the formulation process and, if it were also capable of accessing and plotting historical hydrologic data to guide the scientists upon their request, then the product as well as the process would be improved.

This idea was conceptually refined by the Hydrologic Engineering Center and The Nature Conservancy with an initial focus on defining the role that the software was envisioned to fill in water resources planning. What capabilities should it have? How will it complement existing software? In what settings will it be applied? Why will this software be unique? During this period, it was recognized that possible applications of the tool were not limited to defining ecological strategies. The tool also had potential to help advance any stakeholder discussion working with hydrographs to collaboratively create or refine management plans for rivers.

The first public release of RPT was in October 2006 followed by version 1.1 in January 2007 and version 2.0 in February 2011. RPT is designed to help different interest groups reach consensus about how rivers should be managed. The software is generic in the sense that it can display flow data and help define management alternatives, in terms of quantified flow recommendations, for any regulated river. RPT is intended for use in real-time settings where suggestions from group members are actively, visually, and quantitatively integrated into a collective recommendation, which can then be exported for use in more detailed analytical tools such as reservoir simulation, river hydraulics, and ecosystem function models (USACE 2012).

3.1 Collaborative Decision Software

RPT is typically applied as part of a broader planning process that encompasses problem definition, identification of alternatives, and assessment, implementation, and testing of those alternatives (figure 14). RPT is used during alternative formulation. It allows desired management regimes (i.e., flow recommendations in the form of customized hydrographs) to be shaped based on expert knowledge and stakeholder input. Successful application of RPT produces flow recommendations that represent the collective ideas of the group of participants. Defining success of the broader process is difficult to do as succinctly, though “realizing improvements to water resources management” would be a good opening.

Terms like group settings, expert knowledge, and stakeholder input are common in discussions of computer-aided negotiation (Thiessen et al. 1998), consensus building through modeling (Stave 2003; Giordano et al. 2007), stakeholder-based modeling (Palmer et al. 1999; USACE 2009c), and participatory modeling (Pahl-Wostl et al. 2007; Voinov and Bousquet 2010). These related paradigms (Imwiko et al. 2007) are more about process than choice of technology and all espouse common principles of transparency, communicativeness, and engagement of involved parties (Korfmacher 2001; Cockerill et al. 2006; Cardwell and Langsdale 2011; Sandoval-Solis et al. 2013).

Many technologies have been applied in this field (Imwiko et al. 2007; Voinov and Bousquet 2010). Vionov and Bousquet (2010) identify more than a dozen software tools (STELLA, Vensim, Powersim, Delphi, Madonna, Simile, Extend, Goldsim, Simulink, Excel, and others) that have been used for stakeholder-based modeling. Several of these tools, like STELLA (Richmond 2004), are generic platforms that allow modelers to build applications based on input from participants (stakeholders, mediators, experts) in a planning process. This is done purposefully to maintain transparency throughout the modeling process in hopes of building trust and knowledge amongst participants such that results of the planning effort will be more widely accepted and therefore more implementable.

RPT is also generic in the sense that it can be applied to many systems and its applications begin as a blank slate and can be constructed in a participatory modeling setting. However, RPT is designed specifically for use in regulated river systems with flow management decisions. It assists only with alternative formulation and does not perform detailed alternatives analyses.

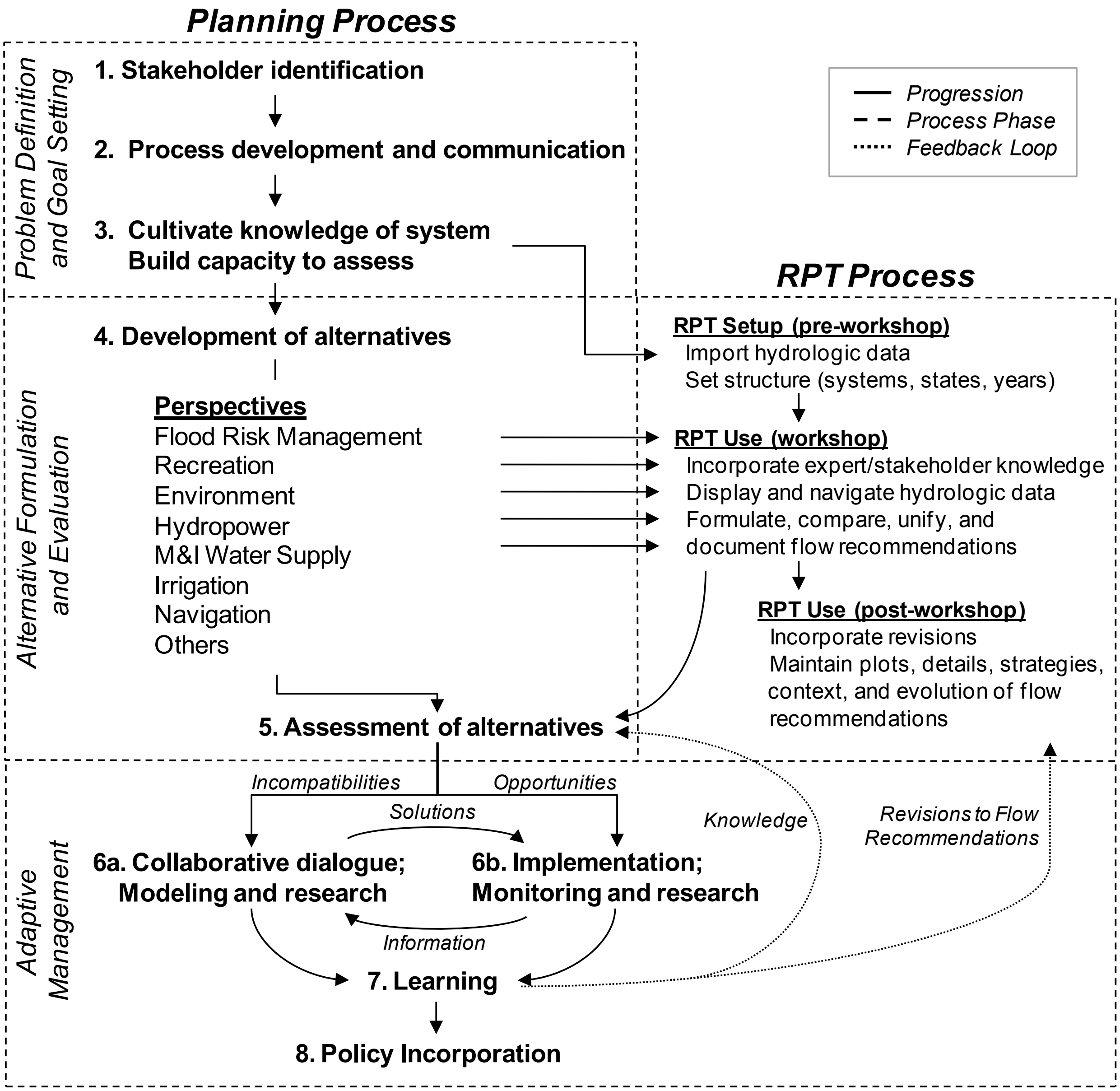


Figure 14. Roles of HEC-RPT in a generic planning process, adopted in part from Richter et al. 2003.

The contributions of RPT to the planning process include simple access, visualization, and navigation of hydrologic data, tracking and maintaining a context of hydrologic conditions, electronic creation and shaping of flow recommendations, simple comparisons of flow recommendations from different stakeholder groups, and assistance with integration of different flow recommendations into a single alternative.

All these functions adhere to the aforementioned principles. Alternatives are built piece-by-piece per participant input (transparency and engagement), display of data and alternatives are inherently visual and responsive to participant inputs (transparency and communicativeness), alternatives are compared visually to identify incompatibilities with historical data and potential conflicts with other alternatives (transparency, communicativeness, and engagement), and alternatives are unified as much as possible through further shaping of the alternatives per negotiation and compromise amongst participants (transparency, communicativeness, and engagement).

3.2 Software Features and Use

In RPT, the basic framework for flow recommendations is that flows are 1) created for different subjects of interest, 2) related to a hydrologic condition or season, and 3) expressed as combined time series of low flows, pulse flows, and flood flows (figure 15).

3.2.1 Spatial or topical framework (Systems)

A "system" describes a subject of interest for which flows will be recommended. There tends to be several systems within one project; there is no limit to the number of systems per project. A system may refer to a location on a river - such as an important gage location, or to an important ecosystem connected to the river - such as a floodplain forest community, or to a guild of creatures - such as fishes, or to different points of view for river management - such as water supply, hydropower operations, or recreation. Systems of an RPT project usually share a common typology. For example, flow recommendations of the Savannah River workshop were formulated for three river reaches, each having a different type of ecosystem and each being analogous to a system in RPT: Augusta shoals - a relatively short (~7 km) reach, whose defining and namesake characteric is a multitude of in-channel rock structures that are partially exposed at low flows, that provides habitat for a unique assemblage of fishes, mussels, and plants; floodplain - a long (~65 km) unleveed reach with a broad and heavily forested floodplain; and estuary - a reach of roughly 20 km between the floodplain reach and the Atlantic Ocean comprised of riverine, floodplain, and tidal freshwater and saltwater marsh habitats (Meyer et al. 2003; Richter et al. 2006).

3.2.2 Hydrologic framework (States)

"State" refers to a prevailing hydrologic condition associated with a set of flow recommendations. There tends to be multiple states within one project and there is no limit to the number of states per project. The same set of states is used for all systems in a project. Flow recommendations are prepared for each state in each system. States can be defined by “name and year”, where each water year is assigned a single state, or by “scripting” with time series, which allows users to import time series, perform calculations with those time series, and, ultimately, use a logic statement to determine state. For example, flow recommendations of the Savannah River workshop were formulated for three hydrologic states: wet, average, and dry (Meyer et al. 2003; Richter et al. 2006).

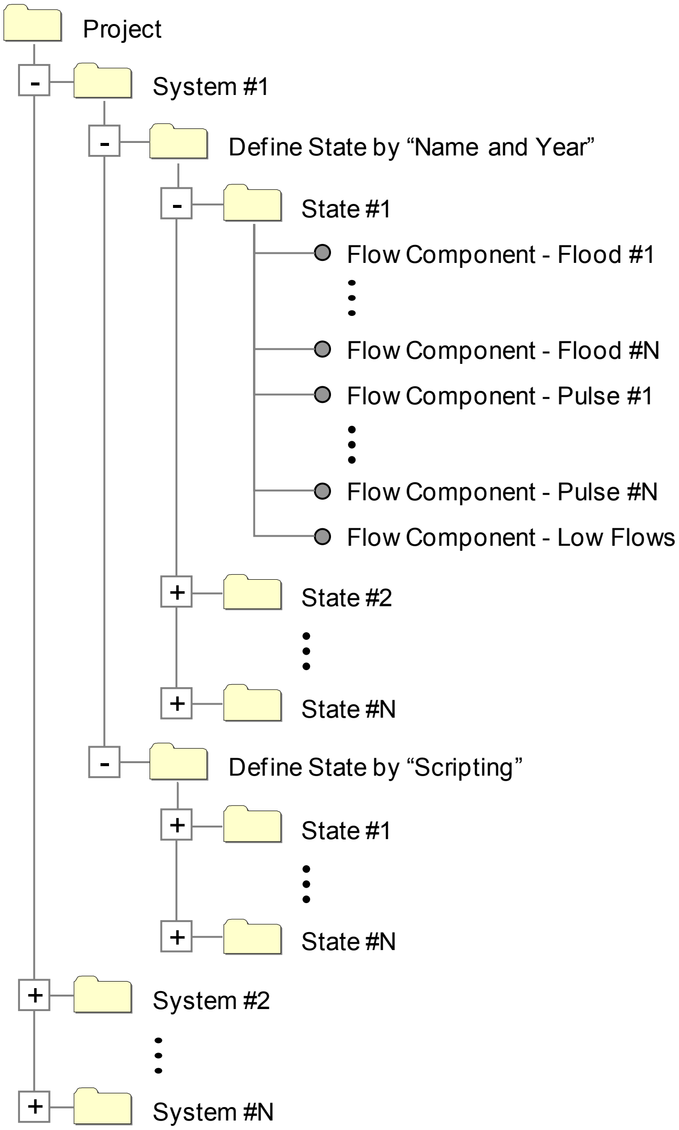


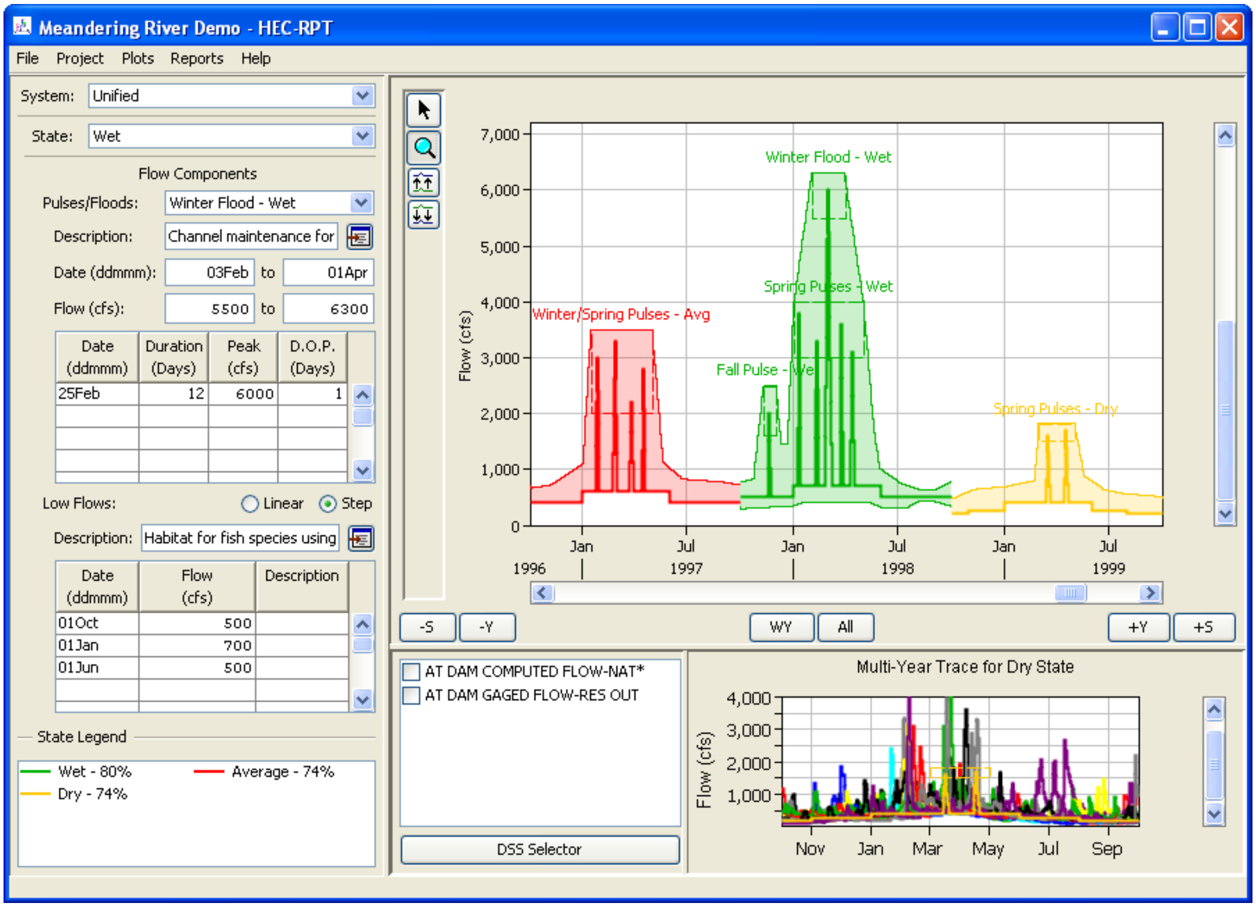
Figure 15. Structure of an RPT application.

3.2.3 Flow recommendations (flow components)

"Flow components" are the building blocks of a recommended flow time series. There are three types of flow components - low flows, pulse flows, and flood flows. Low flows are the foundation of the time series. Low flows are defined for each day in a water year (for each state in each system). Pulse flows and flood flows deviate from this base. A flow recommendation (for one state in a system) can have many pulses and floods, but only one series of low flows. Both pulses and floods are defined by timing, duration, magnitude, and duration of peak. In RPT, flow recommendations are formulated as daily time series. This bottom-up approach, now known as "the Savannah Process", was developed by The Nature Conservancy (Richter et al. 2006) and was adapted in part from the "Building Block Methodology" (King et al. 2000) and the "Holistic Approach" (Arthington et al. 1992) methods for defining environmental flows, which were formalized and first used in South Africa and Australia in the 1990's.

3.2.4 Supporting capabilities (banding, volume tracking, predefined plots, importers, notes)

The RPT software has several features that support the definition of flow recommendations. “Banding” can be used to draw flow recommendations as ranges of acceptable flows, which is a helpful way to illustrate seasonal flexibilities (wide band) and rigidities (narrow band) for flow recommendations. “Volume Tracking” allows users to compare the volumes of water that would be needed to meet a set of flow recommendations with the corresponding volumes of water in an imported time series, which can provide a real-time accounting of how much of a river’s flow would be required to wholly implement a set of flow recommendations. “Predefined Plots” offer point and click summaries of historical data and comparisons of flow recommendations. “Importers” allow systems from multiple applications to be combined into a single project for quick comparisons of the similarities and potential conflicts between the flow recommendations of different management perspectives. “Notes” fields are provided throughout the software (for systems, states, and flow components) to allow documentation of the framework, strategies, and justifications for flow recommendations during formulation (figure 16).



System: Unified

State: Wet

Flow Components

Pulses/Floods: Winter Flood - Wet

Description: Channel maintenance for

Date (ddmmm): 03Feb to 01Apr

Flow (cfs): 5500 to 6300

Date (ddmmm)	Duration (Days)	Peak (cfs)	D.O.P. (Days)
25Feb	12	6000	1

Low Flows: ○ Linear ● Step

Description: Habitat for fish species using

Date (ddmmm)	Flow (cfs)	Description
01Oct	500	
01Jan	700	
01Jun	500	

State Legend

- Wet - 80%
- Average - 74%
- Dry - 74%

☐ AT DAM COMPUTED FLOW-NAT*

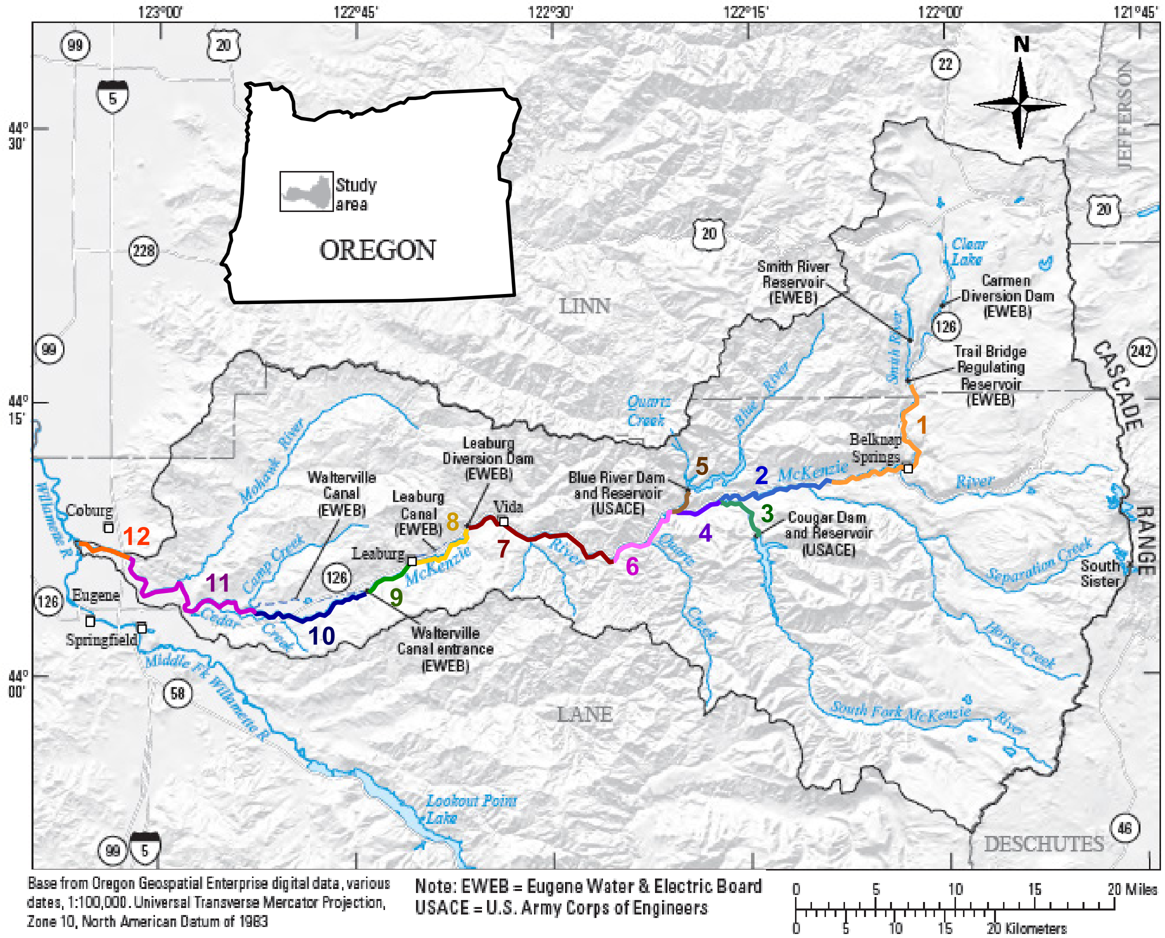
☐ AT DAM GAGED FLOW-RES OUT

Figure 16. Main interface of RPT. Flow recommendations, banding, and states are shown for the RPT demonstration project. The lower right hand plot window displays a multi-year trace, which is one of the predefined plot options in RPT. Data are shown for dry state flow recommendations and all historical dry years in the unimpaired flow regime.

3.3 Application for Environmental Flows

The first application of HEC-RPT was performed in 2007 for the Coast and Middle Forks of the Willamette River, Oregon, USA (Gregory et al. 2007). This case study discusses a more recent application for the McKenzie River, also in Oregon, that occurred in 2010. Both supported definition of environmental flows, which are flows in a water system that sustain local ecosystems and the goods and services they provide (TNC 2006; Hirji and Davis 2009).

The McKenzie River drains a 1,300 square mile area in western Oregon (figure 17). It joins the Willamette River near Eugene, Oregon, which then flows north to meet the Columbia River on its westward path to the Pacific Ocean (Risley et al. 2010a). There are three storage reservoirs in the McKenzie basin, two diversion dams, one reregulation facility, and a series of canals that divert and return river flows to generate hydropower. The two biggest reservoirs, Blue River and Cougar, are owned and operated by the U.S. Army Corps of Engineers. Both have multiple operating purposes including flood risk management, recreation, irrigation, water quality, and fish and wildlife. During periods of high flows, Blue and Cougar are operated both to reduce potentially damaging flows along the McKenzie and as part of the Willamette flood risk management system, which involves 11 storage reservoirs operating for a series of communities located along the mainstem from Eugene to Salem. Cougar is also used to generate hydropower (USACE 1992).



Base from Oregon Geospatial Enterprise digital data, various dates, 1:100,000. Universal Transverse Mercator Projection, Zone 10, North American Datum of 1983

Note: EWEB = Eugene Water & Electric Board
USACE = U.S. Army Corps of Engineers

Figure 17. Major tributaries, dams, and river reaches of the McKenzie River Basin, Oregon, USA (as in Risley et al. 2010a).

As in the encompassing Willamette basin, reservoirs in the McKenzie are primarily on tributaries or relatively high in the watershed such that most drainage areas are unregulated by dams. Accordingly, key hydrologic dynamics (e.g., seasonality and variability) and geomorphic processes (e.g., sediment transport and channel migration) are muted but present. In a comparison of the McKenzie River channel forms existing in 1939 and 2005, Risley et al. (2010a) note a general reduction in the length of secondary channels and area of active gravel bars and hypothesize that these trends are related to a combination of interacting anthropogenic factors including hydrologic alteration, channel clearing, land conversion, timber harvest, and their effects on sediment transport.

The McKenzie provides drinking water for roughly 200,000 people and power to nearly 20,000 households in the city of Eugene and its surrounding areas (www.eweb.org, Eugene Water and Electric Board). It is also a popular and scenic area for outdoor recreation, offering excellent opportunities for boating, hiking, and, especially, fishing for the eight species of salmon and trout that inhabit the basin's lakes and rivers. Ecologically, the McKenzie is strongly connected to the Willamette. Perhaps most visibly during the seasonal runs of salmon and steelhead that use the McKenzie for spawning and rearing.

In 2008 and in recognition of the range of services provided by the McKenzie, The Nature Conservancy, the Corps of Engineers, the Eugene Water and Electric Board, and the U.S. Geological Survey (USGS) began an environmental flow study for the river. The study generally followed the sequential process for developing environmental flow recommendations detailed in Richter et al. 2006, which is now referred to as the "Savannah Process" after its initial application for the Savannah River in 2003. Milestones included development of a summary report on the hydrology, geomorphology, and ecology in the McKenzie River basin (Risley et al. 2010a), convening of a workshop to define environmental flows, and completion of a report to document the workshop, its structure and products (Risley et al. 2010b). The RPT software helped facilitate the workshop by recording and archiving the flow recommendations and associated justifications and uncertainties as set forth by the 55 scientists, engineers, and water managers at two day workshop. The rest of this section describes the three phases of the McKenzie River application of RPT: initial development, use during workshop, and role of software in preparing the workshop report.

3.3.1 Initial Development

Initial development of an RPT application is typically done by a small group of people in anticipation of a larger meeting of stakeholders and experts to discuss water management alternatives. The small group includes the conveners and future facilitators of the larger group as well as the RPT modelers. Conveners and facilitators are primarily interested in planning the formulation process (objectives, activities, structure, and schedule) to be used during the larger meeting and understanding the capabilities and role of RPT. Modelers are responsible for aligning the RPT application with the anticipated formulation process, preparing and analyzing hydrologic data, and becoming proficient enough with the software and application to be comfortable using it in real-time. The first two steps for the modelers are identifying systems and states.

For the McKenzie, RPT systems were adopted from the hydrologic section of the summary report where Risley et al. (2010a) characterized the river as 12 reaches of distinct streamflow and geomorphic conditions. Each reach was treated as a system in RPT. Time series of regulated and unimpaired flows were imported for each system. Regulated flows were obtained from USGS streamflow gaging stations. Unimpaired flows, computed as estimates of streamflows that would have occurred if Blue and Cougar had not been constructed, were obtained from the Portland District of the Corps of Engineers (Risley et al. 2010a).

States were based on a statistical analysis of the flow record for the McKenzie River near Vida gage, 1925-2004 (USGS 14162500). Mean flows were computed for the full water year, a winter-spring season, a spring season, and a summer-fall season. Results for each statistic were then ranked from highest to lowest and split into bins, where the upper bin included the wettest 27 means, the middle bin had the 26 means closest to the 50th percentile, and the lower bin had the driest 27 means. The lower bin was then further split into categories for dry (14 means) and critically dry (13 means).

States were defined for “Wet”, “Average”, “Dry”, “Critical”, and “None” using the by name and year method in RPT (Risley et al. 2010b). A year was associated with a state based on how consistently its statistics sorted into the bins. Any water year whose statistics (at least three of the four means) fell into the upper bin was designated as “Wet”, middle bin “Average”, and so on. Years where less than three of the four means fell in the same bin were designated as “None”.

This system-state framework served as the RPT starting point for the McKenzie flow recommendations workshop. Details are specific to the McKenzie, but there is much in common with other applications. To the knowledge of the authors, all RPT applications have been initiated by efforts interested in forwarding a dialogue about river management, use hydrologic data to support discussion, and incorporate a framework anticipated to be an effective structure for the flow recommendations, logical from the perspective of the participating stakeholders, and of value, pertinent, and interpretable for water managers.

3.3.2 Use during Workshop

In water resource planning, the overwhelming majority of software applications are done without others seeing every keystroke of the modeler, much less having a group of people telling the modeler what to do and then voicing their concurrence or objections to its incorporation. This makes RPT use in real-time settings both challenging and insightful. Challenging to keep pace with the amount of information that can be shared easily through oral communications in group settings and insightful to be part of and help accelerate an organic process where many voices contribute to a common set of ideas. The roughly prioritized roles of RPT in these settings are 1) to record suggestions of the group, 2) display and navigate hydrologic data sets, and 3) unify suggestions from different groups by comparing and contrasting their recommendations.

The McKenzie Environmental Flows Workshop started with a review of its purpose (defining the river flows needed to support a healthy and functioning ecosystem) and expected outcomes (a quantified set of flow recommendations). This was followed by presentations about the hydrology and associated ecosystems of the river. To simplify the challenge, the 12 reaches and their systems were aggregated into 4 sections (figure 17): South Fork McKenzie River below Cougar (reach 3), Middle McKenzie (reaches 4-7), McKenzie between Leaburg and Camp Creek (reaches 8-10), and Lower McKenzie (reaches 11-12). Reaches 1 and 2 were not considered due to a lack of hydrologic alteration. Also, attendees were instructed to focus attention on the flows and related processes needed to support nine native species of particular importance, which included five fishes (spring Chinook Salmon, bull trout, Pacific and western brook lamprey, and the Oregon chub), one amphibian (red-legged frog), one reptile (western pond turtle), and two riparian trees (black cottonwood and white alder). Species were selected based on information in the literature and communications with regional and local biologists (Risley et al. 2010a).

Participants were then split into four subgroups, each with a similar mixture of expertise in hydrology, geomorphology, riparian and floodplain ecology, and fisheries and aquatic biota. Flow needs for each of the 4 river sections were formulated by 2 or more subgroups. The South Fork McKenzie River reach was worked on by subgroups 1, 2, and 4, the Middle McKenzie by subgroups 2 and 3, the McKenzie between Leaburg and Camp Creek by subgroups 2 and 3, and the Lower McKenzie by subgroups 3 and 4. Subgroups worked independently and were instructed to define flows for the "Average" state, detail how those "Average" recommendations pertained to the different states, and continue on to other states as time allowed. Each subgroup was assigned a facilitator and an RPT modeler.

Subgroups began the formulation process by overlaying life stages of the key species with unimpaired flow patterns of the McKenzie. Connections between the species and the flows were identified, debated, and, if there was agreement, incorporated into the flow recommendations. As part of this process, RPT was used to build, display, and annotate the flow recommendations electronically, in real-time (figure 18). When a flow component (flood, pulse, or low flow) was proposed, its magnitude, duration, and timing were entered into text fields along the left hand side of the software's main interface. Plots in HEC-RPT update automatically with each new entry, which allowed the groups to immediately review and revise their recommendations.

A strength of HEC-RPT is its ability to display and navigate hydrologic data sets. For the McKenzie, data were imported to HEC-RPT that showed how the river has been managed since construction of the dams, as well as how the river would have flowed without reservoirs. Imported data can be made visible or hidden with the click of a button and were used throughout the workshop as visual references while crafting recommendations.

After flow recommendations were formulated, the workshop returned to a plenary setting where subgroup recommendations were unified into a single set of flow recommendations for the McKenzie. A modeler used the import systems feature in RPT to bring recommendations for all sections and subgroups into the same project. Subgroup recommendations for each river section were plotted using RPT and presented by the subgroup facilitators. Members of the two subgroups that had defined recommendations for that river section worked to integrate their recommendations by tweaking the timing and magnitude of recommended flows without sacrificing ecological purposes (figure 18). This process also offered attendees from the other subgroups an opportunity to learn about and question the information and strategies underpinning recommendations for river sections they had not worked with initially. Aided by the visual comparisons in RPT, subgroup strategies were quickly melded into a single unified set of flow recommendations that was then displayed to ensure continuity between river sections.

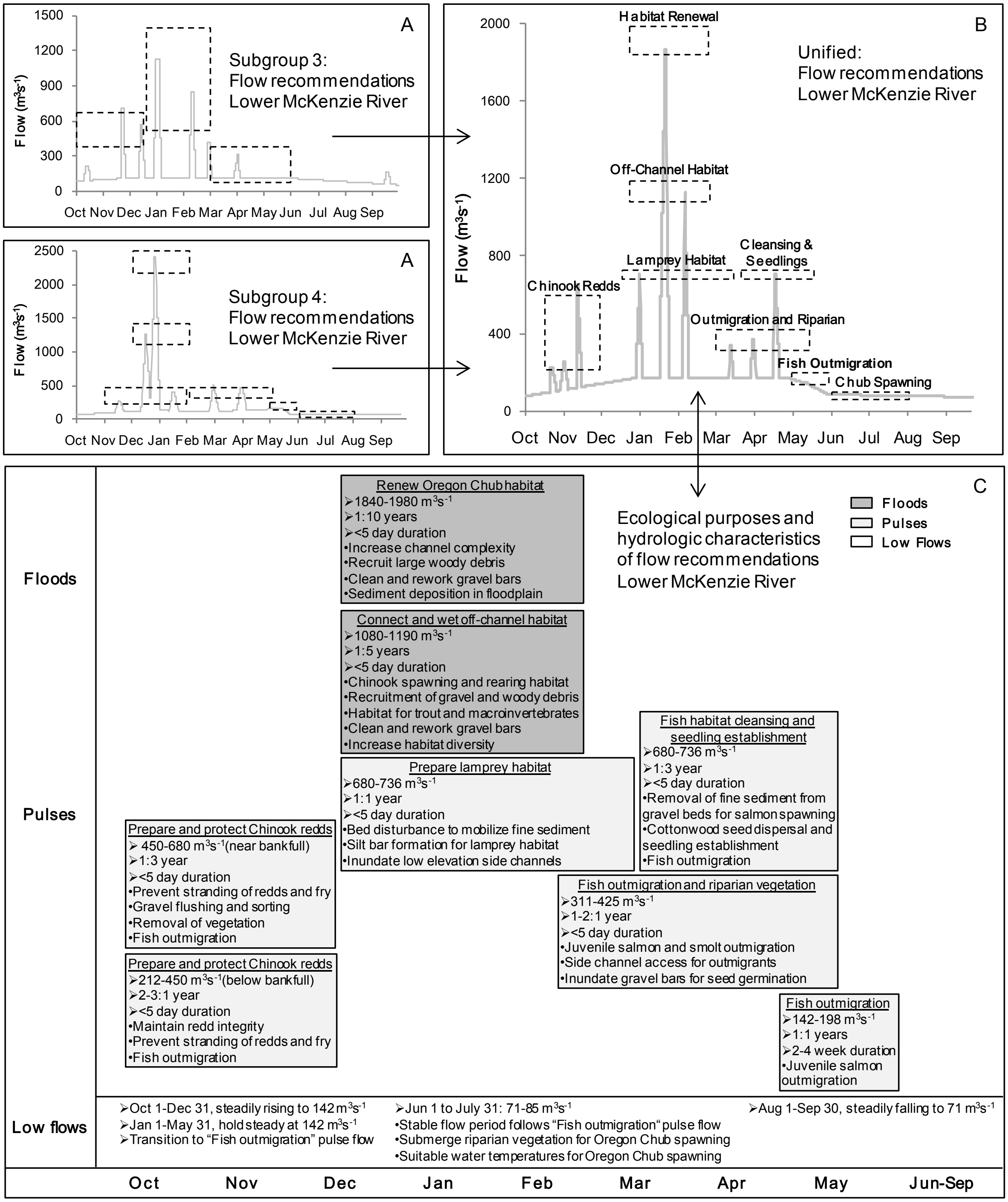


Figure 18. Formulation (A), unification (B), and justification (C) of flow recommendations for the Lower McKenzie River.

3.3.3 Help with Workshop Report

For conveners, facilitators, and modelers (and attendees), meetings like the McKenzie Environmental Flows Workshop tend to be somewhat consuming experiences. Much effort goes into organizing and orchestrating the meeting and when it is over, documentation of the products is often given a lower priority than the other important tasks that were pushed aside during preparation and participation. With lag, specifics about conclusions reached lose clarity, which has proven to be a challenge when revisiting workshop materials during documentation and implementation of flow recommendations.

Information stored in RPT applications is a useful reference while preparing workshop summary reports. For the McKenzie, flow recommendations were stored as a progression of values, strategies, and uncertainties thereby recording a temporal status during formulation and unification. Electronic notes were taken for all key parts of the RPT structure, especially for individual flow components (e.g., purpose, recommended frequency, contingencies, and uncertainties), all of which were available for incorporation into the workshop summary.

3.3.4 Since the Workshop

In 2012, environmental flows were defined for the Santiam River (Risley et al. 2012; Bach et al. 2012). This completed the sequence of definitions for all main tributaries of the Willamette River initiated in 2007 for the Coast and Middle Forks. In each year since 2007, components of those initial definitions have been implemented on the Middle Fork Willamette (Warner et al. in press). Implementation has been opportunistic in the sense that flow changes are being made within the bounds of operational flexibility for Middle Fork reservoirs and have been enabled by hydrologic conditions conducive to environmental releases (e.g., storms generating inflows that could be stored temporarily and then released with timing and shapes per environmental components for transport of juvenile salmon, creation of lateral habitat on floodplain margins, and maintenance of bars, pools, and riffles). Associated monitoring has been conducted as possible.

Focus is now shifting to efforts that will support a more complete and basin-wide implementation of environmental flows. Work is progressing on a strategic monitoring plan designed to validate environmental flow recommendations and reinforce informational loops between scientists and water management decision-makers. An overall implementation plan is being developed to help maintain the integrity of the recommendations during the current partial implementation phase and to guide the search for solutions for flow components that are beyond existing operational flexibilities. Environmental flow efforts are also aligning with ongoing endangered species consultations and other basin planning activities, especially in the modeling arena where environmental flow needs for tributaries and endangered species requirements at mainstem locations are being assessed with reservoir simulation models.

3.4 Conclusions

Both the McKenzie and Coast and Middle Fork Willamette applications of RPT were used to facilitate definition of environmental flows and thereby build consensus among environmental stakeholders. The software has also been applied outside the U.S. In China, RPT was used to help facilitate a workshop to define managed river flows to sustain ecosystems in the Upper Yangtze River’s Native Fish Reserve, which includes more than 350 kilometers of the mainstem Yangtze upstream of Three Gorges Dam reservoir and downstream of a cascade of dams now under construction. During the workshop, participants reached an initial consensus on flow conditions needed to support key native fishes in the Reserve (CTGPC and TNC 2009). An application for the Patuca River, Honduras, focused on both ecological and agricultural water management needs and integrated those perspectives into a unified flow recommendation for consideration in the operation of a proposed hydropower reservoir (Esselman and Opperman 2009).

Throughout its development, RPT has emphasized simplicity and visual responses to user commands and input. It is not intended to perform detailed quantitative analyses. This may seem a bit odd for software in water resource planning, where tools are typically designed to assist with computationally challenging questions. Instead, RPT contributes in the early stages of plan formulation, formalizing ideas and expert knowledge into a structure easily visualized and considered in other specialized software. RPT helps organize and focus group conversations that seek to create consensus-based alternatives for water management. Seasonal requirements, flow dynamics linked with purpose, changing sensitivities, comparisons of diverse perspectives, alignment of common services, identification of potential conflicts, and annotated details for flow strategies and uncertainties, are all detailed and archived in RPT. And all are developed in real-time group settings to encourage a collective agreement and improved understanding of the variety of services provided by managed rivers.

CHAPTER 4

HEC-EFM - Using Habitat to Quantify Ecological Effects of Management Alternatives

The U.S. Army Corps of Engineers (USACE) has continuing authorities to perform aquatic habitat restoration (Section 206, U.S. Congress 1996), modify existing projects to improve the environment (Section 1135, U.S. Congress 1986), and beneficially use dredged material for habitat creation, restoration, and protection (Section 204, U.S. Congress 1992), as well as management and stewardship responsibilities at nearly 400 multi-purpose reservoirs. These diverse assignments, in addition to many of the USACE civil works projects specifically authorized by Congress, share the common themes of water and environment.

In USACE restoration planning, alternatives are considered according to their expected benefits and costs (USACE 2000). Many methods and technologies have been used to estimate the environmental benefits of restoration projects. Most are designed and constructed to analyze the specific ecosystem and opportunities at a project site. None are required or mandated for use in USACE projects (USACE 2011a), though the Habitat Evaluation Procedure (HEP; USFWS 1980) developed by the U.S. Fish and Wildlife Service (USFWS) has an extensive history of application in federal water and land resource planning, within and beyond the Corps.

The Ecosystem Functions Model (HEC-EFM) is a software that aids in analyzing ecosystem responses to changes in the flow regimes of rivers and connected wetlands. The Hydrologic Engineering Center (HEC) is developing EFM to enable project teams to visualize existing ecologic conditions, highlight promising restoration sites, and assess and rank restoration or management alternatives according to relative changes in different ecosystem aspects.

At its most fundamental level, the software computes statistics requested by the user to characterize different ecosystem dynamics using daily mean flows and stages of the river or connected wetland of interest (USACE 2013). Users have many statistical options to choose from. Existing applications have helped define links between hydrology and ecology for both biota (vegetation, benthic macroinvertebrates, fish, and waterfowl) and processes (recruitment of large woody debris, depth to shallow groundwater, and channel migration).

In addition to statistical computations, EFM analyses typically employ hydraulic models to translate statistical results to spatial layers of water depth, velocity, and inundation, and use of Geographic Information Systems (GIS) to display these layers as well as other relevant spatial data (i.e., soils, vegetation, and land-use maps).

The software is generic in that it relies wholly on the user to define which aspects of the ecosystem are of key interest, how those aspects are to be investigated, and which hydrologic (e.g., climate change), operational (e.g., reservoir manipulation), or restoration scenarios (e.g., channel topographies) should be considered (USACE 2004). This chapter introduces EFM and describes its application for ecosystem and water resources planning and management.

4.1 Related Technologies

Using characteristics of a riverine or wetland flow regime to gain insights about related ecosystems is not a new concept. Engineering plans commonly use hydrograph characteristics to design restoration projects based on considerations such as the percentages of time different areas will be inundated, frequency-based flow magnitudes, and sediment transport rates. Scientific studies have dissected hydrographs to gain insights about a wide array of ecosystem dynamics, including migratory cues for fish, drift rates for macroinvertebrates, population fluctuations for a wide range of flora and fauna as reviewed by Lloyd et al. (2003; examined 70 papers) and Poff and Zimmerman (2010; examined 165 papers).

Several software tools have been developed for statistical hydrograph analyses, each with a different approach to the same fundamental goal of supporting better stewardship of managed aquatic systems (table 6). Three related technologies are the Indicators of Hydrologic Alteration (IHA) by The Nature Conservancy, the Hydroecological Integrity Assessment Process and associated Hydrologic Assessment Tool (HIP/HAT) by the U.S. Geological Survey, and the River Analysis Package (RAP) by the Australian Cooperative Research Centre for Catchment Hydrology, which was succeeded by the eWater Cooperative Research Centre in 2005.

Table 6. Selected software tools that perform statistical analyses of time series (most commonly applied to river flows).

Model Name	Purpose	Input	Spatial	Applications	Citations
Indicators of Hydrologic Alteration (IHA)	Analyze flow regimes, mainly statistically, to help users understand ecological implications of management alternatives	Time series of daily data (usually flow), dates of alteration (if applicable), parameters for any customized queries	Not spatial defined, apart from location of flow time series	Many	Richter et al. 1996; TNC et al. 2009
Hydroecological Integrity Assessment Process and Hydrologic Assessment Tool (HIP/HAT)	Statistical template used with a stream classification system to customize statistics for instream flow management	Time series of daily data (usually flow), stream classifications developed separately	Not spatial defined, apart from location of flow time series	Applied for whole states, including New Jersey and maybe others	Henriksen et al. 2006
River Analysis Package (RAP) and Eco Modeller	Analyze combinations of time series relevant to ecosystems statistically to compare water management alternatives	Time series of interest (flow, temperature, etc.) and related eco-response functions	Not spatial defined, apart from location of time series	Hattah Lakes, Murray River, Australia	Marsh et al. 2010; Little et al. 2011
Hydrology-based Environmental Flow Regime (HEFR)	Computes seasonal and monthly statistics to populate an initial estimate of environmental flow requirements	Time series of daily data (usually flow), dates of alteration (if applicable), parameters for any customized queries	Not spatial defined, apart from location of flow time series	Used in Texas in support of state legislative initiatives for environmental flows	SAC 2011; Opdyke 2012

The IHA began as a tool that computed a template of 32 hydrologic statistics - identified as being ecologically relevant by developers – to help users understand the ecological implications of a particular water management scenario (Richter et al. 1996). Those original statistics, now known as the IHA Parameters, characterize the magnitude, timing, frequency, duration, and rate of change of hydrologic regimes and have not changed significantly since the software's first version. Recent versions have added capabilities to compute flow duration statistics, parse and assess hydrographs as a series of environment flow components (low and extreme low flows, high flow pulses, and small and large floods), and to perform calculations and compare results for two flow data sets (TNC et al. 2009).

The HIP/HAT package also uses a statistical template, but where IHA applications typically focus on a particular scenario at one location, HIP/HAT begins with a broad statistical template at a regional scale to help users identify key hydrologic statistics as part of a stream classification system. The template has 171 ecologically relevant statistics, including the IHA Parameters, related to the magnitude, timing, frequency, duration, and rate of change of hydrographs (Olden and Poff 2003). A stream classification system or list of stream types is customized for the region of interest. Available records of flow at many locations, all essentially unaffected by human influences, are assigned to one of the stream types. The template is then computed for each location and statistical methods are used to identify which of the 171 statistics are significant and nonredundant in characterizing each stream type. Resulting statistics and their stream types offer a framework for developing and specifying instream flow criteria, assessing the degree of alteration in regulated rivers, and considering proposed changes in water management (Henriksen et al. 2006).

Whereas IHA and HIP/HAT begin with hydrologic statistics identified a priori as ecologically relevant, RAP (and EFM) has taken a different approach that allows users to define the ecologically relevant statistics for their work. In RAP, this work was done in the Ecological Response Module, which is now handled through a related tool named Eco Modeller. Eco Modeller provides users with the option of selecting ecological response models from a library provided with the software or creating new models by specifying which aspects of imported time series (flow and other variables) support viable conditions for the species of interest. After these rules have been entered, the user-defined statistics are computed and results are compared to gain insights for one or more water management scenarios (Marsh et al. 2005, Marsh et al. 2010, and Little et al. 2011).

Conceptually, EFM is most similar to RAP-Eco Modeller in that it also relies on users to define the ecologically relevant statistics of interest, though all of these tools share some common ground. Each use daily time series to gain insights about ecosystems. IHA and HIP/HAT use these time series to compute statistics that were determined by others to be of general relevance to ecosystems connected to aquatic systems. RAP-Eco Modeller and EFM use these time series to compute statistics defined by the user to be indicative for whichever aspects of the ecosystems are being investigated. The process of applying EFM analyses also extends from statistical analyses to the use of GIS to map habitat, which to the knowledge of the authors is unique amongst the statistically-oriented tools discussed in this section.

Habitat analyses tend to be performed by a different set of tools (table 7). The most commonly applied method is the Habitat Evaluation Procedure (HEP) developed by USFWS (USFWS 1980). HEP thinks about habitat in terms of "habitat units", which are computed by multiplying the quantity of available habitat (i.e., the spatial area being considered) by the quality of the habitat. Quality is determined by measuring key habitat variables of the area and then obtaining their corresponding suitabilities from Habitat Suitability Indices (HSI). Quantity and quality values differ between management scenarios, which allows alternatives to be compared based on the amount of habitat units provided. As this method reports habitat units for an area of interest, HEP is not inherently spatially explicit, except for delineating the spatial area(s) being considered.

Table 7. Selected software and methods that perform stream and river habitat analyses.

Model Name	Purpose	Input	Spatial	Applications	Citations
Habitat Evaluation Procedure (HEP)	Multiplies Habitat Suitability Indices (HSI) for individual species by the project area to compute habitat units (HU) which can be compared between management alternatives or different points in time to evaluate impacts or restoration improvements	Habitat characteristics that support life requisites of selected species	Not spatially defined, apart from delineation of overall project area or spatial resolution in variables that determine habitat quality	Many; HEP is a standard method in planning activities of federal agencies especially w/USWFS involvement.	USFWS 1980; www. fws.gov/ policy/ ESMindex .html
Habitat Suitability Index Models (HSI)	Developed for many species and life stages; Comprised of sets of simple plots that relate suitability (0 to 1) with a variable important to the habitat of the species of interest; Used in HEP and PHABSIM	HSIs are based on field observations of the species and life stages in their natural habitats; Commonalities in observed use ultimately define suitability preferences	Spatial only in that HSIs for a single species can be defined regional or locally	Many; As a component of HEP and PHABSIM, these are widely used	Terrell 1982; www.fort. usgs.gov
Physical Habitat Simulation Software (PHABSIM)	Uses hydraulic simulations and habitat suitability info to compute weighted usable area for species and life stages of interest	Cross sections, habitat suitability and related physical data (substrate, cover)	Hydraulics model defines spatial scale; Meso- and macrohabitat summarized for simulating alternatives	Many; This is the quantitative habitat part of the widely used IFIM	Milhous et al. 1989; Bovee et al. 1998; www.fort. usgs.gov
Ecosystem Diagnostic and Treatment (EDT)	Identifies limiting habitats/river areas for key fish species (salmons, trout, perhaps sturgeon); Express river reach's restoration and protection values	Seasons, biological rules that relate biota and environmental attributes (temp), move rates	Map of stream system mesohabitats	Used in Pacific Northwest, US	Mobrand Biometrics 2005
Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR)	Simulate habitat suitability for bullhead with weir removal project; Output expressed as percent suitability for model elements under different flow and weir scenarios	Fuzzy sets of depth; velocity, and substrate. Rules that define the combinations of fuzzy variables that lead to suitable habitat	Aquatic habitat parsed into reaches and then parsed into compartments from bank to bank	River Zwalm, Belgium; Several other studies since 1990's	Mouton et al. 2007

The Physical Habitat Simulation Software (PHABSIM) is another common method for analyzing habitat. It couples hydraulic simulations (both 1-D and 2-D modeling has been used) with habitat suitability information to determine the amount of suitable habitat provided at different flow rates. These flow-habitat curves are then used to translate flow time series to habitat time series, which can be compared for different management scenarios (Stalnaker et al. 1996; Bovee et al. 1998).

EFM and PHABSIM handle temporal considerations at different stages of their application. PHABSIM defers temporality to analyses of the habitat time series produced, which is useful in that temporal dynamics of habitat are still intact, but the spatial distribution of that time series of habitat is rarely rendered though it could have useful applications in summarizing the occurrence of habitat (e.g., a spatial habitat duration map which would show the percentage of time different areas provide habitat when that habitat had potential to be utilized) or in population dynamics models that could use time sequences of habitat distribution as a variable considered by simulated communities. EFM considers inter- and intra-year dynamics when applying life history criteria to flow and stage time series (the statistical analyses phase described more fully in Section 4.2), which means only the condition meeting those criteria is advanced for habitat mapping such that a single spatial representation (i.e., one habitat map) for the ecosystem aspect being considered is produced.

Decoupling of condition and timing is a common weakness for methods such as EFM that use statistics to characterize ecosystem dynamics (Shenton et al. 2012). Work has begun on EFM features that allow the spatial and temporal linking of ecosystem dynamics as part of a generic population dynamics model. These capabilities are being developed in parallel to EFM’s current capabilities so modelers will not be obligated to use the new population dynamics features. This scalability, where EFM applications can be statistical analyses of flow time series or also map habitat or simulate population dynamics, is useful because the hierarchy 1) allows modeling to be easily customized the level of technical support required by different studies and 2) offers opportunities to engage study teams and stakeholders by producing results at each stage of application.

The rest of this chapter focuses on use of EFM to analyze flow regimes and map habitat.

4.2 Process, Terminology, and User Interfaces

The process of applying EFM involves three basic phases: statistical analyses, hydraulic modeling, and use of GIS (figure 19). Most user interfaces in EFM support the statistical phase where users identify water management scenarios (“flow regimes”) and aspects of the ecosystem (“relationships”) to be investigated. Results from the statistical phase are then input to external hydraulic models that generate layers of water depth, velocity, and inundation, which are then used in GIS to investigate spatial criteria and results for the flow regimes and relationships.

The logic of applying EFM follows: if EFM is used to look at a hydrograph (flow regime) in an ecologically meaningful way (relationship), the result will be relevant to the ecosystem aspect of interest (statistical results) and since the result is ecological relevant, a map of that result will also be ecologically relevant (hydraulic modeling) and since maps are spatial, additional criteria like depth and velocity preferences can then be considered to further refine the representation of the ecosystem aspect of interest (spatial results).

4.2.1 Flow Regimes

An EFM "flow regime" is defined as two concurrent daily time series that reflect conditions at a single location. Typically, the two series are daily mean flows and stages. Time series can be

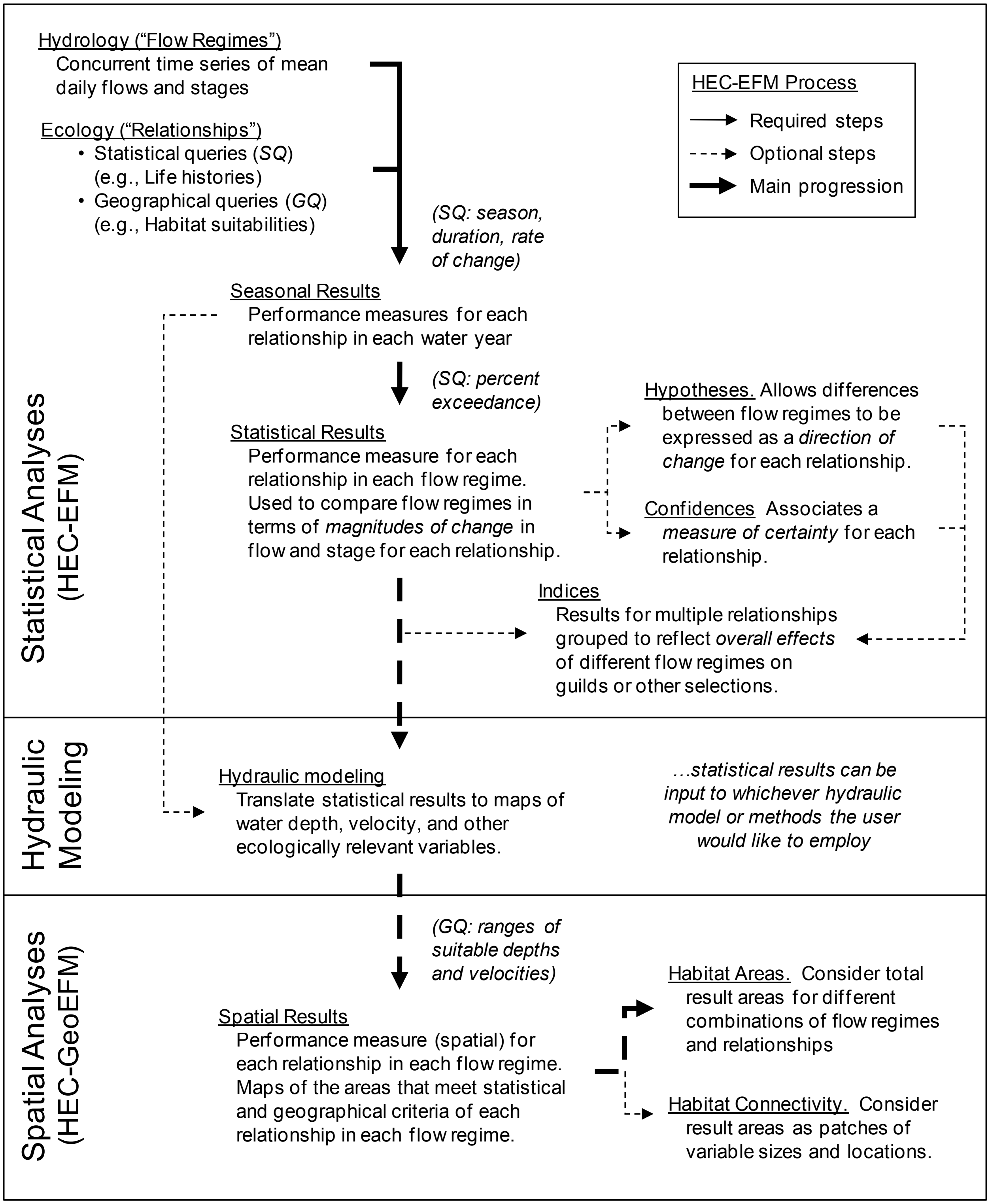
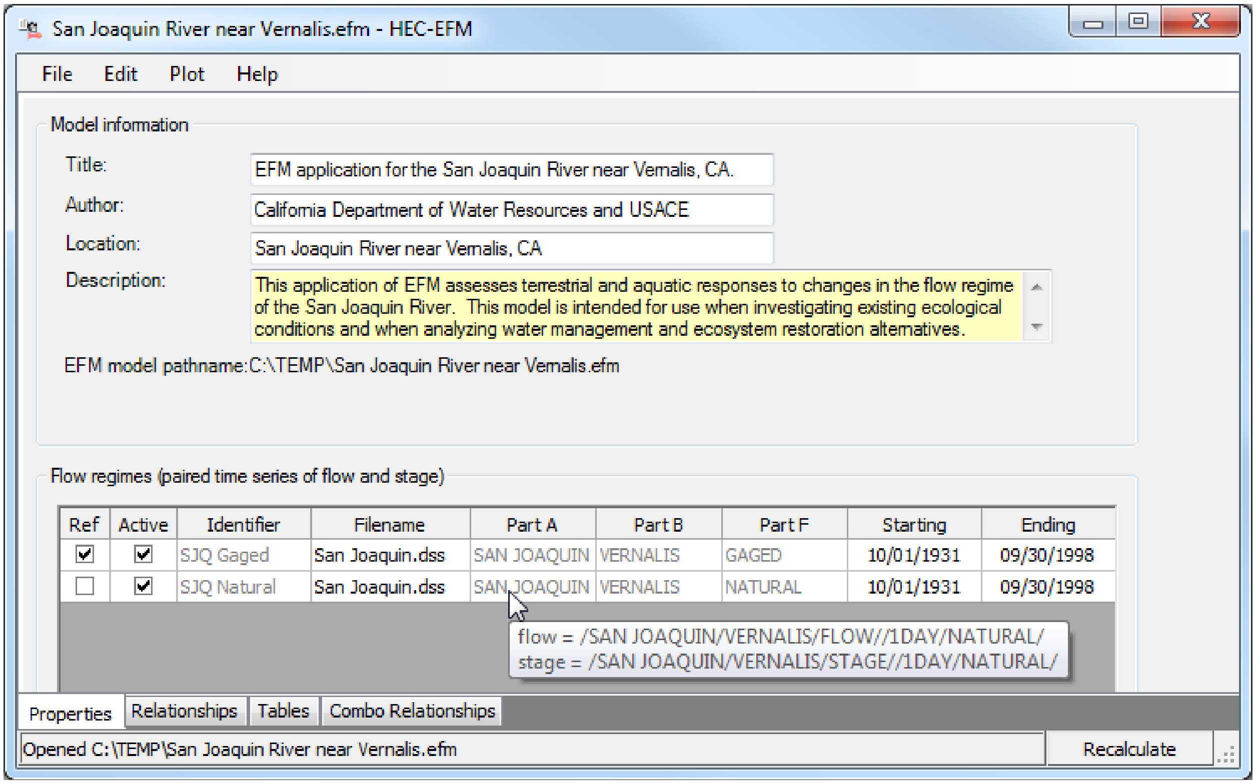


Figure 19. Detailed inputs, outputs, and sequence for the EFM process.

imported in a variety of text formats (i.e., comma, space, and tab delimited) and directly from the Data Storage System (HEC-DSS), which is the database used by HEC models for storage of time series and other data (USACE 2009a).

Data for flow regimes are imported via the Properties Tab (figure 20). EFM allows thousands of flow regimes to be analyzed within one application. Over 340 flow regimes were analyzed in the Bill Williams River application (discussed, in part, later in this chapter).



Title: EFM application for the San Joaquin River near Vernalis, CA.

Author: California Department of Water Resources and USACE

Location: San Joaquin River near Vernalis, CA

Description: This application of EFM assesses terrestrial and aquatic responses to changes in the flow regime of the San Joaquin River. This model is intended for use when investigating existing ecological conditions and when analyzing water management and ecosystem restoration alternatives.

EFM model pathname:C:\TEMP\San Joaquin River near Vernalis.efm

Ref	Active	Identifier	Filename	Part A	Part B	Part F	Starting	Ending
☑	☑	SJQ Gaged	San Joaquin.dss	SAN JOAQUIN	VERNALIS	GAGED	10/01/1931	09/30/1998
☐	☑	SJQ Natural	San Joaquin.dss	SAN JOAQUIN	VERNALIS	NATURAL	10/01/1931	09/30/1998

flow = /SAN JOAQUIN/VERNALIS/FLOW//1DAY/NATURAL/
stage = /SAN JOAQUIN/VERNALIS/STAGE//1DAY/NATURAL/

Opened C:\TEMP\San Joaquin River near Vernalis.efm

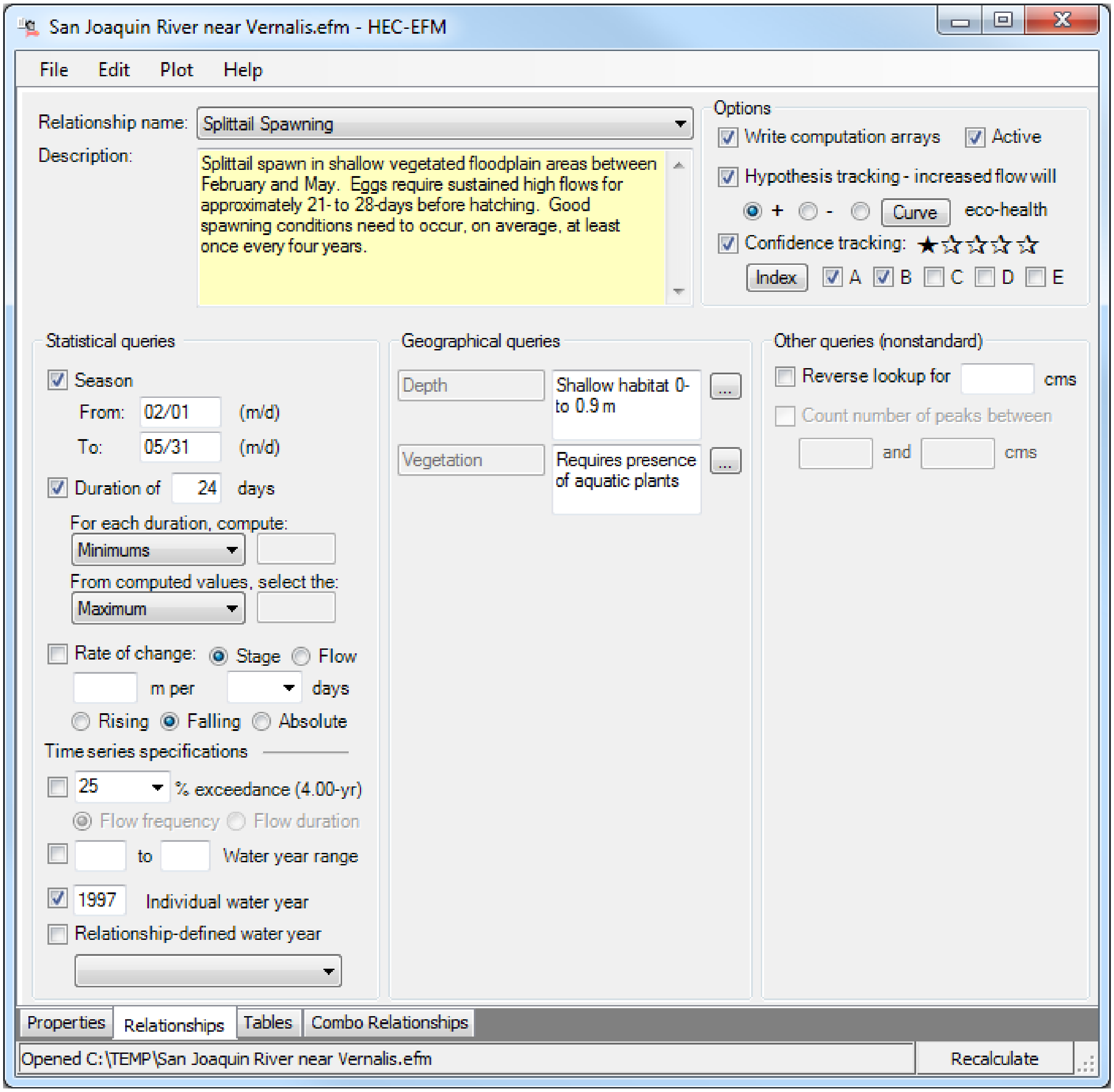
Figure 20. Properties tab of EFM, which supports entry of flow regimes to be studied as well as general information about the modeling effort.

Flow regimes can be selected or deselected for analysis via the “Active” checkbox on the Properties Tab. Only one may be identified as the reference, which is the flow regime that all other active flow regimes will be compared to when considering statistical and spatial outputs.

4.2.2 Relationships

Central to EFM analyses are "relationships" that link characteristics of the flow regimes to elements of the ecosystem through statistical and geographical queries (figure 21). Most EFM applications use a combination of expert knowledge, scientific literature, and field data to define relationships. At a fundamental level, each source reflects a level of understanding for connections between hydrology and ecology, whether for biotic responses or processes related to flow dynamics such as channel migration, depth to groundwater, and recruitment of woody debris.

Life history information has proven useful in defining statistical queries for relationships that investigate biota. This information provides insights into the timing of species life stages, requisite conditions for their success (e.g., a fish that spawns in the spring during the high flows of the wet season), and can be interpreted in terms of simple statistical criteria such as start date and end date as well as help to identify which flow dynamics (e.g., high flows or low flows) are



Relationship name: Splittail Spawning

Description: Splittail spawn in shallow vegetated floodplain areas between February and May. Eggs require sustained high flows for approximately 21- to 28-days before hatching. Good spawning conditions need to occur, on average, at least once every four years.

Options
☑ Write computation arrays ☑ Active
☑ Hypothesis tracking - increased flow will
● + ○ - ○ Curve eco-health
☑ Confidence tracking: ★☆☆☆☆
Index ☑ A ☑ B ☐ C ☐ D ☐ E

Statistical queries
☑ Season
From: 02/01 (m/d)
To: 05/31 (m/d)
☑ Duration of 24 days
For each duration, compute: Minimums
From computed values, select the: Maximum
☐ Rate of change: ● Stage ○ Flow
m per days
○ Rising ● Falling ○ Absolute
Time series specifications
☐ 25 % exceedance (4.00-yr)
● Flow frequency ○ Flow duration
☐ to Water year range
☑ 1997 Individual water year
☐ Relationship-defined water year

Geographical queries
Depth: Shallow habitat 0- to 0.9 m
Vegetation: Requires presence of aquatic plants

Other queries (nonstandard)
☐ Reverse lookup for cms
☐ Count number of peaks between and cms

Opened C:\TEMP\San Joaquin River near Vernalis.efm

Figure 21. Relationships tab of EFM, which supports entry of relationships to be studied, including statistical and geographical queries and options for hypothesis tracking, confidence tracking, and generating output.

important for a given life stage. Users enter these parameters to instruct EFM how to narrow all dynamics of a hydrograph to those most relevant to the particular ecosystem aspect. Equations are determined by the statistical queries selected for each relationship and then parameterized based on user input. This first lens applied to assess a relationship is the statistical phase of the EFM process.

Habitat preferences, or habitat suitability indices, are commonly used in defining geographical queries for relationships that investigate biota. These are most typically expressed as ranges of suitable depths or velocities (e.g., a fish that spawns during high flows in the spring and requires water depths between 0 and 0.9 m) and are applied to the layers generated by the hydraulic models to determine which areas meet the geographical queries. This secondary lens guides how relationships are assessed spatially using GIS.

Many relationships can be analyzed within one application. A diagnostic application used to test the statistical features of EFM has 806 relationships. In addition to the statistical and geographical queries, relationships may also be defined by hypotheses, confidences, and membership in indices, though these are all optional.

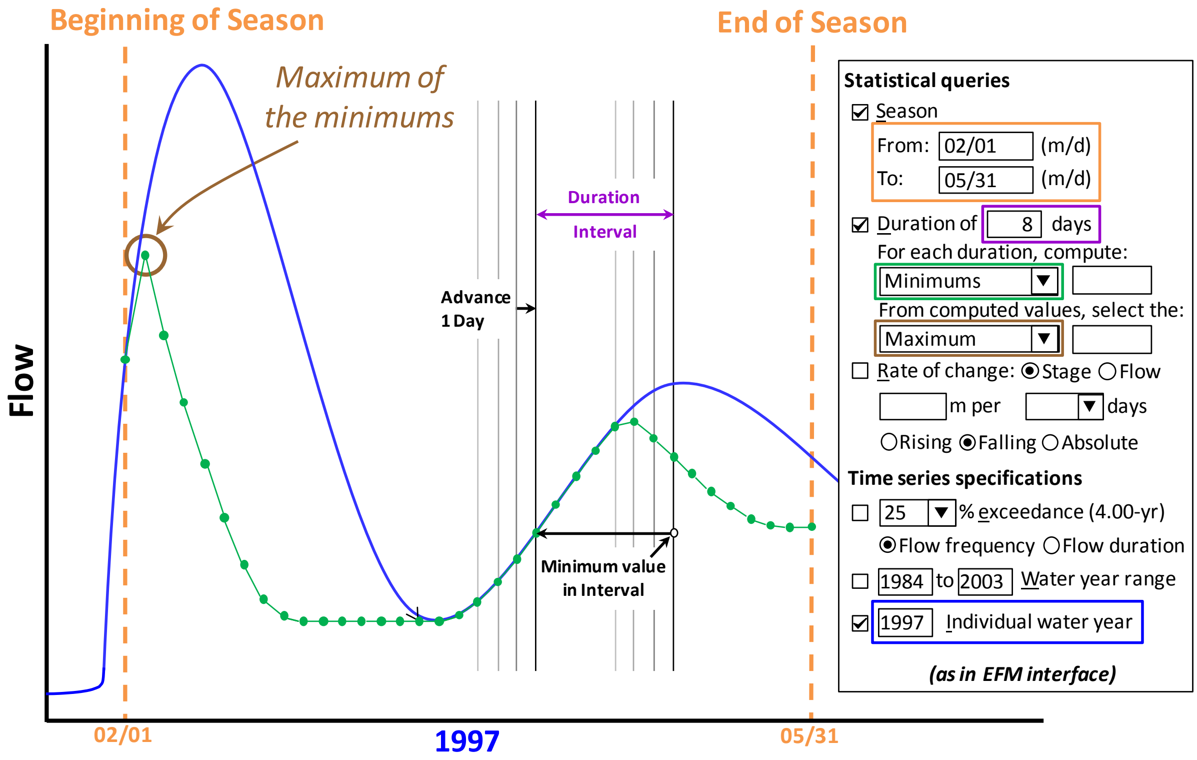
4.2.3 Statistical Queries

Statistical queries (figure 21) are defined as combinations of four basic parameters: 1) season, 2) duration, 3) rate of change, and 4) percent exceedance (for flow frequencies or flow durations). The first three guide how EFM goes from a full flow regime to "seasonal results" (one per water year; each is a performance measure for the relationship in that year); the fourth informs how seasonal results are used to determine a "statistical result" (one per period of record; a single performance measure for the whole flow regime) for each individual relationship. This winnowing procedure, where full periods of hydrologic time series are reduced to single statistical results, is repeated for each pairing of flow regime and relationship.

Season. Ecosystem dynamics typically occur in specific time periods of the year (e.g., fish spawning or seed germination). Within EFM, season is defined by start and end dates. During computations, daily data required to analyze the season are taken from each water year being investigated. All duration and rate of change queries are performed on these seasonal extracts.

Duration. Duration is a versatile, but complicated query. It has three settings: 1) duration interval, 2) a selection of statistics to be computed for each duration interval in the season, and 3) a selection of statistics to be computed using the time series of interval values computed per setting 2. Calculations are performed from the beginning of season to the end of season. So for the start date, EFM considers all data values within the duration interval (per setting 1), computes a statistic of minimums, medians, maximums, user defined percentages, or means (per setting 2), records that value for the start date, and then advances a day and repeats the process until the end of season is reached. This produces a statistical time series that has one value for each day of the season. The final step in the duration query involves selecting the minimum, median, maximum, user defined percentage, or mean value (per setting 3) of the statistical time series. This produces a time series of seasonal results that has one value per season. Figure 22 provides an example of this process using an 8 day duration interval, minimums, and then maximum of the minimums, a combination of settings which has been used in EFM relationships for fish egg incubation (as described in the San Joaquin River case study), fish floodplain access, and bird nest protection via suppression of predators.

Rate of change. The rate of change query allows users to investigate rising, falling, and absolute rates of change for both stage and flow. The query uses two parameters: a threshold value for change and number of days. For each day beginning at the end of the season and working backwards in time, the actual rate of change is computed by subtracting the current flow or stage and the flow or stage at the end of the time interval defined by the number of days. The actual rate of change is then compared to the threshold value. If actual does not violate the threshold, the rate of change is deemed acceptable, EFM moves backwards one day, and the test is repeated. This continues until the threshold is violated or the beginning of season is reached. If the threshold is violated, EFM selects the previous successful test (one day later than the failed test) as the seasonal result, which represents the date and conditions where rates of change became consistently acceptable for the rest of the season. If the beginning of season is reached and passes the rate of change test, EFM selects that date and its corresponding conditions as the seasonal result. Figure 23 provides an example of this process for stage recession, which has been used in EFM relationships for recruitment of riparian tree seedlings (as described in the Bill Williams River case study).



Statistical queries

☑ Season

From: 02/01 (m/d)

To: 05/31 (m/d)

☑ Duration of 8 days

For each duration, compute: Minimums ▼

From computed values, select the: Maximum ▼

☐ Rate of change: ● Stage ○ Flow

m per ▼ days

○ Rising ● Falling ○ Absolute

Time series specifications

☐ 25 ▼ % exceedance (4.00-yr)

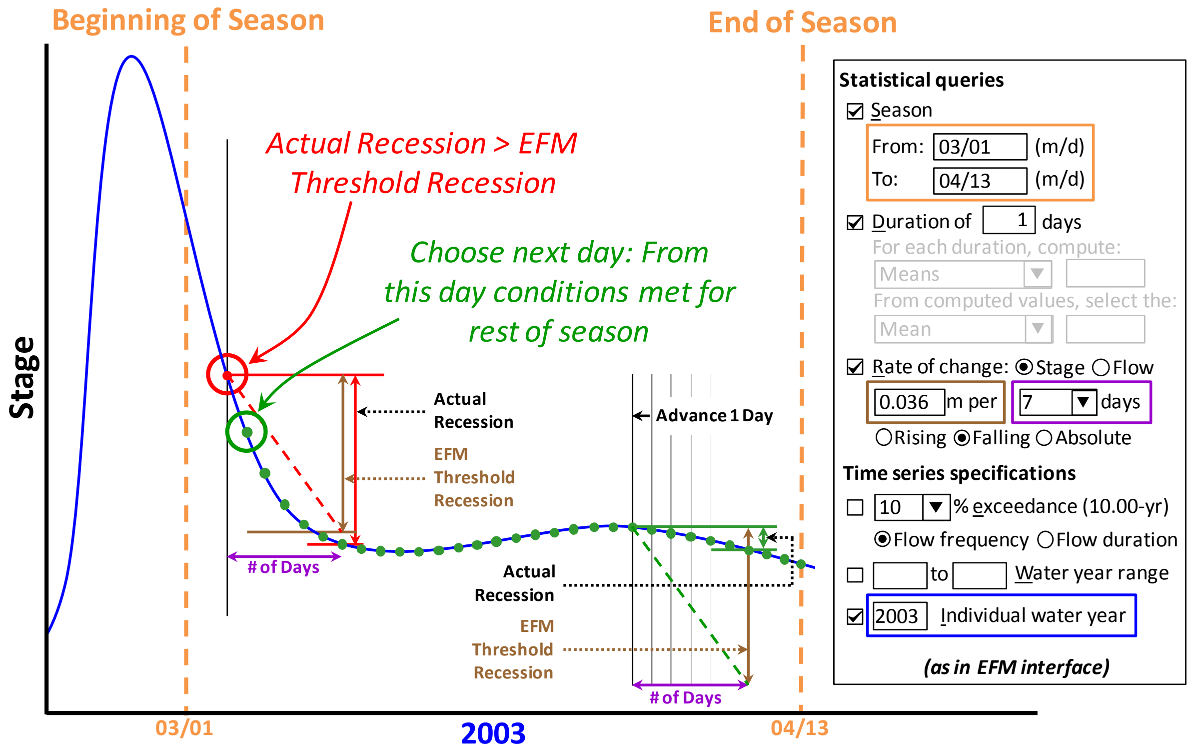
● Flow frequency ○ Flow duration

☐ 1984 to 2003 Water year range

☑ 1997 Individual water year

Figure 22. Sample use of the duration query in EFM. Computations are shown for one water year.

Percent Exceedance. The percent exceedance query offers a choice of either flow frequency or flow duration. When flow frequency is selected, EFM ranks the seasonal results for each year (computed via the Season, Duration, and Rate of change queries) and interpolates to obtain the flow (or stage, if Rate of change is being used to investigate stage dynamics) that is equaled or exceeded for the user-defined percentage of years. The resulting value would be the statistical result (figure 24). When flow duration is selected, EFM generates a flow duration curve using mean daily values obtained from the flow regimes in the seasonal extract and then interpolates to obtain the flow that corresponds to the user-defined percentage. The resulting value would be the statistical result. Figure 24 provides an example of a flow frequency query with a percent exceedance of 25%, which has been used in EFM relationships where desired ecological conditions are needed in only a fraction of years (as described in the San Joaquin River case study).



Statistical queries

☑ Season

From: 03/01 (m/d)

To: 04/13 (m/d)

☑ Duration of 1 days

For each duration, compute:

Means ▼

From computed values, select the:

Mean ▼

☑ Rate of change: ● Stage ○ Flow

0.036 m per 7 ▼ days

○ Rising ● Falling ○ Absolute

Time series specifications

☐ 10 ▼ % exceedance (10.00-yr)

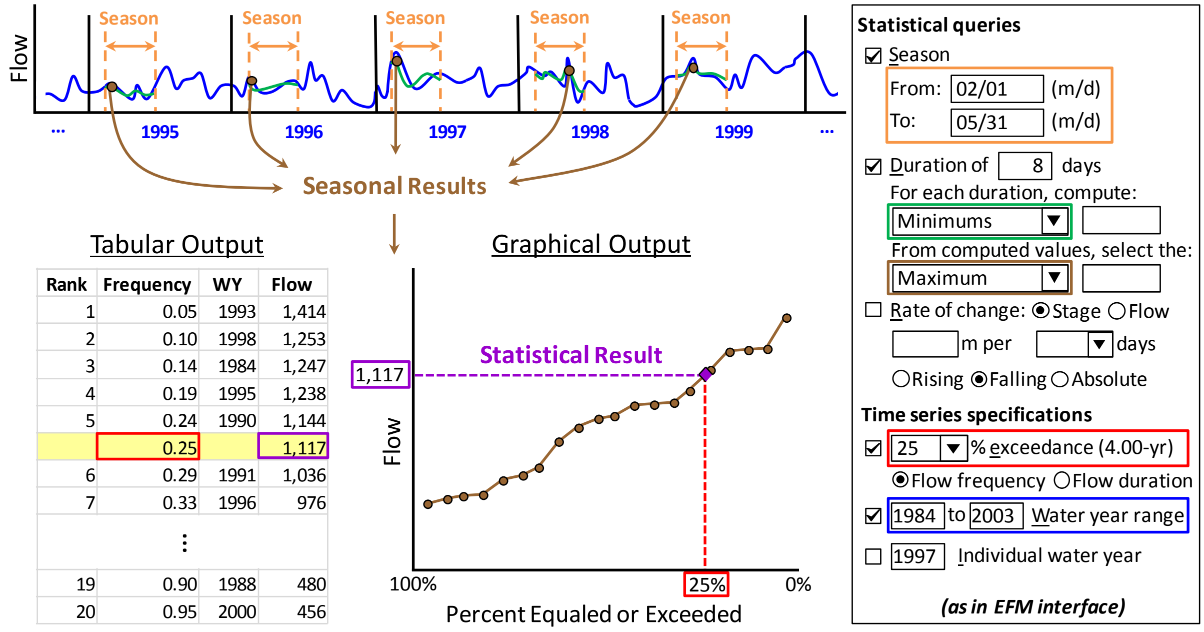
● Flow frequency ○ Flow duration

☐ to Water year range

☑ 2003 Individual water year

(as in EFM interface)

Figure 23. Sample use of the rate of change query in EFM. Computations are shown for one water year.



Rank	Frequency	WY	Flow
1	0.05	1993	1,414
2	0.10	1998	1,253
3	0.14	1984	1,247
4	0.19	1995	1,238
5	0.24	1990	1,144
	0.25		1,117
6	0.29	1991	1,036
7	0.33	1996	976
	⋮		
19	0.90	1988	480
20	0.95	2000	456

Statistical queries

☑ Season

From: 02/01 (m/d)

To: 05/31 (m/d)

☑ Duration of 8 days

For each duration, compute:

Minimums ▼

From computed values, select the:

Maximum ▼

☐ Rate of change: ● Stage ○ Flow

m per ▼ days

○ Rising ● Falling ○ Absolute

Time series specifications

☑ 25 ▼ % exceedance (4.00-yr)

● Flow frequency ○ Flow duration

☑ 1984 to 2003 Water year range

☐ 1997 Individual water year

(as in EFM interface)

Figure 24. Sample use of the time series specifications (percent exceedance – flow frequency – water year range) for a relationship with season and duration queries (as in figures 21 and 22). The statistical result is the flow meeting the parameters in those queries that is equaled or exceeded in 25% of the seasonal results.

4.2.4 Hypothesis Tracking

Users have the option to enter a hypothesis about whether a higher statistical result (i.e., more flow or stage) will help, hurt, or have a non-linear response for an individual relationship. EFM uses this information to perform the first predictions of ecosystem responses by comparing statistical results of each active non-reference flow regime with the statistical result of the reference flow regime.

4.2.5 Confidence Tracking

Confidence tracking provides a way to track the relative certainty of EFM relationships. When this option is used, EFM tracks a single confidence value per relationship. The default is one star out of a maximum of five (figure 21). This starting point implies that there is the same amount of scientific understanding for each relationship. As confidence in a particular relationship grows, its number of stars can be increased. This usually occurs at the discretion of the study team, perhaps when the relationship is verified with field data, backed with scientific literature, or approved by a group of scientists or agencies. Confidence tracking is used to help maturation of individual relationships within an EFM project. Confidence also serves as a weighting factor when relationships are grouped in indices.

4.2.6 Indices

If both hypothesis tracking and confidence tracking are used, relationships can then be enrolled in indices. In EFM, indices are used to numerically group relationships that share some commonality. For instance, if multiple relationships are created for different species of fish, those could be grouped into a single “fish” index, which could be used to reflect the overall effects of flow regimes on fish. Each index is computed using a combination of information about relationships and statistical results based on the following equation:

$$Index = \sum_{i=1 \ldots n} (Direction\_of\_Change_i * Confidence_i * \%Change\_in\_EcoValue_i)$$

where *n* is the number of relationships in the index, *direction of change* indicates whether a relationship is faring better (+1), worse (-1), or the same (0) in the alternative flow regime as compared to the reference flow regime, *confidence* is the confidence value (integer 0 to 5) of a relationship, and *percent change in ecovalue* is the magnitude of change between reference and alternative flow regimes.

Ecovalues are computed using a paired flow and ecovalue table entered via the hypothesis tracking feature for a specific relationship. This process allows 1) consideration of non-linear hypotheses and 2) application of dimensionless scales to statistical results. Non-linear hypotheses are useful when statistical results (in terms of flow) are not directly proportional to ecological responses. For instance, if a fish spawns during high flows and requires water depths between 0 and 0.9 m, the amount of spawning habitat is related to both flow and topography. Habitat might increase with flow until inundation reached high ground such that additional flow would result in a net loss of habitat (shallow habitats gained on the slightly expanding edge of inundation would be more than offset by already inundated areas becoming too deep). This example can also illustrate the application of scales to statistical results. Using a 0 to 10 scale, the flow rate that generates the most spawning area would be optimal and have an ecovalue of 10. Zero flow would likely correspond to an ecovalue of 0. Any additional points shape the piecewise linear function of flow versus ecosystem response over the range of possible statistical results. The term "ecovalue" was actually coined to label the output of this scaling process, or specifically, as a dimensionless measure of how successfully a flow regime met the criteria of a relationship.

For indices, statistical results are translated to ecovalues. *Percent change in ecovalue* is equal to the difference between a relationship's ecovalue for an alternative flow regime and its ecovalue for the reference flow regime, which is then divided by the relationship ecovalue of the reference and multiplied by 100. When flow-ecovalue tables are not used, percent change is based on statistical results instead of ecovalues.

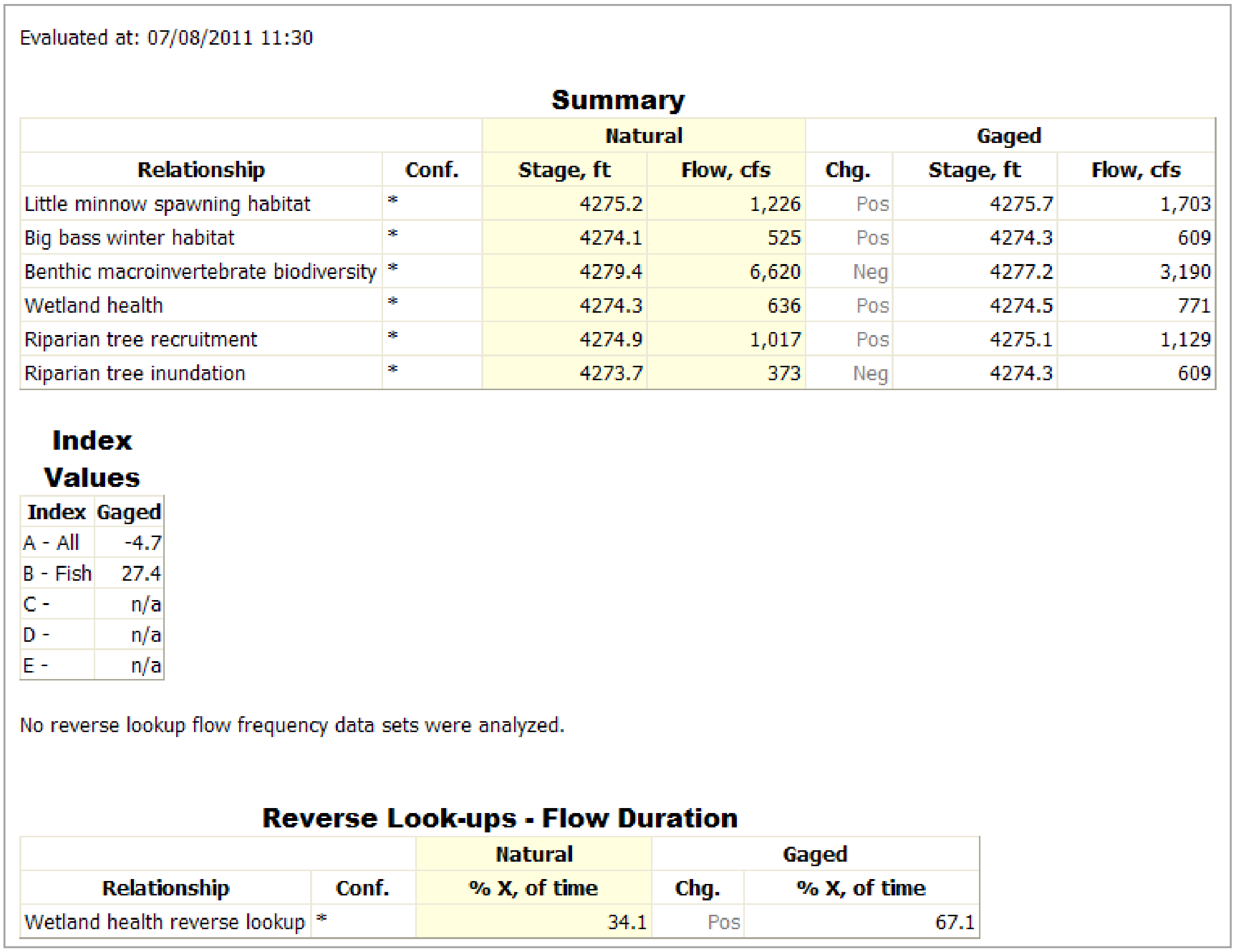
4.2.7 Time Series Specifications

Each flow regime has a start and end date (figure 20). These dates bracket the maximum period of record specified for analysis. Relationships offer time series controls that allow users to specify a water year range or an individual water year to be computed (figures 21-24). The combination of these dates and settings determine the period of analysis for each pairing of flow regime and relationship. Seasons with missing data, whether blank, non-numeric, or identified per user settings, may be omitted from analyses at the direction of the user.

4.3 Statistical Results

After flow regimes have been imported and relationships developed, EFM performs the statistical calculations called for by each user-defined relationship for each active flow regime. This produces a single flow and stage value (statistical result) for each combination of flow regime and relationship. Ecosystem responses for different flow regimes can be predicted based only on these statistical results and the hypothesis tracking. Figure 25, for example, shows statistical results for two flow regimes, 7 relationships, and 2 indices. Natural is the reference flow regime. Success of most (5 of 7) relationships improved with the alternative flow regime, as indicated by the "Pos" responses noted in the change column. The "Fish" index, which included the little minnow and big bass relationships, showed a net positive effect for fishes. The "All" index, which included all relationships except for "Wetland health reverse lookup", showed a slight overall negative effect.

For some applications of EFM, this statistical comparison of different flow regimes is as far as the analytical process needs to be carried. Other applications proceed to spatial investigations through the use of hydraulic modeling.



Evaluated at: 07/08/2011 11:30

Summary

		Natural			Gaged	
Relationship	**Conf.**	**Stage, ft**	**Flow, cfs**	**Chg.**	**Stage, ft**	**Flow, cfs**
Little minnow spawning habitat	*	4275.2	1,226	Pos	4275.7	1,703
Big bass winter habitat	*	4274.1	525	Pos	4274.3	609
Benthic macroinvertebrate biodiversity	*	4279.4	6,620	Neg	4277.2	3,190
Wetland health	*	4274.3	636	Pos	4274.5	771
Riparian tree recruitment	*	4274.9	1,017	Pos	4275.1	1,129
Riparian tree inundation	*	4273.7	373	Neg	4274.3	609

Index Values

Index	Gaged
A - All	-4.7
B - Fish	27.4
C -	n/a
D -	n/a
E -	n/a

No reverse lookup flow frequency data sets were analyzed.

Reverse Look-ups - Flow Duration

		Natural		Gaged
Relationship	**Conf.**	**% X, of time**	**Chg.**	**% X, of time**
Wetland health reverse lookup	*	34.1	Pos	67.1

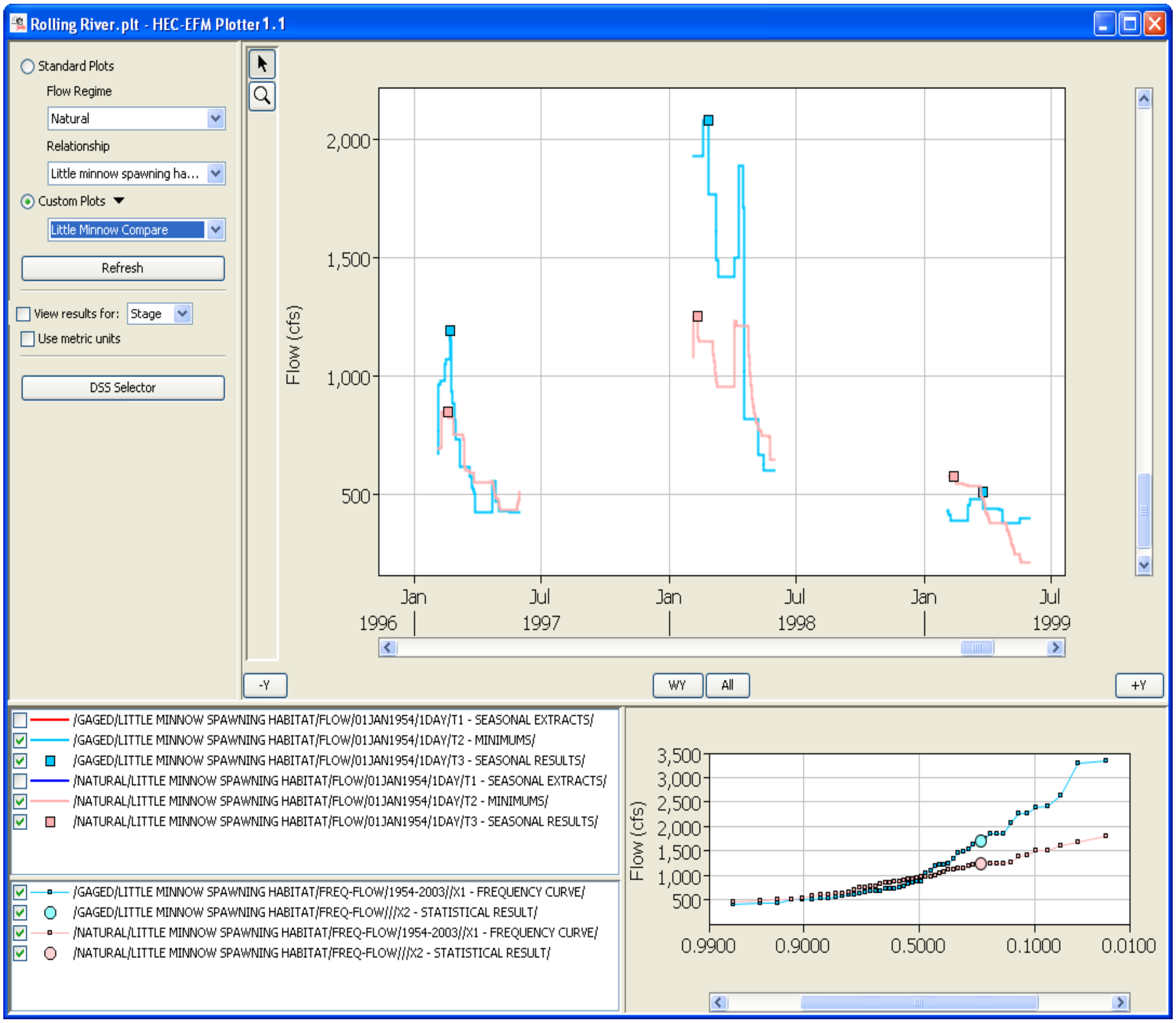
Figure 25. Statistical results reported by EFM.

4.4 Viewing Statistical Output (EFM Plotter)

As a default, only the statistical results are reported to the user when a compute cycle is completed. However, users can obtain output detailing every step of the statistical analyses, which can then be displayed using a EFM accessory called EFM Plotter. Plotter helps users view output and compare results for different flow regimes and relationships. Additionally, by displaying each computational step that EFM performs while analyzing time series, Plotter offers an opportunity to understand the statistical processes being used by EFM and provides a way for teams to interactively explore and refine the statistical settings that define the relationships between hydrology and ecology (figure 26).

4.5 Hydraulic Modeling

Hydraulic models are used in the EFM process to generate maps of the statistical results. The most common hydraulic outputs are maps of water depths and velocities though there is much potential to expand this to include maps of shear stress, wetted perimeter, and other hydraulic variables that may have ecological significance. EFM does not have any internal hydraulic modeling capabilities. Instead, statistical results generated by EFM can be input to whichever



○ Standard Plots
Flow Regime: Natural
Relationship: Little minnow spawning ha...
● Custom Plots
Little Minnow Compare
☐ View results for: Stage
☐ Use metric units

☐ /GAGED/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T1 - SEASONAL EXTRACTS/
☑ /GAGED/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T2 - MINIMUMS/
☑ /GAGED/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T3 - SEASONAL RESULTS/
☐ /NATURAL/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T1 - SEASONAL EXTRACTS/
☑ /NATURAL/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T2 - MINIMUMS/
☑ /NATURAL/LITTLE MINNOW SPAWNING HABITAT/FLOW/01JAN1954/1DAY/T3 - SEASONAL RESULTS/

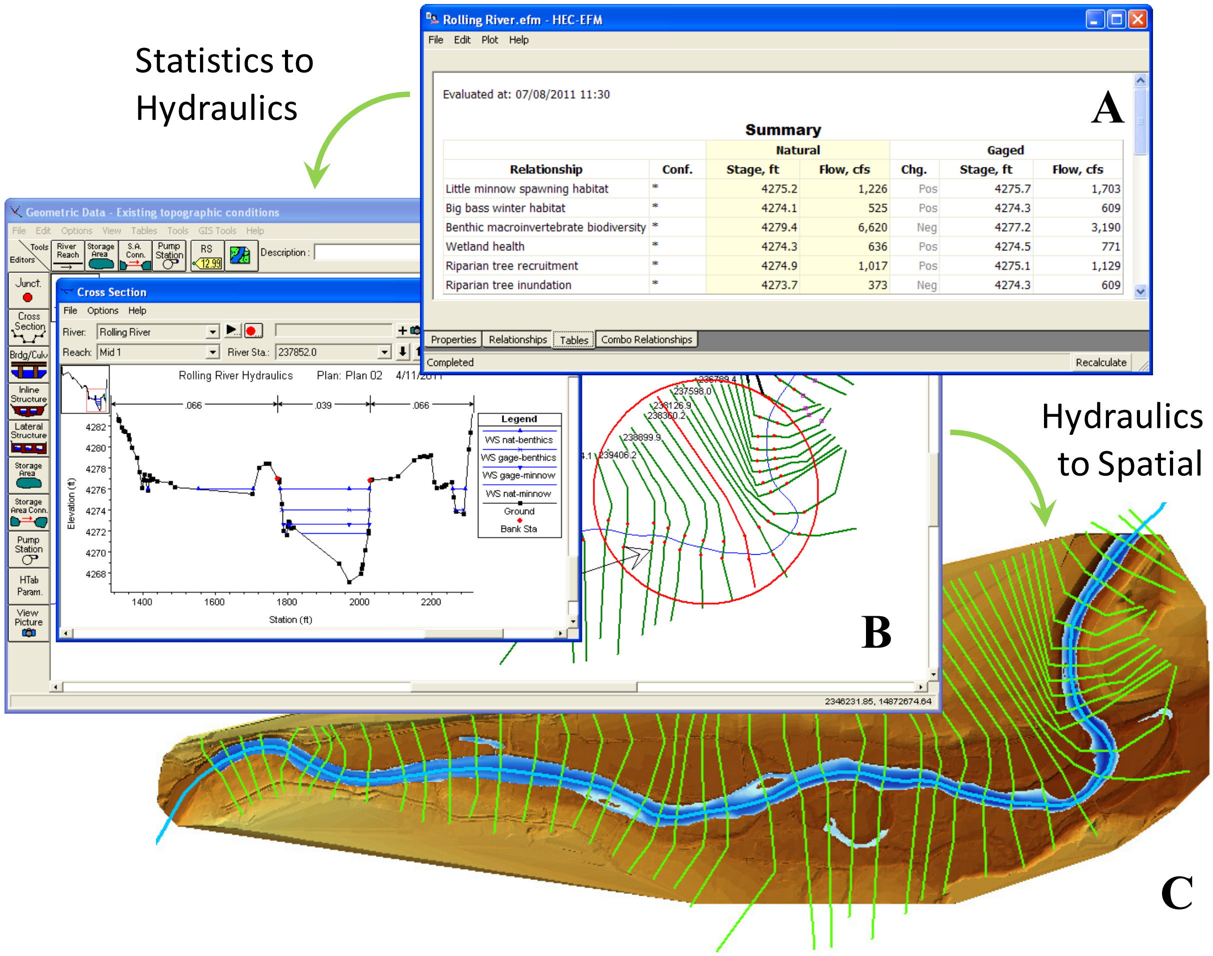
☑ /GAGED/LITTLE MINNOW SPAWNING HABITAT/FREQ-FLOW/1954-2003//X1 - FREQUENCY CURVE/
☑ /GAGED/LITTLE MINNOW SPAWNING HABITAT/FREQ-FLOW///X2 - STATISTICAL RESULT/
☑ /NATURAL/LITTLE MINNOW SPAWNING HABITAT/FREQ-FLOW/1954-2003//X1 - FREQUENCY CURVE/
☑ /NATURAL/LITTLE MINNOW SPAWNING HABITAT/FREQ-FLOW///X2 - STATISTICAL RESULT/

Figure 26. Graphical display of statistical computations and output using EFM Plotter.

hydraulic model the user is inclined to employ. As statistical results are expressed as a single flow and stage that meet the user-defined criteria for a relationship, steady-state simulations (flow values are simulated independently as opposed to being simulated as part of a dynamic hydrograph) are typically used to map the hydraulic conditions associated with the statistical results (figure 27; figure 19).

4.6 Use of GIS

Using statistical analyses and hydraulic modeling results, GIS can be used to show relevant areas in accordance with the geographical queries of a particular relationship. The resulting layer is known as the “spatial result” and represents the areas that meet both the statistical and spatial criteria used to define a relationship. Spatial results can overlay different base maps and data layers to highlight promising areas for restoration or management actions.



Evaluated at: 07/08/2011 11:30

Summary

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Wetland health	*	4274.3	636	Pos	4274.5	771
Riparian tree recruitment	*	4274.9	1,017	Pos	4275.1	1,129
Riparian tree inundation	*	4273.7	373	Neg	4274.3	609

Figure 27. Transitions in the EFM process where statistical results (A) are input to river hydraulics modeling (B) with modeling results being imported to GIS for spatial analyses (C).

4.6.1 HEC-GeoEFM

HEC and the Environmental Systems Research Institute (ESRI) are developing a tool called HEC-GeoEFM to serve as the spatial component of EFM (USACE 2011b). GeoEFM is being programmed as an extension for ArcMap and packages several GIS functions commonly used in EFM applications, including management of spatial data sets, comparisons of spatial result areas for different flow regimes and relationships, and calculators for performing geographical queries. GeoEFM also has a patch tool that analyses the connectivity of spatial result areas or other layers.

4.7 Case Studies of Habitat Quantification

Data requirements of EFM applications are related to the desired level of detail. If only statistical results are desired, required data consist of only the flow regimes to be analyzed and the relationships between hydrology and ecology. If the user wants spatial results, data (and software) requirements increase significantly to include digital topography, a geo-referenced hydraulic model, and any other spatial data relevant to the investigation.

This section shows use of the EFM process to statistically and spatially analyze spawning conditions for the Sacramento splittail minnow (*Pogonichthys macrolepidotus*) during gaged and unimpaired flow regimes for the San Joaquin River near Vernalis, California (Jones & Stokes 2000; USACE and Rec Board 2002), and cottonwood (*Populus fremontii*) seedling establishment for an experimental flood on the Bill Williams River in Arizona (Fields 2009; Shafroth et al. 2010).

Statistical criteria for splittail minnow and cottonwood seedling relationships (table 8) were adapted from existing EFM applications for the San Joaquin River and the Bill Williams River, respectively. Limited backgrounds for these analyses are described below to provide context for the demonstrations as opposed to providing support, documentation, or justification for the full applications (which appear in the references).

Table 8. Parameters for the Sacramento splittail minnow spawning and cottonwood seedling establishment relationships in EFM (Jones & Stokes 2000; Fields 2009; Shafroth et al. 2010).

		Sacramento splittail minnow		***Cottonwoods***	
Statistical Queries		Splittail Spawning	Channel Habitat	Seedling Establishment	Open Water
Season	Start Date	01Feb	01Oct	14Mar	30Mar
	End Date	31May	30Sep	13Apr	31Dec
Duration	Interval	21 days	1 day	1 day	20 days
	Interval Statistics	Minimums	Means	---*	Minimums
	Seasonal Result	Maximum	Maximum	---*	Maximum
Rate of Change	Threshold Rate	---*	---*	0.06 m/day 0.20 ft/day	---*
	Interval (days)	---*	---*	7	---*
Percent Exceedance	Flow Frequency	25%	67%	---*	---*
Time Series Settings	Individual Water Year	---*	---*	2006	2006

*** Statistical queries noted with an asterisk (“---*”) mark options not applied as part of the relationship.**

Both studies used the River Analysis System (HEC-RAS; USACE 2010b) to perform the steady-flow simulations used to translate statistical results to water surface profiles. Water surface profiles were then exported to GIS and used with a digital terrain model to generate layers of water depth using HEC-GeoRAS (USACE 2009b). HEC-GeoRAS also can generate layers of water velocity and shear stress, although those data were not used here.

4.7.1 Sacramento splittail minnow spawning, San Joaquin River, California

The Sacramento splittail is a large minnow that lives in sloughs and valley rivers in California, primarily in the Delta area of the Central Valley and parts of the San Francisco estuary. Splittail populations have declined (in magnitude and range) as dams and diversions cut access to upstream river stretches and as floodplain areas, critical for splittail spawning, were developed as agricultural lands (Moyle 2002). Splittail were briefly listed as a threatened species under the federal Endangered Species Act and remain a species of special concern for the California Department of Fish and Game.

Flow regimes. Splittail spawning was investigated for gaged and unimpaired flow regimes for the San Joaquin River near Vernalis, 1931-1998. For the gaged flow regime, daily mean flows at the Vernalis gage were obtained from the U.S. Geological Survey (USGS 11303500). A flow-stage rating curve (current at the time of the study) was used to compute a concurrent time series of stage. Unimpaired flows were estimated by removing the effects of upstream reservoirs; concurrent unimpaired stages were computed using the same rating curve, extended to cover the higher flows of the unimpaired regime.

Relationships and life history information. Splittail spawning requires floodplain areas to be inundated during their spawning season, which peaks in March and April, and remain inundated long enough for adults to access the flooded areas and lay eggs, for egg incubation (3 to 7 days), and then to provide cover for larval fish (10 to 14 days). Most splittail minnows mature sexually at the end of their second year of an estimated life span of 5 to 7 years (Moyle 2002).

This life history was used by scientists and engineers to estimate parameters for the San Joaquin application EFM. Season was set from February 1st to May 31st to include the month before and after the peak spawning season. Duration was set as an interval of 21 days to accommodate both incubation and larval cover, to compute a time series of minimums (to ensure continued inundation) and then select the maximum of those minimums (the highest flow that supported effective spawning habitat) as the seasonal result. A percent exceedance query was used with a flow frequency setting of 25% of years based on the logic that good spawning conditions are not needed every year, but it is important that they occur on average at least once during the 3-5 year adult life stage of the splittail minnow (Jones & Stokes 2000; USACE and Rec Board 2002).

The San Joaquin River application also used a complementary relationship called “channel habitat” to delineate inundated areas that occur in the main channel of the river as opposed to the floodplain habitat areas preferred by spawning splittail minnows. As channel geometries reflect and, in some ways, evolve due to the actual flows a channel experiences through time, this relationship was only considered for the gaged flow regime. Other studies have used geographical queries to separate suitable and unsuitable habitats. That is, instead of using a complementary relationship (i.e., channel habitat), ranges of depths and velocities characteristic of floodplain areas were applied to hydraulic modeling output to separate inundated areas that behave as floodplain habitat from those that behave as channel habitat.

Statistical Analyses. Statistical results for the splittail spawning relationships were computed based on the criteria in table 8. The process used to obtain seasonal and then statistical results for each flow regime followed the same procedures shown in figures 17 and 19, respectively. Statistical results, which, again, are the flow and stage that meet all statistical criteria for a relationship and serve as a performance measure for each relationship and flow regime, are reported in table 9.

Table 9. Statistical results for EFM relationships related to Sacramento splittail minnow spawning, San Joaquin River near Vernalis, California.

	San Joaquin River near Vernalis, CA, 1931-1998			
	Unimpaired		Gaged	
Relationships	Stage, m (ft)	Flow, cms (cfs)	Stage, m (ft)	Flow, cms (cfs)
Splittail Spawning	7.8 (25.5)	1,023 (36,138)	5.4 (17.7)	521 (18,400)
Channel Habitat	---	---	2.7 (8.9)	182 (6,419)

Spatial Analyses. Depth grids based on the statistical results were created using HEC-RAS and HEC-GeoRAS. Spatial results for splittail spawning were created by clipping the area identified as “channel habitat” for the gaged flow regime from the splittail spawning depth grids for both the gaged and unimpaired flow regimes (table 10; figure 28). The remaining areas meet all statistical and geographical criteria for the splittail spawning relationship and, as a spatial representation of the statistical results, also serve as a performance measure for splittail spawning under the different flow regimes.

Table 10. Spatial results for EFM relationships related to Sacramento splittail minnow spawning, San Joaquin River between the Stanislaus River confluence and the I5 bridge near Manteca, California.

	San Joaquin River near Vernalis, CA, 1931-1998	
	Unimpaired	Gaged
Relationships	Habitat area, km^2 (ac)	Habitat area, km^2 (ac)
Splittail Spawning	9.9 (2,444)	4.1 (1,022)

Summary. Statistical results for the gaged flow regime were significantly lower than for the unimpaired flow regime. As splittail require floodplain habitat for spawning and higher flows typically translate to more floodplain inundation, statistical results indicates that splittail spawning is less successful with the gaged flow regime. Spatial results corroborate this interpretation of statistical results. The gaged flow regime provides 58% less habitat for splittail spawning than the unimpaired flow regime (table 10). Spawning habitat for both flow regimes is limited to areas between the levees, with the unimpaired flow regime activating nearly that whole area for splittail spawning and the gaged flow regime being more limited to areas along the main channel margins and abandoned flow paths.

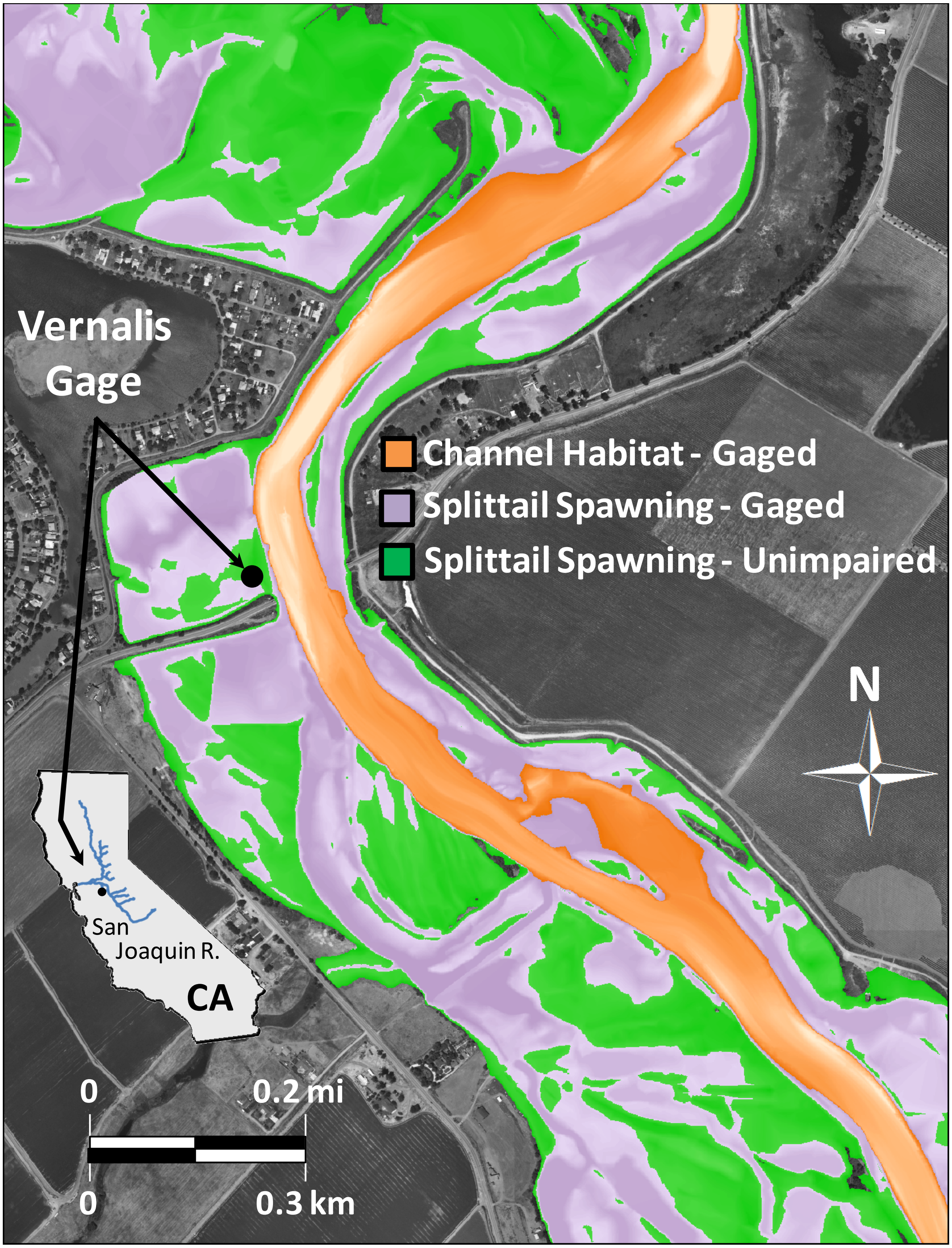

Figure 28. Spatial results for the splittail minnow spawning relationships, gaged and unimpaired flow regimes, for a stretch of the San Joaquin River near Vernalis, California. Spawning conditions for the gaged flow regime are represented by the purple layer of water depths and for the unimpaired flow regime by the green layer. The orange layer represents spatial results for the channel habitat relationship (gaged flow regime), which was used to separate aquatic habitat in the main channel from those in floodplain areas.

4.7.2 Cottonwood seedling establishment, Bill Williams River, Arizona

Cottonwood trees are fast growing and provide habitat for many species of animals, birds, and insects. Cottonwoods are a key riparian species in the western United States, but have generally declined in extent due to a combination of land use changes, hydrologic alteration, and invasive species (Auble et al. 1994; Cooper et al. 1999; Amlin and Rood 2002; Rood et al. 2005; Shafroth et al. 2010).

Flow regimes. EFM was used to simulate the cottonwood seedling establishment produced by an experimental flood released from Alamo Dam on the Bill Williams River in March of 2006. The experimental release was shaped with a sharp peak and gradual recession to encourage establishment of riparian tree seedlings (Shafroth et al. 2010). Daily mean flows for March and April 2006 were obtained for the Bill Williams River below Alamo Dam (USGS 09426000). Rating curves at each river cross section in the hydraulic model were produced by HEC-RAS and used by EFM to generate local stage time series.

Relationships and life history information. Cottonwood establishment occurs when seed release from adult trees coincides with a stage recession that is gradual enough to allow seedling root growth. Field studies of these dynamics have been performed for the Bill Williams River. Shafroth et al. (1998) estimated that the timing of cottonwood seed release began between the 19th and 26th of February and concluded between the 13th and 27th of April, depending on river location. Maximum rates of stage recession for test areas that supported cottonwood seedlings were measured at approximately 6 cm/day.

In EFM, beginning of season was set to March 14th to correspond to the peak of the experimental flood. The end of season was set to April 13th, though flows in April were nearly constant so results would not have changed with any end of season between the 13th and the 27th. The threshold recession rate was set at 0.06 m/day (0.20 feet/day) over a period of 7 days (Shafroth et al. 2010).

The Bill Williams River application used a complementary relationship to delineate channel areas that were continuously inundated for a period of 20 days after the 2006 experimental release. These resulting areas were predicted not to support seedling establishment due to either having open water throughout seed release and germination period (prevent initiation of seedlings) or inundating seedlings for a long enough duration to cause failure (loss to drowning).

Statistical Analyses. Rates of stage recession were tested by EFM using the statistical criteria in table 8 and the procedures shown in figure 23 to determine the portion of the flood recession gradual enough to support seedling root growth at each river cross section in the HEC-RAS model. This generated a set of seasonal and statistical results (since only one season was considered, the two results sets are identical) that was spatial distributed (table 11, figure 29, Fields 2009).

Table 11. Statistical results for EFM relationships related to Cottonwood seedling establishment, Bill Williams River, Arizona.

	Bill Williams River below Alamo Dam, AZ Experimental Flood (2006)	
Relationships	Flow, cms (cfs)	Number of Cross Sections
Seedling Establishment	55.5 (1,960)	25
	28.6 (1,010)	57
	12.5 (440)	236
	6.4 (226)	13
	6.1 (216)	6
	5.3 (187)	4
Seedling Drowning or Open Water	1.4 (48)	---

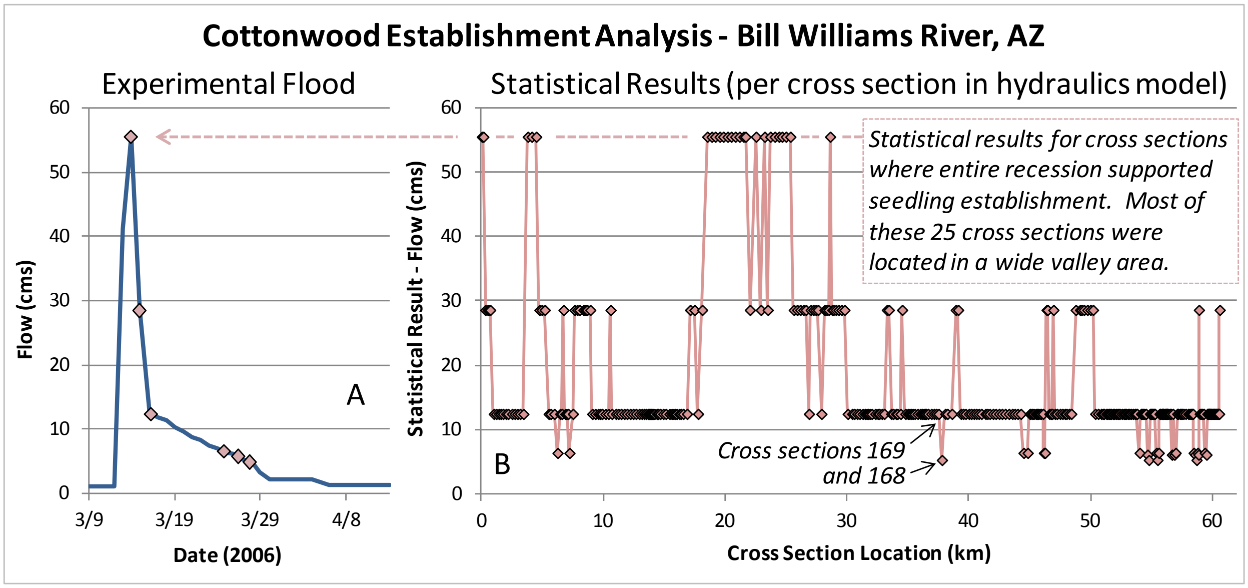

Figure 29. Hydrograph (A) and corresponding statistical results (B) for simulated cottonwood seedling establishment associated with an experimental flood, Bill Williams River, Arizona. Statistical results were generated for each of 341 cross sections in a river hydraulics model. Higher statistical results reflect river locations where channel shapes led to more gradual recession rates and were therefore predicted by EFM to be more conducive to seedling establishment. The most frequent statistical result was 12.5-cms.

Spatial Analyses. Creating spatial results for cottonwood seedling establishment required a more complicated process than splittail minnow spawning because a statistical result was computed at each cross section in the hydraulics model. While this allowed consideration of local stage recessions, it also led to a mixed set of results because flatter and wider cross sections were less likely to violate the rate of stage recession parameter and, therefore, statistical result at those locations would be higher on the recession limb of the experimental flood. Of the 341 cross sections, the rate of recession threshold was never violated for 25 cross sections, which, according to EFM, means that all inundation created by the experimental flood at those cross sections was conducive to seedling establishment. The remaining 316 cross sections violated the threshold at one of 5 subsequent points along the flood recession, which means that only the portion of the recession from the statistical result forward supported seedling establishment. Depth grids for the peak and the 5 points were generated independently and spliced halfway between cross sections with differing statistical results. A separate depth grid for the "open water" relationship was generated and clipped from the spliced layer to generate the spatial results layer for cottonwood seedling establishment (table 12; figure 30).

Table 12. Spatial results for EFM relationships related to cottonwood seedling establishment, Bill Williams River below Alamo Dam, Arizona. The seedling establishment value is the total area of spliced seedling area minus area that was subsequently inundated for more than 20 consecutive days (seedling drowning).

	Bill Williams River below Alamo Dam, AZ
	Experimental Flood (2006)
Relationships	Area, km^2 (ac)
Seedling Establishment	5.0 (1,227)
Seedling Drowning or Open Water	1.8 (445)

Summary. The experimental flood was predicted to establish 5.0 km^2 of cottonwood seedlings. The distribution of seedling areas varied spatially as a function of local topography with gentle sloped valley areas being most conducive to seedling establishment. These results are based on actual outflows from Alamo Dam in 2006. The same process of statistical and spatial analyses could be used in a forecast mode to customize hydrographs to produce specific ecological responses.

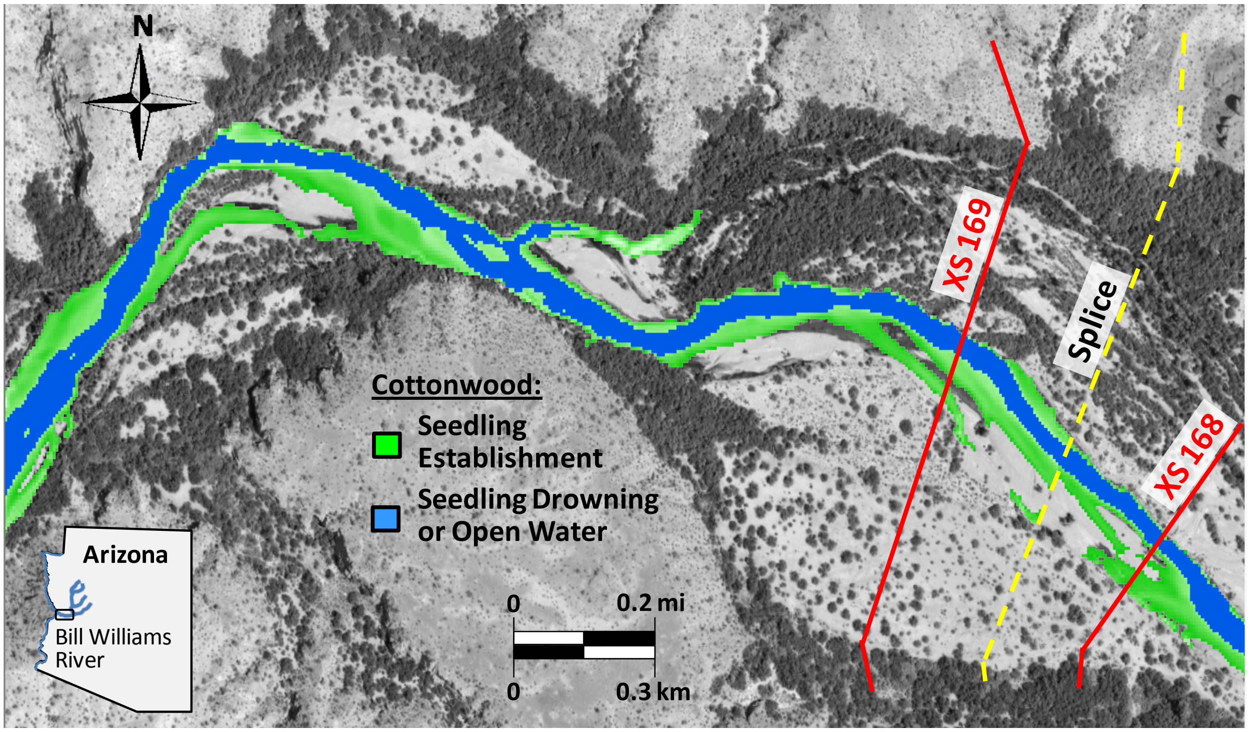

Figure 30. Spatial results for the cottonwood establishment relationships, experimental flood of March 2006, Bill Williams River below Alamo Dam, Arizona.

4.7.3 Discussion

The seasonal, statistical, and spatial results generated via the EFM process are each informative and useful in their own ways.

Seasonal results are the most direct measure of how ecosystem aspects fare in individual water years and, therefore, as a progression through time. These results are easily correlated with field data expressed annually (e.g., strength of year classes for fauna populations). A logical and powerful use of the EFM process would be to simulate seasonal results with a hydraulic model to produce sets of spatial seasonal results. This would allow habitat suitabilities to be considered in each water year and correlations to be performed spatially or in terms of habitat areas.

Statistical results are a simple and single performance measure for each relationship and flow regime. These are most useful when many ecological aspects and management alternatives are being considered. In these complex planning situations, too much information can obscure desirable alternatives. Statistical results offer a way to quickly compare alternatives and identify which are most effective at achieving project objectives.

Spatial results are visual and tend to generate the most attention and discussion. As a map of the areas that meet all the statistical and geographical criteria used to define a relationship, spatial results are also the most refined output of the EFM process. Resulting areas indicate the ecosystem benefits produced by different alternatives and can be used as input to the incremental cost analyses required in Corps restoration planning.

The splittail spawning and cottonwood seedling examples demonstrate applications of EFM. The splittail spawning example used a single channel topography with differing flow regimes. While the regimes were gaged and unimpaired, the same process could be used to assess any factors that affect flow without an immediate change in channel topography, including water diversions, reservoir reoperations, and climate change scenarios. The cottonwood seedling example showed how EFM can help plan and understand the effects of environmental flows. Alternative shapes, timings, and magnitudes of release patterns could be simulated with the software to hone design of prescribed flow events, forecast ecological effects, and guide decision-making per ecological objectives. In this way, EFM can also help to connect reservoir operations with field science and monitoring activities.

4.8 Conclusions

To summarize, the logic and process for applying EFM follows: if EFM is instructed to look at a hydrograph (flow regime) in a particular way (relationship), the result (statistical analyses) will be relevant to the ecosystem aspect of interest. Since the result is ecologically relevant, a map of that result (hydraulic modeling) will also be ecologically relevant and allow additional criteria such as depth and velocity preferences to be considered to further refine the representation of the ecosystem aspect of interest (spatial analyses).

Both demonstrations here focused on rivers in the western United States. EFM also has been applied to the Savannah River in Georgia and South Carolina to assess reservoir management during droughts (USACE 2006), the Truckee River in Nevada to study responses to the restoration of channel meanders, a navigation pool on the Mississippi River in Missouri to investigate alternative strategies for regulating pool stage fluctuations, the Sandy River in Oregon as part of a dam removal project, and the Ashuelot River in New Hampshire to examine flow effects on an endangered species of mussel.

EFM's strengths include:

- <u>Testing ecological change for many flow regimes and relationships.</u> It is difficult to fathom the number crunching potential of EFM. The Bill Williams application has been the most ambitious in terms of numbers of flow regimes analyzed to date, but the 341 regimes examined use less than 1% of the tool's designed capability. Potentially, EFM could compute statistics for all stream flow gages currently operated by USGS in the United States (7,400 sites; USGS 2007) or, as in the Bill Williams River demonstration, assess cottonwood seedling establishment along the entire length of the Missouri River, 4,100 km (2,540 mi; USGS 1990), if locations of interest were separated, on average, by at least 110 m (360 ft).

- <u>Linking ecology with established hydrologic, hydraulic, and GIS tools.</u> Development of engineering software has largely been guided by the needs of tasks like floodplain delineation, channel design, and reservoir simulations for flood routing, hydropower, and water supply. Although ecosystem concerns have not been dominant influences, those software still have much latent potential for use in ecological analyses. By working with those tools to predict the ecosystem responses created by different scenarios, EFM fills an important niche in decision support systems for water management and ecosystem management and restoration.

- <u>Quick, inexpensive means to incorporate expert knowledge.</u> Starting with only a flow time series, ecological information, and familiarity with EFM, seasonal and statistical results can be produced and displayed in minutes. Subsequent changes to relationships and redisplay of results can be done in seconds, which allows teams to explore relationships and incorporate expert knowledge interactively. Expanding to hydraulic modeling and GIS requires more data, time, and expertise, but even this is practical in real-time group settings if hydraulic models are prepared beforehand. It is hoped that this openness and nimbleness of the EFM process will encourage ecologic modeling to be performed before or in parallel with development of other parts of decision support systems such as reservoir simulation and river hydraulic models. Too often, ecologic modeling is delayed pending completion of other parts of decision support systems and thereby suffers any logistical failings of those efforts.

- <u>Generic software tool, applicable to a wide range of riverine and wetland ecosystems, water management concerns, and restoration projects.</u> Subjects considered for EFM applications have ranged at least from beluga whales in an Alaskan estuary to crayfisheries in Louisiana (personal communication, USACE). In all cases, the efficacy of EFM depends on the same fundamental question: Are the ecosystem aspects of interest affected by fluctuations in the flow and stage of the related water body? If so, EFM can be used to test management scenarios and predict responses for a wide variety of flora, fauna, and processes. And at its best, EFM will also refine the modeler's understanding of the ecosystem and provide an objective platform to verify hypotheses that involve hydrology, hydraulics, and ecology.

EFM also has key limitations, including:

- Uses only daily data. Statistical queries of EFM are coded for use with daily data and will not be sensitive to ecological dynamics driven by sub-daily fluctuations in flow or stage, unless those fluctuations are or can somehow be represented in characteristics of daily time series. This limits use of the software in areas affected by hydropower peaking or tidal fluctuations.

- No explicit tracking of inter-year dynamics. Ecological responses can require years to complete. For example, a riparian tree species may require a wet year followed by multiple dry years for new recruits to establish with enough resilience to survive subsequent inundations. EFM does not connect sequences of events for time periods longer than one year, which limits its applicability for concerns like population dynamics. Seasonal results can be visually reviewed for meaningful inter-year sequences or exported for additional analyses, but this is limited to post-processing of EFM results.

- Outputs are often proxies. Results of the EFM process, whether statistical performance measures or spatial tallies and distributions of habitat, are often indicators for more tangible ecological attributes such as species population levels and ecosystem services. Separation between what is computed and what is of interest is inherently a weakness, but is also a concern because proxies do not always represent their intended attributes consistently. This is true in ecosystem responses, which are influenced by many variables and can take many years to reveal a trajectory of change.

Work has begun on EFM features that allow the spatial and temporal linking of ecosystem dynamics as part of a generic simulation model. Already, study areas can be defined and parsed into spatial elements. Environments within elements are defined by imported spatial and temporal data. Users nominate what gets simulated (e.g., communities, habitats, etc.), the units describe them (e.g., height, weight, etc.), and other related characteristics (e.g., economic value, board-feet timber, carbon sequestered, etc.). For population simulations, ecological communities inhabit and can navigate the elements seeking advantageous combinations of environment and population distributions.

These advances are being developed in parallel to EFM’s current capabilities so modelers will not be obligated to use the new features. This scalability, where EFM applications can be statistical analyses of flow time series or also map habitat or simulate population dynamics, allows modeling to be easily customized to the level of technical support required by different applications and offers opportunities to engage study teams and stakeholders by producing results at each stage of application.

CHAPTER 5

A Strategic Shift in Environmental Operation of Reservoirs

Ecosystems provide an array of services to human communities, including improved water quality, protection from floods and storms, and provision of food and fiber. Over time, human influences have degraded ecosystems to the point where it can be difficult to appreciate their productivity. Freshwater ecosystems, including rivers and floodplains, are among the most altered in the United States today. In fact, 98% of all rivers in the U.S. are now regulated by human interventions.

Several methods have estimated the percentages of river flows needed to maintain riverine ecosystems across a spectrum of conditions. And while percentages and definitions of condition differ between methods, the works of Tennant (1976), Arthington and Pusey (2003), Acreman and Ferguson (2009), and Richter et al. (2012) concur that maintaining flow dependent ecosystems in good condition requires a high percentage of natural flows to remain in the waterways without alteration (consistently more than 60% and occasionally more than 90% for sensitive ecosystems or during particular hydrologic conditions). These concepts apply to volumes and patterns of flow. There is an established and growing literature that highlights the need to incorporate variability into environmental flow strategies at reservoirs (Poff et al. 1997; Bunn and Arthington 2002; and Postel and Richter 2003).

Currently, 17.8% of waters released at reservoirs with federally authorized flood space is mandated by environmental requirements (figure 10, part a); 84% of these reservoirs have a constant or zero minimum flow requirement (figure 13).

These facts underscore a situation where scientific understanding has outpaced the evolution of operational policies at dams. They also bring into question the adequacy of water allocations for environmental purposes as well as the corresponding choices about whether and how the gap between the current status and the flow requirements needed for maintaining ecosystems in good condition might be closed.

This chapter presents a series of ideas for improving reservoir operations from an environmental perspective. Four fundamental actions are introduced. Motives and anticipated benefits are detailed for each. Creation of an environmental storage zone within reservoirs is proposed and debated. Conclusions are drawn regarding the efficacy of these ideas in improving water and ecosystem management at reservoirs and the potential use of the previously introduced software to help formulate (HEC-RPT) and quantify the ecological benefits (HEC-EFM) of water and ecosystem management alternatives.

5.1 Reoperations for environmental enhancements

Changes in reservoir operations can be motivated locally for individual projects and stakeholder groups or programmatically across aggregations of reservoirs. For surveyed reservoirs, at an operational level, most changes reported were reactive, spurred by requests from interest groups or new legislation, litigation, and organizational directions. A minority were proactive with water managers taking the initiative to alter operations to improve project performance. Most changes are implemented within operational flexibilities or within bounds set forth in organizational policies.

Each reservoir has operational guidance. Typically, this guidance is published in a water control plan. Operational changes that have long-term effects on reservoir management are ultimately incorporated as a water control plan update. Corps policies state that plans should be updated as needed to conform with changing watershed, technological, and legislative conditions (USACE 1982) at an interval not to exceed 10 years (USACE 1995). In practice, the average interval between updates is more than 10 years and is increasing as budgets tighten and as analyses required to assess the changes become increasingly complex.

Local adjustments are important. These efforts produce real and meaningful benefits, serve to demonstrate concepts, and can affect operations at other projects by encouraging similar reoperations or additional increments of change. However, given the magnitude of disparity between current environmental mandates and the estimates of flow required to sustain ecosystems in good condition as well as an increasingly challenging policy process for institutionalizing changes, programmatic shifts in environmental strategies are also needed to broadly improve the status of ecosystems influenced by reservoir management.

Proposals to shift environmental strategies might now be well timed. A review of surveyed reservoirs showed that environmental purposes are now the most common motivation for operational changes (figure 31; FW and WQ). Changes for environmental purposes began to outnumber changes for recreation, infrastructure, hydropower and navigation in the 1990's and then also water supply and flood risk management in the 2000's. If trajectories hold, adaptation of Corps reservoir operations will continue to face environmental challenges in the 2010's and beyond.

5.1.1 First Steps

Four fundamental actions that would strengthen the ability of water managers to operate reservoirs for environmental considerations are:

- Computation and databases of unimpaired flows and habitat conditions
- Creation and authorization of an "Environmental Management" purpose for reservoirs
- Mandate reporting of environmental benefits provided and foregone
- Apply forecast-based operations

Unimpaired flows. Characterization of the unimpaired or natural flows of a river system is needed to understand how river systems have been altered by reservoirs and other human influences and how related ecosystems functioned in the past. Currently, water managers do not

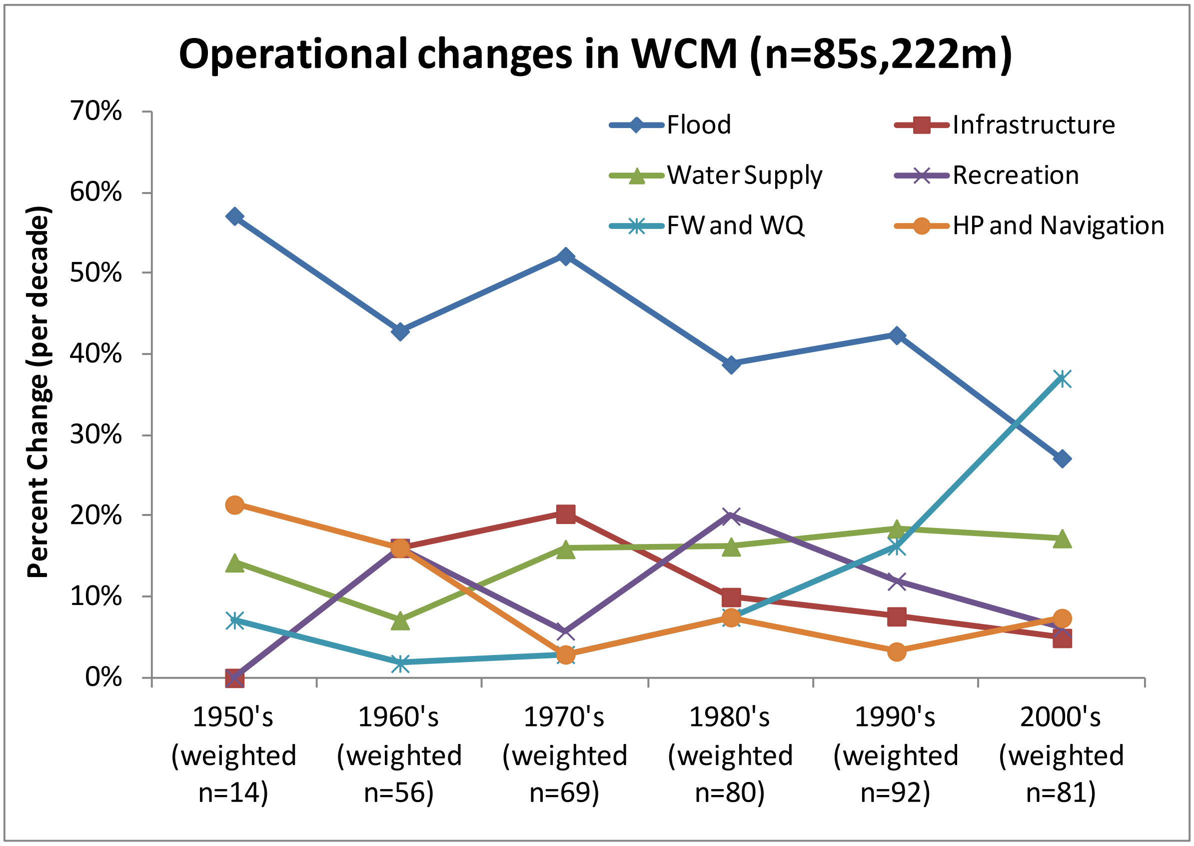

Figure 31. Operational changes incorporated in water control manuals for all surveyed reservoirs by motivating purpose and decade.

routinely track these data. Computation, data development, and dissemination of unimpaired flows and habitat conditions should be mandated for all reservoirs with a federal interest. This mandate could be executed via organizational initiatives or via legislative action. And while this would not directly change reservoir operations, it would build 1) awareness of the degree of alteration, 2) capacity to quantify environmental effects, and 3) ability to weigh environmental considerations in decision-making.

“Environmental Management” authorization. In regards to authorized purposes, environmental considerations are most often associated with operations for fish and wildlife and water quality. Of the 465 surveyed reservoirs, 119 (26%) have authorized purposes for both fish and wildlife and water quality, 134 (29%) for fish and wildlife and not water quality, and 37 (8%) for water quality and not fish and wildlife. Additionally, 86 (18%) are authorized for recreation and not for fish and wildlife or water quality. This totals to 81% of the surveyed reservoirs. Coupled with federal laws for species protection and water quality standards, this would appear a reasonable foundation for environmental considerations at reservoirs, and yet environmental strategies are fragmented. Fish and wildlife is referenced when manipulating pool levels for water fowl or fishes, water quality and fish and wildlife purposes are mentioned when minimum flows are debated, and recreation is managed mainly for in-pool opportunities. To this point, oddly and as a percentage of outflows, minimum flow requirements at Corps reservoirs with an environmental purpose are roughly half of those at Corps reservoirs without an environmental purpose (figure 32).

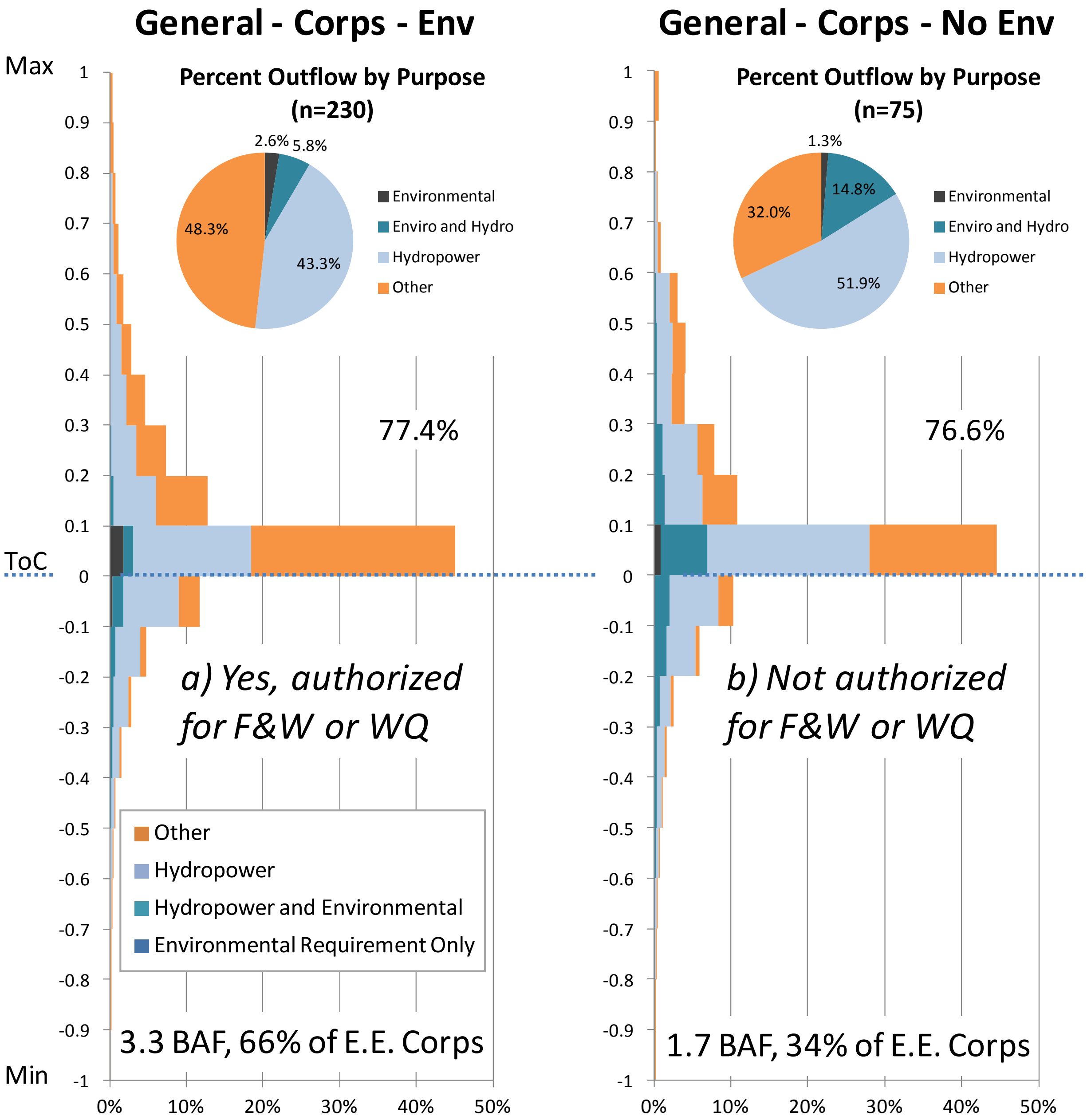

Figure 32. Comparison of outflow purpose and pool status, 1989-2008, for Corps owned reservoirs that were not "big river" or "dry dam" projects a) with and b) without an environmental (fish and wildlife or water quality) purpose. The sum of reservoirs in this figure is equal to the collection displayed in figure 12, part e.

Lacking is a more comprehensive vision for environmental stewardship. Creation and authorization of an overarching "Environmental Management" purpose would 1) reinforce the connectedness and importance of environmental resources, 2) provide an impetus for shifting environmental strategies to a more integrated and sustainable position, and 3) improve accountability for any shortcomings in environmental strategies.

Reporting of environmental benefits. 68 billion kilowatt-hours generated annually - enough for more than 5 million people; 370 million visitor days of recreation per year - equal to roughly 10% of nation's population; 22.3 billion dollars of flood damage prevented on average each year by flood risk management projects (including levees and reservoirs; 1999-2008; USACE 2010a).

Reservoir benefits are quantified for many operational purposes. The flood damages prevented estimate, for example, is computed each year for each reservoir and then aggregated to reflect a total value to the nation. It is not an especially burdensome effort. Water managers identify the annual maximum reservoir inflow and outflow and then use a flow-damage rating curve to estimate the damages that would have occurred if the reservoir was not there (inflow) and the damage that occurred (outflow). The difference between these two values is the estimate of flood damage prevented by the reservoir.

There are no reporting requirements to inform how well reservoirs are meeting environmental purposes with the possible exception of compliance with regulatory requirements, which is a poor characterization of both the sway that reservoirs exert on ecosystems and their potential to generate environmental benefits.

Part of the challenge in reporting environmental benefits is using a consistent and intuitive currency. There is a wide range of possibilities that might serve. A basic and common currency is statistical compliance with flow-based targets (e.g., outflows for environmental purposes need to occur with a target magnitude, frequency, and duration), though this is not especially intuitive from an ecological perspective (imagine what a fish might say if asked whether its needs were satisfied by a 7-day average flow of 100-cfs that will be equaled or exceeded in 50% of years). A less commonly used currency that speaks more directly to ecological status and services is population levels. Expressing the effects of a reservoir as more or less of different species is intuitive, but difficult because population dynamics are complex and fluctuate based on many factors.

Habitat is a currency that falls between statistical compliance and population dynamics regarding both complexity and intuitiveness. It is more tangible than statistics and more feasible than estimating populations. As described in chapter 3, the habitat of a species can be described based on life history characteristics and physical, thermal, and chemical preferences. Habitat is intuitive in the sense that it is viewable and there is a fundamental human appreciation that living things need an amount of suitable accommodations and resources. Quantifying habitat stops short of estimating population levels because the population potential cultivated by a habitat increase for one life stage may be overcome by habitat bottlenecks at different life stages or affected by other abiotic conditions and biotic interactions.

Habitat areas provided and foregone could be used to track the environmental benefits of reservoirs. The process would not need to be difficult. The same mechanism used to estimate flood damages prevented could be employed here, if flow-habitat relationships were used in lieu of flow-damage relationships when translating the select flow values, to estimate total habitat provided and foregone.

Forecast-based operations. Most drivers of operational change (e.g., legislation and litigation) make reservoir operations less flexible and adaptable. Scientific advances can drive change, but often manifest as new demands related to water quantity, quality or timing, which also tend to decrease operational flexibilities. By reducing workloads or enabling the expansion of operational parameters, technological advances systematically increase operational flexibilities. The sophistication of gaging networks, remote sensing techniques, and forecasting capabilities continues to increase the information available for water management. However and with few exceptions, federal flood operations react to current "on-the-ground" conditions. For example, when faced with a forecast that, if accurate, would necessitate the release of damaging high flows, operational guidance typically instructs that no compensating or preemptive releases be made. This logic is rooted in and reinforced by litigation. As long as this continues, any opportunities these technologies offer to increase operational flexibilities and generate additional services, including enhanced environmental condition, will be unrealized.

5.1.2 Environmental Operation Zone

The Corps is the primary federal agency responsible for flood risk management. It is also the main owner and operator of reservoirs with federally authorized flood space. Reallocations of reservoir storage that would seriously affect other authorized purposes or require major structural or operational changes require Congressional approval. Provided these criteria are not violated, minor changes that shift storage allocations between authorized purposes up to 15% of total storage or 50,000 AF may be made at the discretion of the Corps (USACE 2000).

When the reallocation criteria for minor changes are applied to the gross pool capacities of the 465 surveyed reservoirs, the maximum resulting space subject to reallocation without Congressional approval is 13.1 MAF. All told this is just under 4% of the total storage capacity of surveyed reservoirs, though the 15% of total storage criteria is the limiting constraint for most projects (293; 63%).

Several historical reallocations were noted in survey database information pertaining to the evolution of operational guidance. When summed, these known reallocations accounted for 0.4 MAF of the space subject to reallocation without Congressional approval, mostly from the flood zone to the conservation zone for recreation and water supply purposes. Therefore, the discretionary authority of the Corps for reallocations is largely (97%) unexercised.

Using the remaining portion, an environmental operating zone could be created as a storage band at the bottom of the flood zone. The top of the environmental zone would parallel the top of conservation such that it would reflect any seasonal or condition based adjustments to the balance of conservation and flood storage.

Release decisions in these environmental zones could be made in accordance with the following guidance:

1) Environmental strategies for release of water should be defined through the cooperation of water managers and regional scientists. The HEC-RPT software tool could help facilitate this process.

2) Until environmental strategies are defined, outflows should mimic unimpaired patterns of flow quantity and quality, in so far as outflows do not negatively affect native floral and faunal communities of the flow-dependent ecosystems.

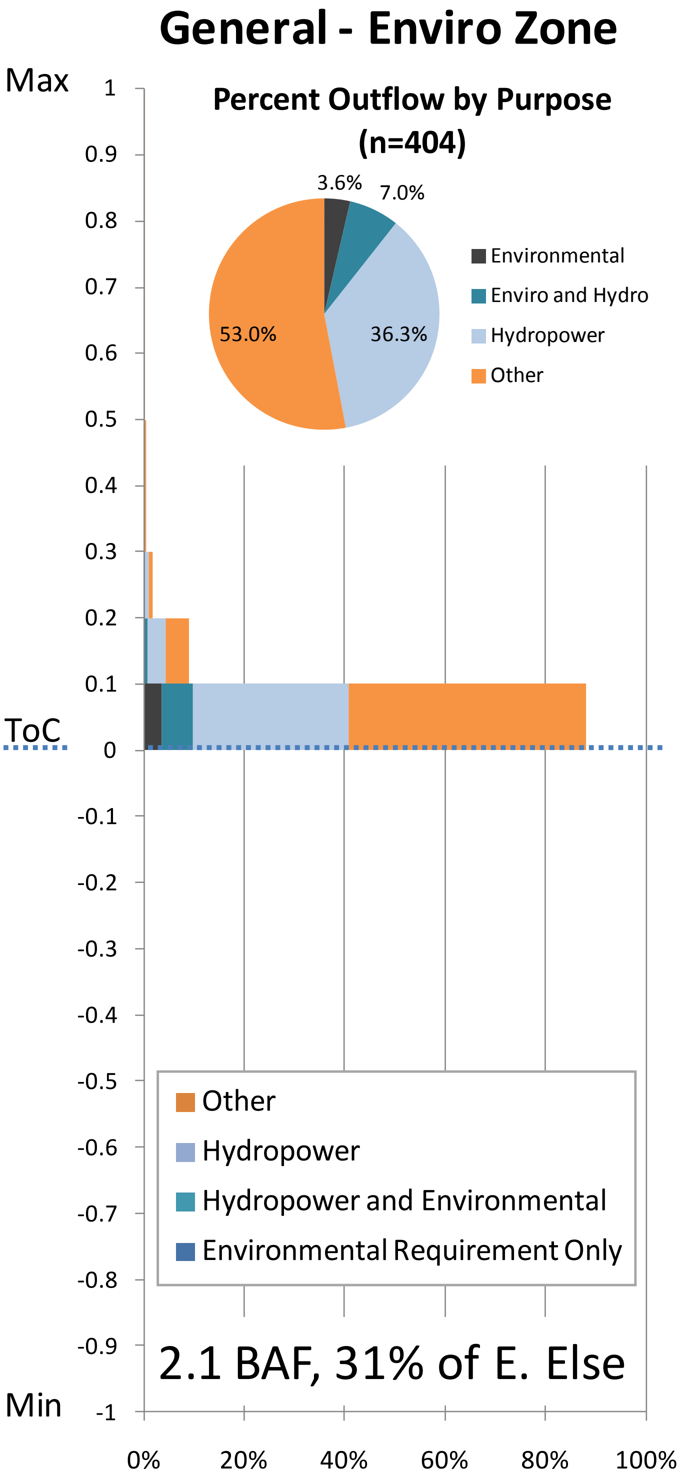

Figure 33. Outflows by purpose and pool status occurring within the proposed environmental zone, 1989-2008, for all reservoirs that were not "big river" or "dry dam" projects. Outflows shown here are subsets of those presented in figure 11, part d.

3) Testing of water management alternatives via the scientific study of ecosystem responses to reservoir management decisions through experimental outflows should be supported, especially when validating defined environmental strategies. Validated strategies should be incorporated into operational policies and guidance as expeditiously as possible. The HEC-EFM software tool could help translate scientific knowledge to operational strategies for water management.

Having a storage zone where environmental considerations are at the forefront of release decision-making is a programmatic shift in water management. It would clearly place responsibilities for stewardship of environmental resources in the hands of the water managers. And while a maximum of 15% of total storage may not seem like a windfall, a historic analysis of outflows for all reservoirs except "big river" and "dry dam" projects (n = 404) shows that, volumetrically, 31% of releases, 1989-2008, occurred at pool levels that would fall within the environmental zone (figure 33). Coupled with the 13.5% of outflows already mandated by minimum flow requirements, the percentage of waters released with an environmental strategy would be increased to 41.6% (table 13), which is a 3-fold shift towards the estimated flows required to maintain ecosystems in good condition.

This opportunity appears most promising for the Corps owned projects in this category (figure 34). Those reservoirs spend more time in the environmental zone (50% versus 12% for non-Corps owned), release a greater percentage of outflows while pool levels are in the environmental zone (38%

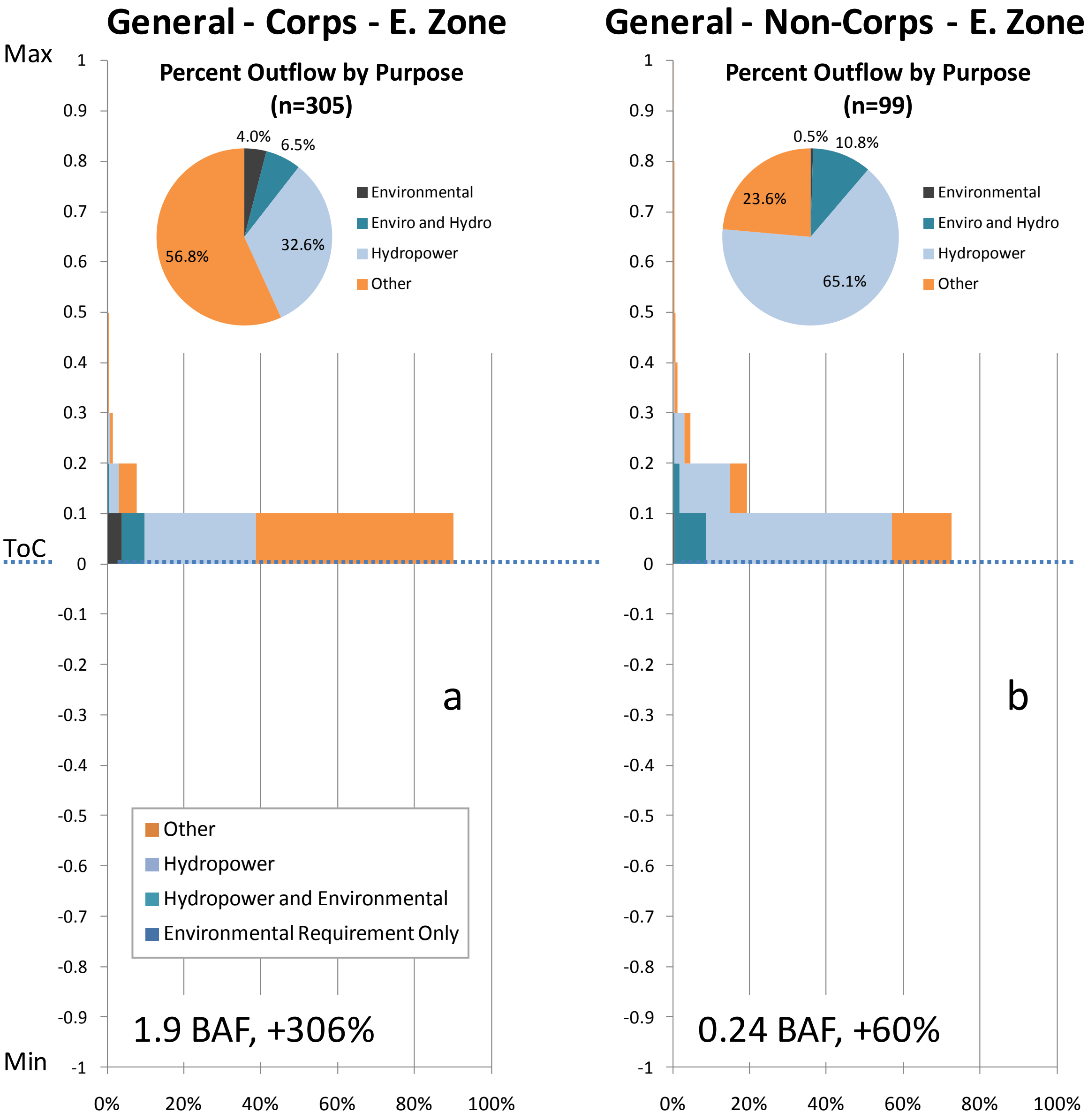

Figure 34. Outflows by purpose and pool status occurring within the proposed environmental zone, 1989-2008, for reservoirs owned by a) the Corps and b) others, which were not "big river" or "dry dam" projects. Outflows shown here are subsets of those presented in figure 12.

versus 14% for non-Corps owned), and have a lower fraction of outflows mandated by minimum flow requirements (11.1% versus 20.4% for non-Corps owned; figure 12), which means that the percent boost in environmental flows is higher (table 13).

5.2 Potential for Enhancements and Limitations

The environmental zone concept seeks to store more water in reservoirs such that releases can support defined environmental strategies. It is debatable whether this could be implemented wholly at the discretion of the Corps. Conceptually, several purposes would be largely

Table 13. Summary of outflows, 1989-2008, that occurred in the environmental zone for all reservoirs that were not "big river" or "dry dam" projects.

	Whole Pool (Current)			Environmental Zone			Whole Pool (w/E-Zone)		
	Outflows (BAF)			Outflows (BAF)			Outflows (BAF)		% Increase in Env
	All	Env	% Env	All	Already Env	New Env	Total Env	% Env	
General*	6.68	0.90	13.5%	2.10	0.22	1.88	2.78	41.6%	208.3%
Gen. - Corps*	4.93	0.54	11.0%	1.86	0.20	1.66	2.21	44.8%	306.0%
Gen. - non-Corps*	1.75	0.36	20.5%	0.24	0.03	0.21	0.57	32.8%	59.9%

*Excludes "big river" and "dry dam" reservoirs.

unaffected or even potentially enhanced, including recreation, water supply, and water quality. Hydropower might be reduced as generation patterns were altered to align with environmental strategies when pool levels were in the environmental zone though this would be offset in part by improvements in generation created by additional head and would only affect 19% of all hydropower releases, excluding those made at "big river" reservoirs. Flood risk management would have systematically less space to attenuate high flows, which could be offset by maintaining a flood purpose within the environmental zone such that pre-releases could be made based on forecasts (USACE 2002). These considerations would need to be assessed, but the environmental potential is compelling.

Assuming a conservative estimate of 20 downstream river miles as the spatial extent directly affected by release decision-making at dams, almost 10,000 river miles and their connected floodplains are influenced by the surveyed reservoirs. Additionally, the Corps owns and operates nearly 200 more reservoirs (mostly supporting navigation) not included in the survey because they lack a flood risk management purpose. With these, the tally of extent would grow to 13,000 river miles, roughly equivalent in length to five Missouri Rivers.

Additionally, 170 of surveyed reservoirs release more than 60% of their outflows within the proposed environmental zone. A selection of those projects could be used to test whether it is possible to maintain good ecological conditions in managed water and ecosystems.

A limitation of the environmental zone idea is that it does not encompass the entire reservoir pool; release decisions in other zones are unaffected. This is problematic because operational priorities differ across reservoir zones, which could create negative environmental effects as the ecological potential cultivated with environmental releases are overcome by other operations. The environmental zone also relies on reservoirs being managed at relatively high pool levels. If other demands (i.e., water supply, hydropower, navigation) increase, pools will trend lower thereby reducing the amount of time spent and volumes of outflows released in the environmental zone. Monitoring would be required to quantify net effects.

5.3 Learning from the Shift

With change comes learning opportunities. If responses to change are studied, resulting knowledge and lessons learned can help advance other changes and perpetuate a culture of adaptive management (Walters and Holling 1990). Too often these opportunities pass unrealized due to insufficient investments of time and resources (Souchon et al. 2008). Operational changes at reservoirs deserve more attention (Petts 2009). Many reservoir systems still have enough flexibility to make meaningful changes that would illuminate more optimal modes of operation. The ideas set forth in this chapter would be better realized if tracked with a strategic monitoring effort.

As set forth in Higgins et al. 2011, developing and implementing environmental flows and evaluating the resulting ecosystem changes involves: 1) defining an environmental flow prescription; 2) assessing the degree to which the prescription is implemented; 3) short-term monitoring of ecosystem responses to environmental flows; and 4) long-term monitoring of ecosystem status and trends that relate to flow. Uncertainties identified during definition of environmental flows that limit implementation would be investigated through experimentation and monitoring.

Monitoring does not need to be exhaustive to be effective. Adaptive dam management requires constructive, informative and timely guidance from scientists to dam operators, with periodic review and revision (if necessary) of environmental strategies and ultimately of water control plans. Though experimentation is fundamentally a local effort, an adaptive management plan associated with a programmatic shift needs a regional component to avoid duplication of effort and identify and invest in the most promising opportunities to reduce uncertainties regarding the ecological effects of water management decision making.

This idea would essentially create a "Learning Watersheds" program that could function in unique ecoregions around the United States. Central to Learning Watersheds are the Water Management Groups that regulate river flows through operation of reservoirs and other structures. These are the groups most capable of using existing flexibilities in the system to perform experiments and to integrate the resulting science with operations (figure 35).

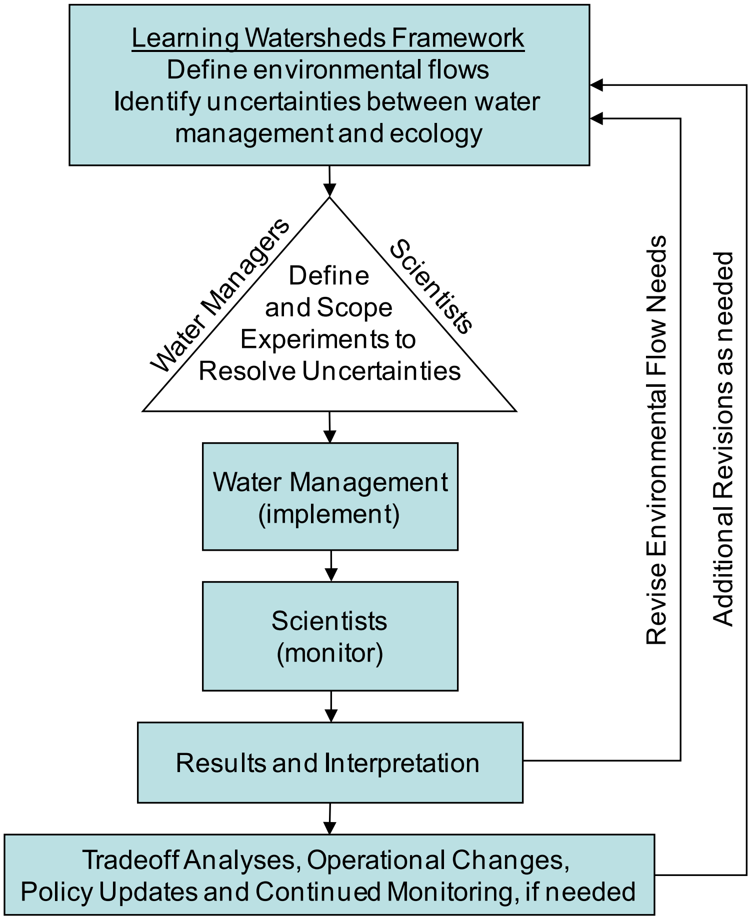

Figure 35. Learning Watersheds framework to encourage and coordinate science-based experimentation in reservoir management.

Scientific support (i.e., field work, data collection, and data analyses) could be performed by any combination of governmental and non-governmental scientists, including academia, with the amount of support fluctuating in accordance with available funds, maturity of experiments, and enabling hydrologic conditions.

Benefits and principles of Learning Watersheds would include:

- Enable better management of water resources through scientific collaborations while creating, fostering, and strengthening interagency relationships.
- Promote sustainability and preempt conflict by generating information needed to better integrate ecological knowledge with water management decision-making.
- Accelerate repair of past degradation and prevent future losses in a very real and applied way.
- Foster adaptive processes and strengthen the role of adaptive management for involved agencies. In this way, Learning Watersheds would improve the ability of water management to evolve by supporting learning and experimentation.
- Encourage river management that maintains or restores functionally sound ecosystems, and, as a national program, would promote these management practices for use on other rivers in the United States and beyond.
- Encourage the connection of science and engineering in a way that builds and strengthens organizational relationships and supports the education of future scientists, engineers, and water managers.

5.4 Conclusions

The environmental strategies of a collection of national significant reservoirs were assessed and found to be out of synch with current scientific understanding of the water resource needs of flow dependent ecosystems. Several ideas were offered to improve this situation, including improvements to:

- Information related to the management of water for ecosystems (i.e., computation and archival of unimpaired flows)
- Clarity of environmental authorities and mandate (i.e., creation and authorization of an “Environmental Management” purpose for reservoirs)
- Accountability of decision-making from an environmental perspective (i.e., a systematic reporting mechanism to quantify the environmental benefits provided and foregone through water management decision making)

- Operational capabilities to manage for environmental purposes (i.e., use of forecasts and an environmental operating zone)
- Scientific knowledge required to reduce operational uncertainties pertaining to environmental benefits (i.e., use of strategic adaptive management processes as part of Learning Watersheds)

Some of these ideas could be implemented immediately at the discretion of the Corps. Others would require legislative actions. Collectively, these ideas would unify an environmental operating mission, improve the environmental resources available to reservoir managers, create and populate a database related to ecological effects of reservoir decision-making, establish an adaptive management framework for operational changes, and provide a significant boost in the volumes of water and operational priority for environmental purposes. This boost would be most pronounced for reservoirs owned and operated by the Corps that already have an authorized environmental purpose. This group of reservoirs, of which there are 230 nationwide, would have a 306% increase in the amount of water released for environmental needs.

CHAPTER 6

Summary

This dissertation explored tools and ideas designed to improve the management of reservoirs from an ecological perspective. Current environmental operations for a collection of nationally significant reservoirs were reviewed. Two emerging, free, and publicly available software tools were introduced and their applications were illustrated via case studies. And finally, ideas for improving environmental operations at reservoirs were presented.

A national reservoir survey produced informational and operational databases for 465 reservoirs and roughly 50% of the reservoir storage capacity in the U.S (figure 3). These databases were used to review current environmental operations for national and regional groupings of reservoirs. It was found that:

- 39% of surveyed reservoirs have no environmental flow requirements, 45% have a constant minimum flow, and 16% have a variable requirement (table 5).

- 17.8% and 13.5% of reservoir outflows were released per these requirements for the "all" and "general" reservoir categories, respectively (table 4), both of which are significantly less than the percentage of flows (60% or more) recommended by scientists as necessary to maintain flow dependent ecosystems in good condition.

- Creation of an environmental operation zone, a storage band at the bottom of a reservoir flood pool in which environmental considerations are prioritized in outflow decision-making, was an effective way to narrow the gap between current and recommended environmental requirements.

- For the "general" category of reservoirs, the percentage of water released for environmental purposes increased by 60% for non-Corps reservoirs and by 306% for Corps owned reservoirs (table 13). This opportunity appears most promising for Corps owned reservoirs that already have an authorized environmental purpose.

- There is a growing focus on environmental concerns related to reservoir operations. Environmental purposes are now the most common motivation for operational changes (figure 31).

- Changes in reservoir operations create learning opportunities. The Learning Watersheds concept (figure 35) encourages adaptive management and would help better define the flow-ecology relationships critical to management decision-making and parameterization of software tools that seek to relate ecological responses to changes in flow, including EFM.

Rivers provide many services and have many stakeholders with common and divergent interests. Maintaining open and clear communications where a diversity of perspectives can be heard and express their goals in a common manner is critical when trying to achieve a generally accepted balance among different uses of rivers. The RPT software:

- Works within a planning process to facilitate development of flow management alternatives.
- Organizes and focuses conversations about flow management.
- Helps stakeholder groups reach consensus about how a river should be managed.
- Incorporates expert and stakeholder knowledge.
- Provides a hydrology-based construct for alternative formulation.
- Allows quick and visual construction of flow recommendations in real-time workshop settings.
- Helps groups formulate, compare, unify, document, and maintain flow management recommendations for multiple stakeholder perspectives and river locations.

Habitat provision is a key ecosystem service that has potential to serve as a common performance metric for ecosystem restoration projects and water and ecosystem management. The EFM process involves statistical analyses, hydraulic modeling, and use of GIS (figure 14). Statistical analyses winnow full hydrologic time series to performance measures that reflect how well the flow regime of a river is meeting ecological needs. Statistical results are imported to hydraulic models which to produce habitat maps for spatial analyses and could also be coupled with habitat rating curves to compute simple estimates of habitat provided and foregone as a reporting mechanism for reservoir operations. The EFM software is:

- Powerful. EFM is capable of testing ecological change for many flow regimes and relationships.
- Scalable. EFM applications can produce statistical performance measures or also habitat maps or simulations of populations, which allows modeling to be easily customized to the level of technical support required by different applications and offers opportunities to engage study teams and stakeholders by producing results at each stage of application
- Growing. Features are being added to EFM (guild-based groupings of flow regimes and relationships, custom output formats, expanded statistical features), GeoEFM (spatial views of statistical results, habitat mosaics, habitat calculators, expanded habitat connectivity methods), and the new population simulator that strengthen the software suite’s capacity to assess ecological benefits and consequences.

- Aligned with established engineering tools. EFM can be applied with rainfall-runoff, reservoir simulation, and river hydraulics models to estimate the ecological responses to changes in hydrology, operations, and channel configurations. This facilitates incorporation of ecological considerations in decision support systems.

The reservoir database and software described herein have potential for use in analyzing several contemporary challenges related to water and ecosystem management, including climate variability, infrastructure renewal, and reservoir reoperations for water quality operations. Climate change questions, for example, might use the reservoir database to investigate the proportion of reservoirs with seasonal separations between flood and conservation storage, or HEC-EFM to quantify changes in the amount or distribution of habitat, or HEC-RPT to formulate alternatives that would help water management adapt to changing conditions.

Fundamentally, these products are all resources that enable a more thorough and informed consideration of opportunities to improve the management of water and ecosystems.

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