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# Using habitat to quantify ecological effects of restoration and water management alternatives

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## ARTICLE INFO

## ABSTRACT

The Ecosystem Functions Model (HEC-EFM) 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). Through this process, study teams define existing ecologic conditions, highlight promising restoration sites, and assess alternatives according to predicted ecosystem changes. HEC-EFM has many strengths, most notably it 1) is capable of testing change for many ecological relationships and management scenarios, 2) links ecology with established hydrologic, hydraulic, and GIS tools, and 3) can be applied quickly, inexpensively, and can incorporate expert knowledge. This paper introduces HEC-EFM and describes its use for statistical analyses and habitat mapping. Two examples are provided: Provision of Sacramento splittail minnow spawning habitat, San Joaquin River, California, USA, and cottonwood seedling establishment, Bill Williams River, Arizona, USA.

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## Software availability

Name of software: Ecosystem Functions Model (HEC-EFM)
Developer: John Hickey
Contact address: CEIWR-HEC, 609 2nd Street, Davis, CA 95616, USA
Email: john.hickey@usace.army.mil
Year first available: 2009, Visual Basic 6; 2013, Visual Basic.NET
Availability: Free download with user guidance and demonstration project at www.hec.usace.army.mil

## 1. Introduction

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 (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 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

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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 often employ hydraulic models to translate statistical results to spatial layers of water depth, velocity, and inundation, and use Geographic Information Systems (GIS) to display these and other relevant layers (i.e., soils, vegetation, and land-use maps) and to apply geographical criteria, such as ranges of suitable depth or velocity, to further refine layers as habitat 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. This paper introduces EFM and describes its application for ecosystem and water resources planning and management.

## 1.1. 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 (USACE, 2001; Hickey et al., 2003; Shields et al., 2003; Heitmuller and Raphelt, 2012). 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 1). Three such 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.

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, perform calculations and compare results for two flow data sets, and to parse and assess hydrographs as a series of environmental flow components (low and extreme low flows, high flow pulses, and small and large floods; TNC et al., 2009). Though not wed to IHA, another method called Hydrology-based Environmental Flow Regime (HEFR), applies this parsing logic and select statistics to populate an initial matrix of environmental flow needs (SAC, 2011; Opdyke et al., 2014).

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

**Table 1**
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) and 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) and 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) and Opdyke et al. (2014) |

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, 2010; 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 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 2). The most commonly applied method is the Habitat Evaluation Procedure (HEP) developed by 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 allow 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.

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 points in their application. EFM computes statistics defined by the user to be ecologically relevant using hydrologic time series. Statistics are often based on life history requirements of species of interest. Different life history stages (e.g., spawning and rearing) are driven by different hydrologic dynamics and are analyzed independently, both from stage-to-stage and from year-to-year for any individual life stage. This can raise questions about sequence. For example, if spawning success is used to gain insights about an adult population comprised of multiple year classes, a one year at a time approach may be insensitive to scenarios where consecutive years of spawning success lead to a boom in adults. Also, if a good spawn is immediately followed by poor rearing conditions, a statistical approach may tally the success and failure separately, without recognition that the potential benefits of the success are subsequently lost. This decoupling of condition and timing is a common weakness for methods that use statistics to characterize ecosystem dynamics (Shenton et al., 2012).

PHABSIM applications also separate life history stages, but otherwise defer questions about temporality until analyses of the habitat time series that the tool helps produce. This is useful because the temporal dynamics of habitat remain intact and provide insights about seasonal and year-to-year habitat fluctuations, though any statistical interpretations of habitat time series would be subject to the same pitfalls mentioned above for hydrologic time series. Spatial distributions of the habitat time series are rarely rendered though those could have value when summarizing the occurrence of habitat (e.g., a habitat duration map to show the percentage of time different areas provide habitat).

EFM enables users to apply life history criteria to flow and stage time series (the statistical analyses phase described more fully later in this paper). Functionally, this is done for each year in the period of record, using only the season relevant to the life stage, and then, based on those results, for the overall performance of the time

**Table 2**
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/USFWS 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 (0–1) 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 et al. (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 Instream Flow Incremental Methodology (IFIM) | Milhous et al. (1989) and Bovee et al. (1998); www.fort.usgs.gov |

series. By considering year-to-year and then overall performance, EFM is able to reduce an entire hydrologic period of record to a single condition (i.e., one flow and stage) that meets the user-defined criteria of the ecosystem aspect being considered. This condition is advanced for habitat mapping (the hydraulic modeling and GIS phases described more fully later in this paper) such that a single spatial representation (i.e., one habitat map) for the ecosystem aspect is produced.

By melding characteristics of statistical and habitat analyses, EFM offers a common platform for consideration of ecosystem restoration and water management alternatives. This scalability, where EFM applications can be statistical analyses of flow time series or also map habitat, is helpful because the hierarchy 1) allows modeling to be adapted to the level of support required by different studies and 2) offers opportunities to engage study teams and stakeholders at each stage of application. This paper describes EFM use for both flow regime analysis and habitat mapping.

## 2. Process, terminology, and user interfaces

The process of applying EFM involves three basic phases: statistical analyses, hydraulic modeling, and use of GIS (Fig. 1). Most user interfaces in EFM support the statistical phase where users identify the 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. Text and figures in this section are largely adapted from the EFM user guidance (USACE, 2013).

### 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. Using two time series allows for a wider variety of relationships to be considered. For example, flows could be queried for a fish spawning relationship driven by high flows and stages could be queried for a riparian vegetation relationship driven by stage recession. If only one type of data is needed, the same data can be used for both concurrent time series. Time series can be 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 (Fig. 2). 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 the case studies section of this paper).

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. In restoration projects, "existing conditions" is a common reference flow regime, against which alternatives are compared and judged based on their respective performance.

### 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 (Fig. 3). 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 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 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. An application for the Connecticut River Watershed included more than 100 relationships investigating resident fishes, mussels, and floodplain forests, among others (Julian et al., in press). 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.

#### 2.2.1. Statistical queries

Statistical queries (Fig. 3) 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,
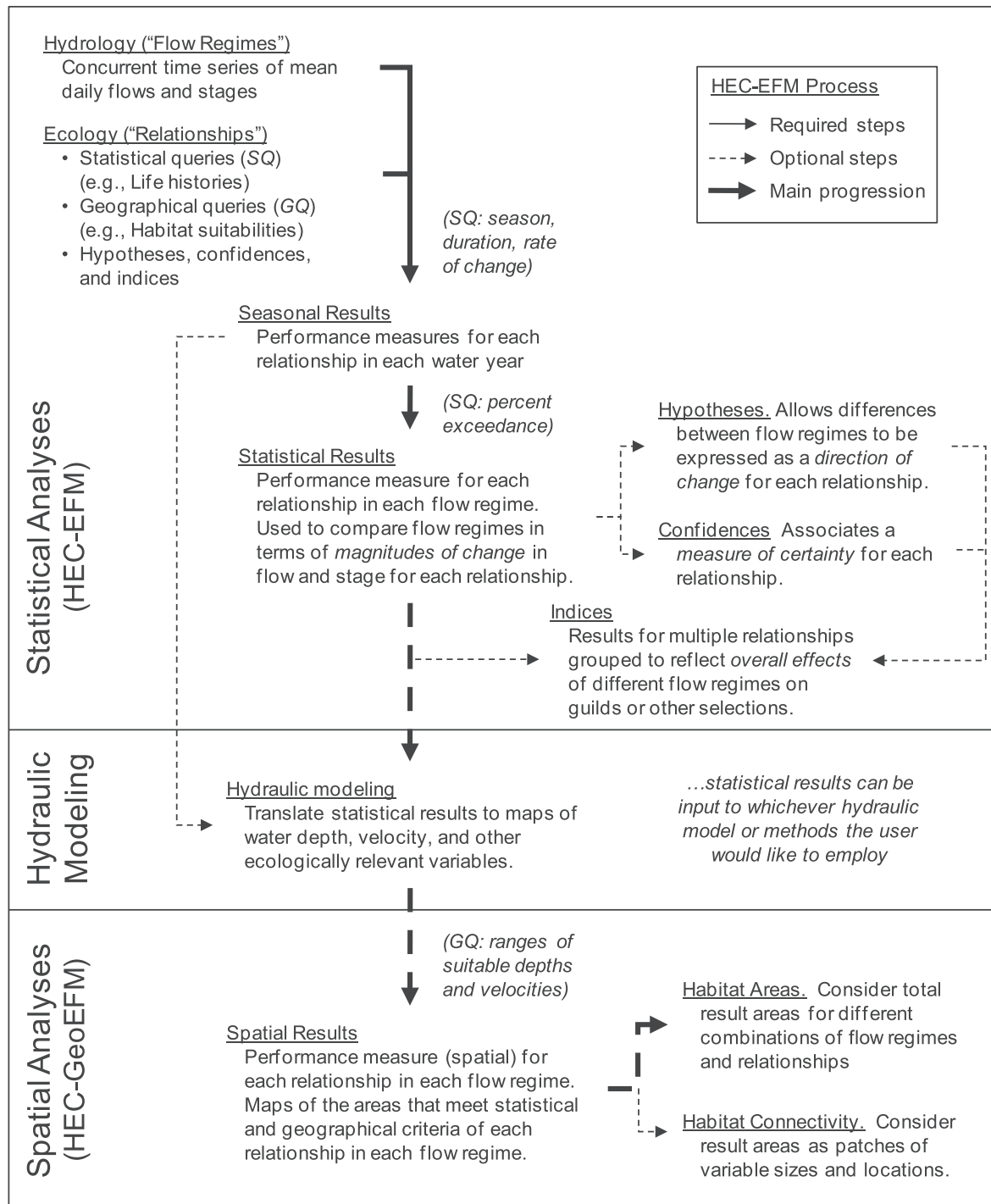
**Fig. 1.** Detailed inputs, outputs, and sequence for the EFM process.

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. Fig. 4 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 flow and

stage. 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
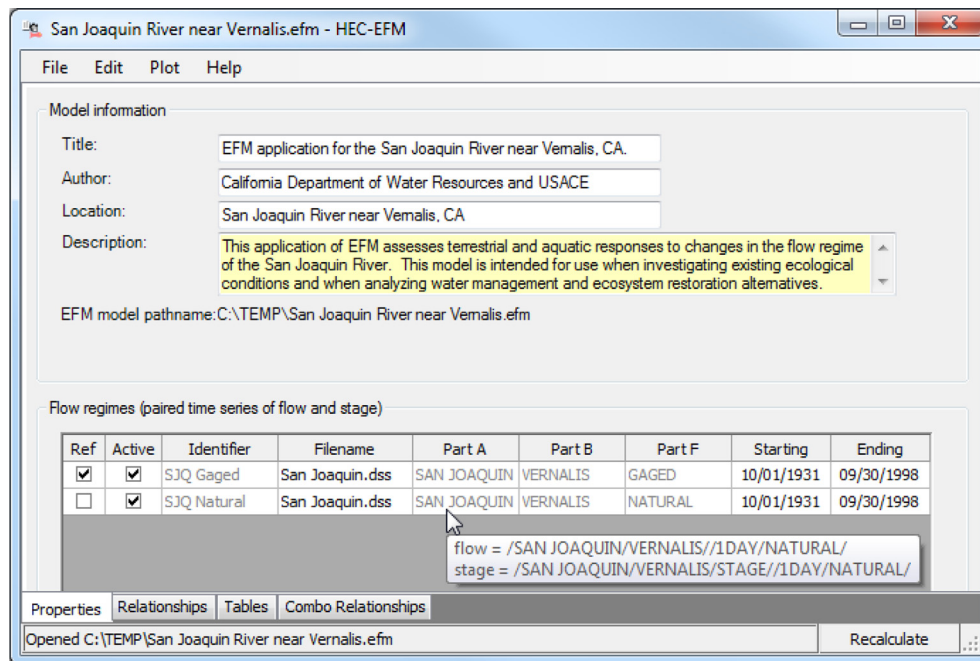
**Fig. 2.** Properties tab of EFM, which supports entry of flow regimes to be studied as well as general information about the modeling effort.
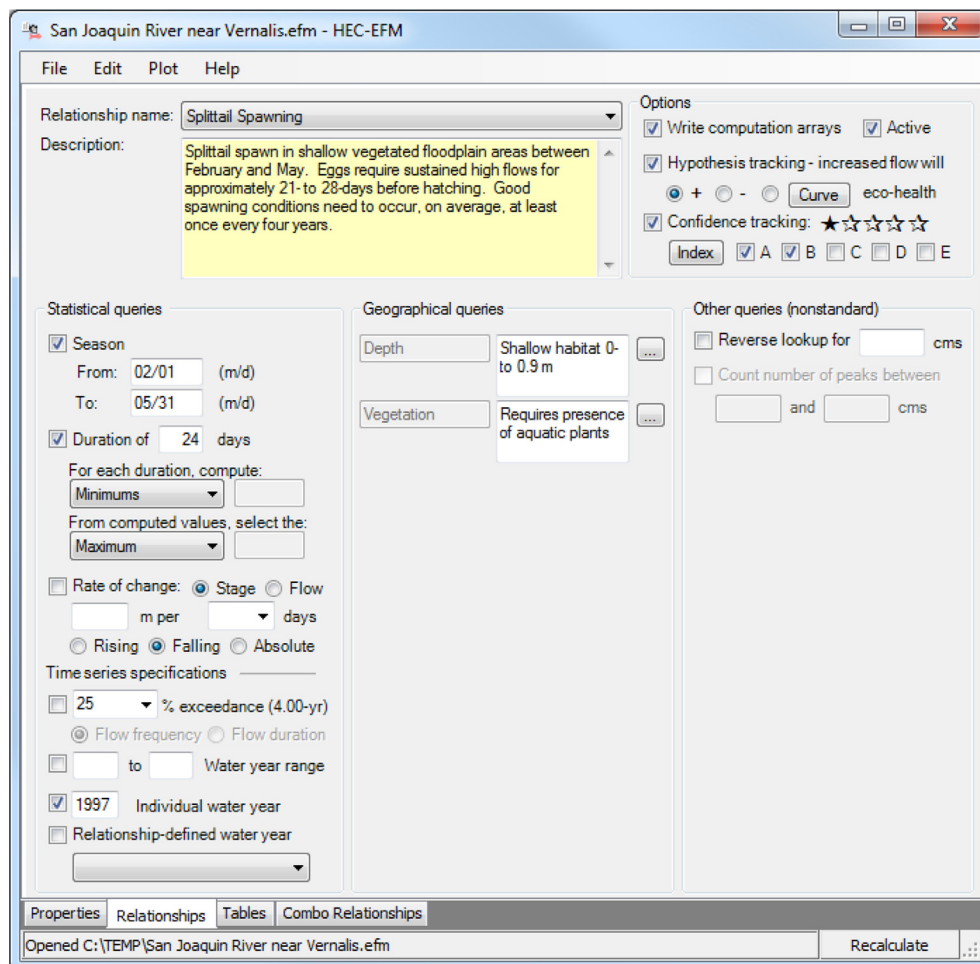


**Fig. 3.** Relationships tab of EFM, which supports entry of relationships to be studied, including statistical and geographical queries and options for hypothesis tracking, confidence tracking, and index membership.
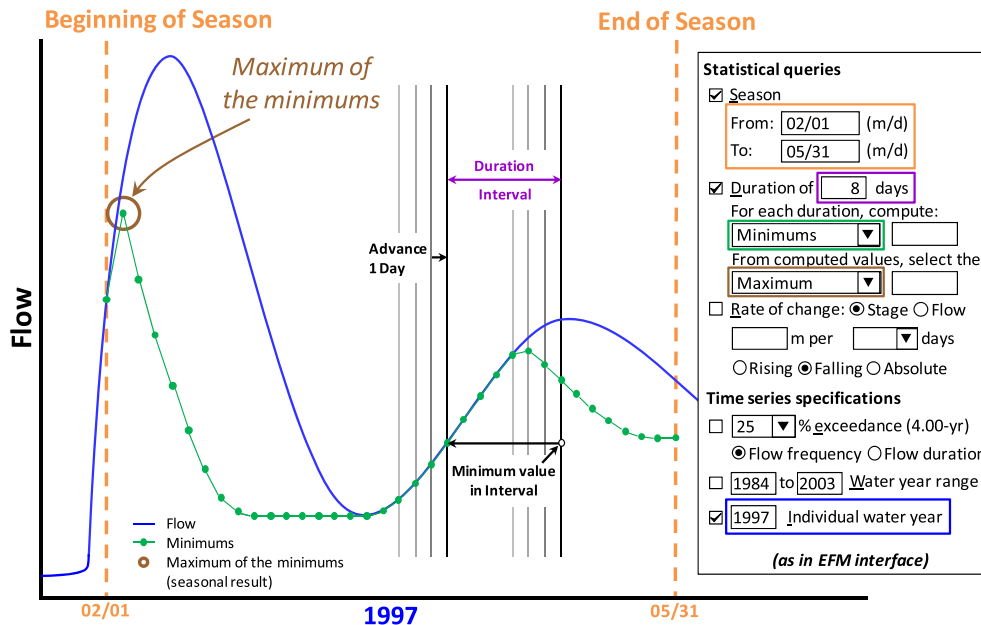
**Fig. 4.** Sample use of the duration query in EFM. Computations are shown for one water year.

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. Fig. 5 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).

*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 (Fig. 6). 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. Fig. 6 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).
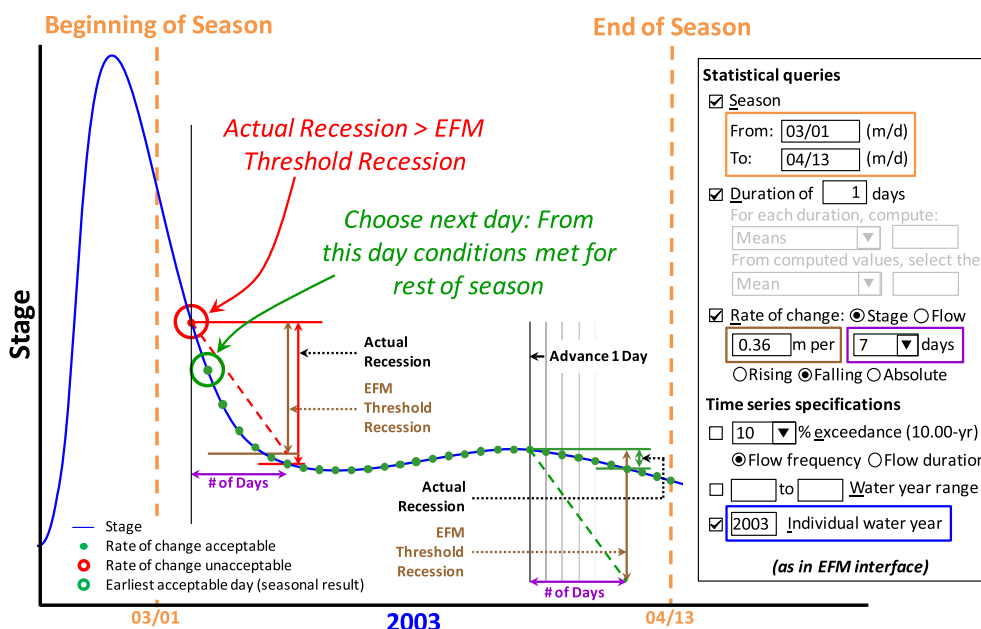


**Fig. 5.** Sample use of the rate of change query in EFM. Computations are shown for one water year.
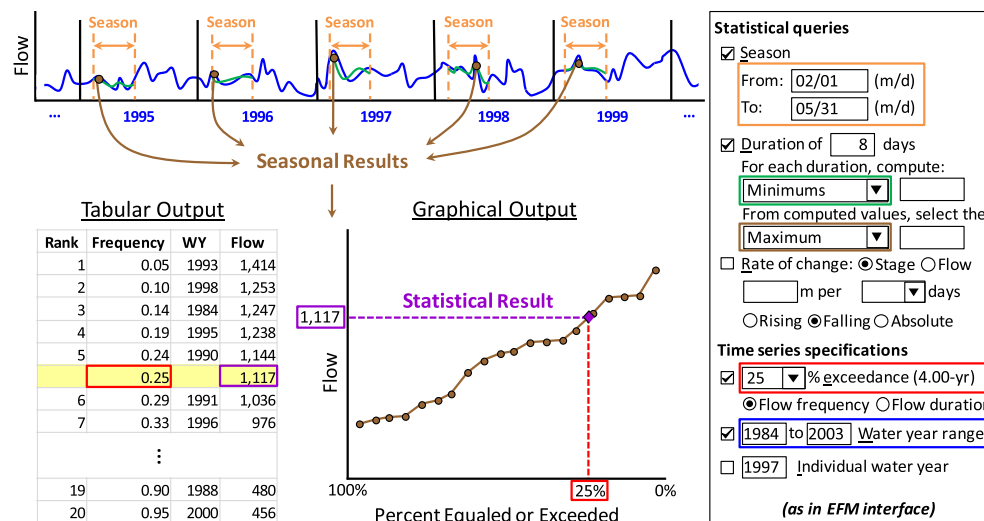
**Fig. 6.** Sample use of the time series specifications (percent exceedance − flow frequency − water year range) for a relationship with season and duration queries (as in Figs. 3 and 4). The statistical result is the flow meeting the parameters in those queries that is equaled or exceeded in 25% of the seasonal results.

### 2.2.2. 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.

### 2.2.3. 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 (Fig. 3). 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.

### 2.2.4. 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 to reflect the composite effects of flow regimes on fish. Each index is computed by summing the product of confidence value (integer 0–5), direction of change (i.e., 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), and magnitude of change between alternative and reference flow regimes for each member relationship.

### 2.2.5. Time series specifications

Each flow regime has a start and end date (Fig. 2). 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 (Figs. 3—6). 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.

### 2.3. Seasonal and 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. For flow frequency relationships, each season is assessed per the duration and rate of change parameters defined by the user. This produces a measure of how ecosystem aspects fare in individual water years. These seasonal results are then ranked and queried with the percent exceedance criterion. 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. Fig. 7, 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. A reverse lookup is a special type of relationship. Instead of setting a percent exceedance and getting a flow and stage, users specify a particular flow or stage value and EFM returns the percentage of time or years where that value is equaled or exceeded.

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.

### 2.3.1. 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 be

**Summary**

| Relationship | Conf. | Natural | | Chg. | Gaged | |
| --- | --- | --- | --- | --- | --- | --- |
| | | Stage, m | Flow, cms | | Stage, m | Flow, cms |
| Little minnow spawning habitat | * | 1303.0 | 35 | Pos | 1303.2 | 48 |
| Big bass winter habitat | * | 1302.7 | 15 | Pos | 1302.7 | 17 |
| Benthic macroinvertebrate biodiversity | * | 1304.3 | 187 | Neg | 1303.6 | 90 |
| Wetland health | * | 1302.7 | 18 | Pos | 1302.8 | 22 |
| Riparian tree recruitment | * | 1302.9 | 29 | Pos | 1303.0 | 32 |
| Riparian tree inundation | * | 1302.6 | 11 | Neg | 1302.7 | 17 |

**Index Values**

| Index | Gaged |
| --- | --- |
| A - All | -4.7 |
| B - Fish | 27.4 |

**Reverse Look-ups - Flow Duration**

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

**Fig. 7.** Statistical results reported by EFM.

displayed using an 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. EFM and EFM Plotter are developed as separate software, with Plotter launched upon user request through the EFM interface and automatically populated with output for viewing.

### 2.4. 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 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 (Figs. 8 and 1).

### 2.5. 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.

#### 2.5.1. HEC-GeoEFM

HEC and the Environmental Systems Research Institute (ESRI) are developing a tool called HEC-GeoEFM to serve as the spatial

accessory of EFM (USACE, 2011b). GeoEFM is 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, calculators for performing geographical queries, and consideration of habitat suitability indices. GeoEFM also has a patch tool that analyzes the connectivity and functionality of spatial result areas. Statistical results from EFM are simulated with a hydraulics model and the resulting maps are imported to GIS with GeoEFM used to apply geographical criteria and perform spatial assessments (Fig. 8).

## 3. 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 (JSA, 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 3) 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).

Both studies used the River Analysis System (HEC-RAS; USACE, 2010) to perform the steady-flow simulations that translated 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).
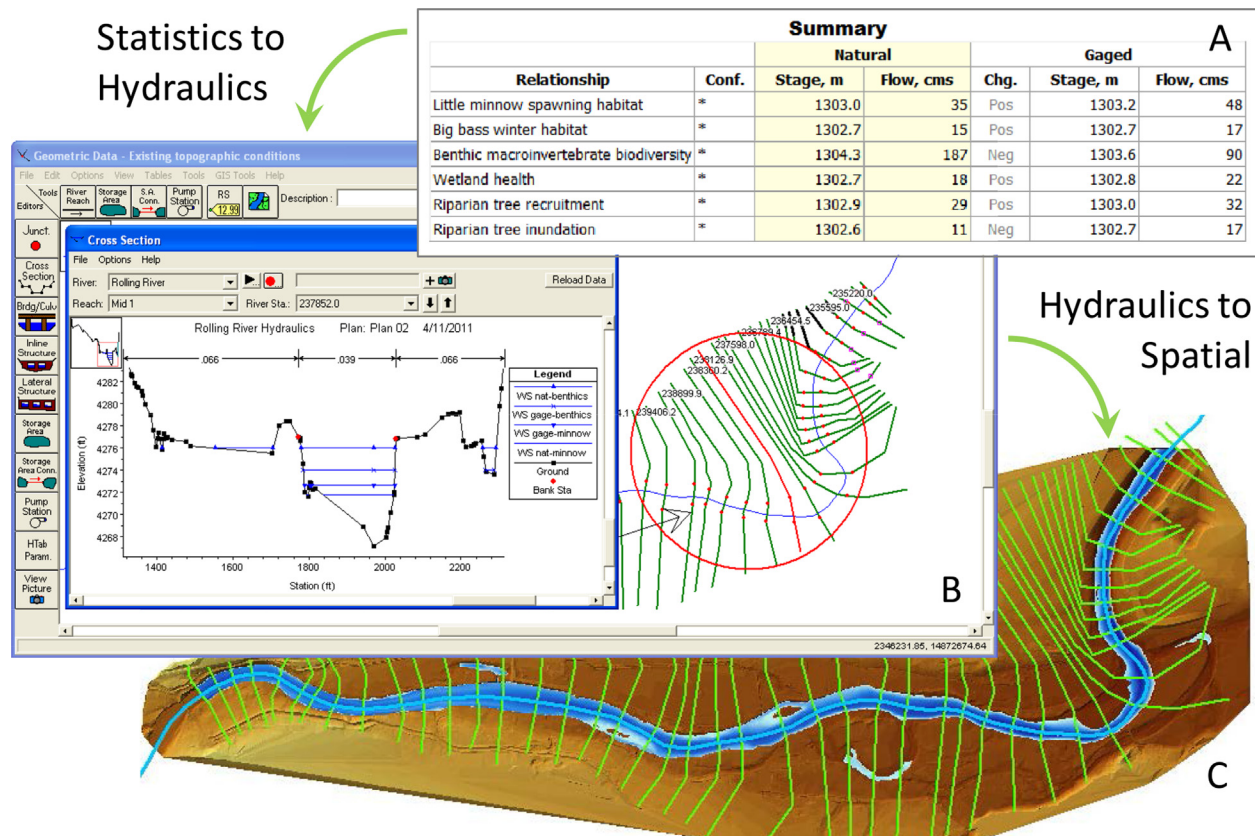
**Fig. 8.** Transitions in the EFM process where statistical results (A) are input to river hydraulics modeling (B) with modeling results being imported to GIS for spatial analyses (C).

HEC-GeoRAS also can generate layers of water velocity and shear stress, although those data were not used here.

### 3.1. 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.

#### 3.1.1. 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.

**Table 3**
Parameters for the Sacramento splittail minnow spawning and cottonwood seedling establishment relationships in EFM (JSA, 2000; Fields, 2009; Shafroth et al., 2010).

| Statistical queries | | San Joaquin River | | Bill Williams River | |
| --- | --- | --- | --- | --- | --- |
| | | Sacramento splittail minnow | | Cottonwoods | |
| | | 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 | —[a] | Minimums |
| | Seasonal result | Maximum | Maximum | —[a] | Maximum |
| *Rate of change* | Threshold rate | —[a] | —[a] | 0.06 m/day | —[a] |
| | | | | 0.20 ft/day | |
| | Interval (days) | —[a] | —[a] | 7 | —[a] |
| *Percent exceedance* | Flow frequency | 25% | 67% | —[a] | —[a] |
| *Time series settings* | Individual water year | —[a] | —[a] | 2006 | 2006 |

[a] Statistical queries noted with ("—") mark options not applied as part of the relationship.

### 3.1.2. 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—7 days), and then to provide cover for larval fish (10—14 days). Most splittail minnows mature sexually at the end of their second year of an estimated life span of 5—7 years (Moyle, 2002).

This life history was used by scientists and engineers to estimate parameters for the San Joaquin application of 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 (JSA, 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.

### 3.1.3. Statistical analyses

Statistical results for the splittail spawning relationships were computed based on the criteria in Table 3. The process used to obtain seasonal and then statistical results for each flow regime followed the same procedures shown in Figs. 4 and 6, 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 4.

### 3.1.4. 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 5; Fig. 9). 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 4**
Statistical results for EFM relationships related to Sacramento splittail minnow spawning, San Joaquin River near Vernalis, California.

| Relationships | San Joaquin River near Vernalis, CA, 1931—1998 | | | |
| | Unimpaired | | Gaged | |
| | 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) |

**Table 5**
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.

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

### 3.1.5. 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 indicate 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 5). 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.
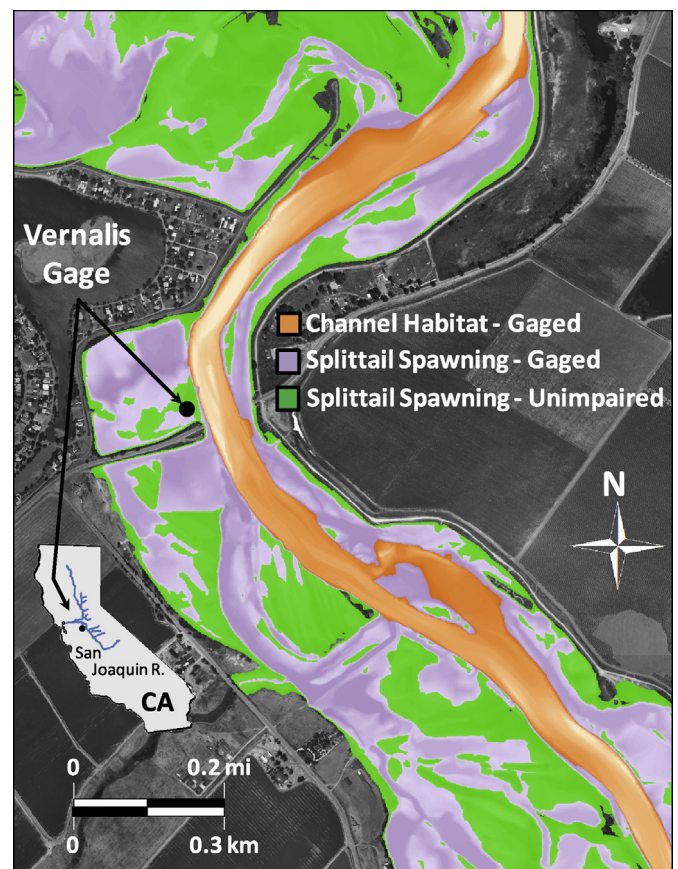


**Fig. 9.** Spatial results for the splittail minnow spawning relationships, gaged and unimpaired flow regimes, for a stretch of the San Joaquin River near Vernalis, California. Spawning conditions for the gaged flow regime are represented by the purple layer of water depths and for the unimpaired flow 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3.2. 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).

### 3.2.1. 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 hydraulics model were produced by HEC-RAS and used by EFM to generate local stage time series.

### 3.2.2. 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. 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).

**Table 6**
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) | – |

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).

### 3.2.3. Statistical analyses

Rates of stage recession were tested by EFM using the statistical criteria in Table 3 and the procedures shown in Fig. 5 to determine the portion of the flood recession gradual enough to support seedling root growth at each of the 341 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 6, Fig. 10; Fields, 2009). Twenty-five cross sections, many of which were located in a wide valley area, were able to support seedling root growth for the entire recession (55.5 cms; 1,960 cfs). The most common statistical result was lower on the recession (12.5 cms; 440 cfs) and occurred at 236 cross sections.

# Cottonwood Establishment Analysis - Bill Williams River, AZ
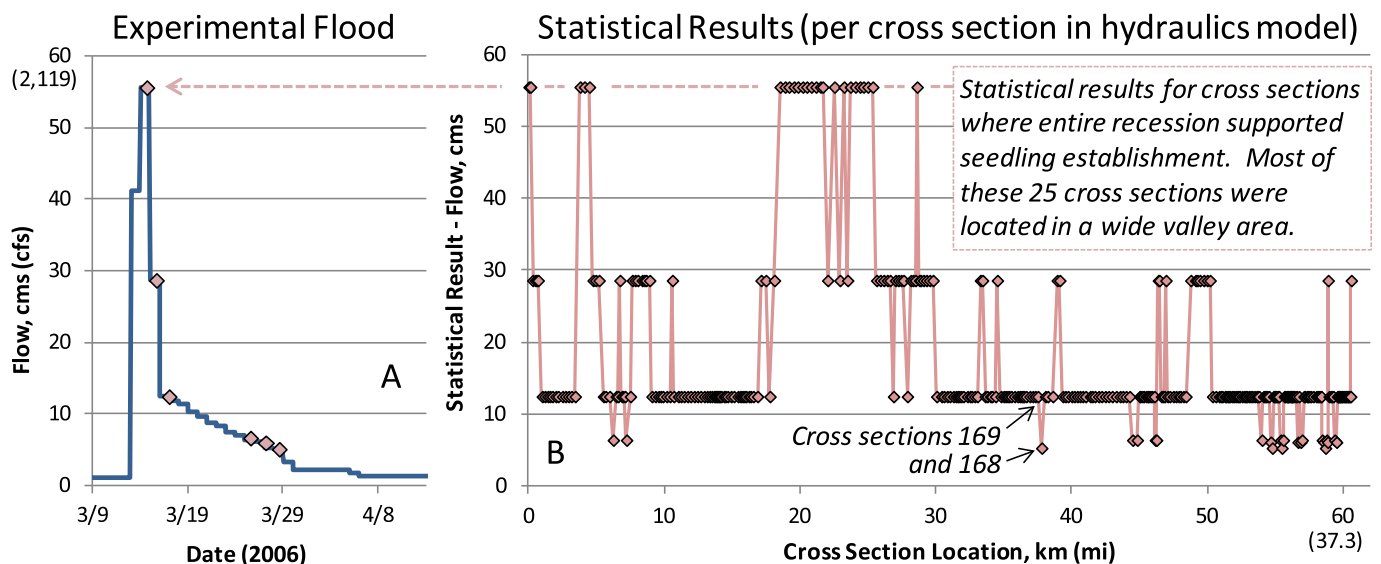


**Fig. 10.** Hydrograph (A) and corresponding statistical results (B) for simulated cottonwood seedling establishment associated with an experimental flood, Bill Williams River, Arizona. Statistical results were generated for each of 341 cross sections in a river hydraulics model. Higher statistical results reflect river locations where channel shapes led to more gradual recession rates and were therefore predicted to be more conducive to seedling establishment.

#### 3.2.4. 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 results 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 7; Fig. 11).

#### 3.2.5. Summary

The experimental flood was predicted to establish 5.0 km² 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 March 2006. In October 2006, scientists boated the entire Bill Williams River below Alamo, recording the number of seedling patches for different riparian tree species. Observed patches were correlated with simulated patches (physically connected seedling

**Table 7**
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, km² (ac) |
| Seedling establishment | 5.0 (1,227) |
| Seedling drowning or open water | 1.8 (445) |

establishment areas from the spatial results layer) for cottonwood seedlings within an assumed line of sight of the scientists. Initial correlations were performed on a reach-scale — the entire river was divided into 12 contiguous reaches with patches tallied per reach and then correlated — and resulted in a simple positive correlation of 0.71, an encouraging result for ecological modeling. Though this case study highlights an actual flow event, the same process of statistical and spatial analyses could be used in a forecast mode to customize hydrographs to produce specific ecological responses.

### 4. Discussion

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 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 evaluation would allow habitat suitabilities to be considered in each water year and correlations to be performed spatially or in terms of habitat areas.
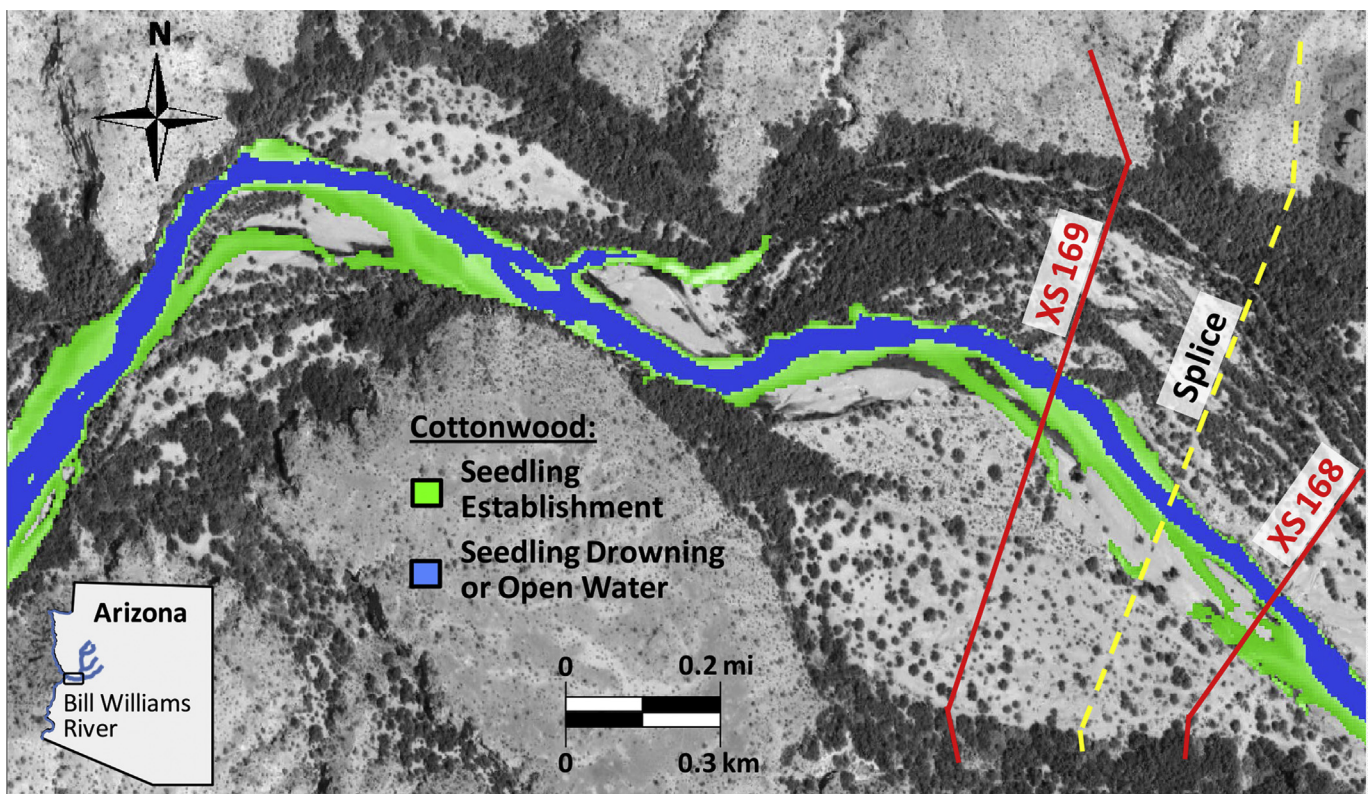


**Fig. 11.** Spatial results for the cottonwood establishment relationships, experimental flood of March 2006, Bill Williams River below Alamo Dam, Arizona.

Statistical results are a simple and single performance measure for each relationship and flow regime. These results 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 statistical and geographical criteria used to define a relationship, spatial results are 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.

Both case studies 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 Connecticut River in the northeastern United States to quantify ecosystem responses to environmental flow scenarios (Julian et al., in press), the Truckee River in Nevada to study restoration of channel meanders (USACE, 2005), a navigation pool on the Mississippi River in Missouri to investigate alternative strategies for managing pool stages, the Sandy River in Oregon as part of a dam removal project, the Sulphur River in Texas to explore responses to proposed dam raises, the Ashuelot River in New Hampshire to examine flow effects on an endangered species of mussel, and the Kibos River in Kenya to estimate ecological effects of water supply development (Wakitolie, 2013). Additionally, there are emerging uses of the EFM process for floodplain reconnection in the Columbia River Estuary, shaping of environmental releases for the Colorado River Delta, and human considerations (system performance for recreation, cultural resources, navigation, water supply, and flood risk management) related to reservoir reoperations for the Missouri River.

Applications of EFM focus on aquatic habitat and land—water interactions inside the maximum inundated area associated with a river, wetland, or reservoir. Within this domain, the software is capable of testing a diverse and extensive array of management scenarios and ecological relationships. This computational capacity provides an inherent ability to investigate model performance (Bennett et al., 2013) via comparisons with field observations and sensitivity analyses (Saltelli and Annoni, 2010) of EFM hydrologic and ecologic inputs. Uncertainties related to ecological inputs can be investigated by creating sets of relationships for a single aspect of interest with each member of the set modified to test different input values.

EFM is often used in tandem with other models. The splittail minnow example was part of a study that used reservoir simulation models to compute alternative flow regimes, which were then assessed by EFM and a river hydraulics model to quantify ecological effects. In these settings, EFM aligns with other engineering software as an ecological component of linked modeling systems.

EFM is not especially well-suited for use when ecosystem responses are driven by multi-year or multi-event sequences or when sub-daily hydrologic fluctuations are critical to ecosystem responses. Hydropower peaking, where flows increase and decrease dramatically for short periods of time within a day, is an example of the latter. EFM is also limited in that the end products of its process are habitat maps, which are useful in project planning but often an indirect measure of project goals.

Work has begun on new software that address these weaknesses by enabling users to simulate spatial and temporal ecosystem dynamics as part of a population model known as EFMSim. 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 that describe them (e.g., height, weight, etc.), the rules that govern behavior (e.g., recruitment, reproduction, growth, stress, etc.), and other related characteristics (e.g., economic value, board-feet timber, carbon sequestered, etc.). Ecological communities interact and move, seeking advantageous combinations of environment and population distributions.

## 5. 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).

EFM's strengths include:

- *Testing ecological change for many flow regimes and relationships.* 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).
- *Linking ecology with established hydrologic, hydraulic, and GIS tools.* 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.
- *Quick, inexpensive means to incorporate expert knowledge.* 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.

- *Generic software tool, applicable to a wide range of riverine and wetland ecosystems, water management concerns, and restoration projects.* 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.
- *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 potential disconnect is true in ecosystem responses, which are influenced by many variables and can take many years to reveal a trajectory of change.

New features are being added to EFM, EFM Plotter, and GeoEFM that advance their collective ability to analyze flow regimes and to map and assess habitats. The spatial and temporal linking of ecosystem dynamics in EFMSim promises to address the key weaknesses noted above and is being implemented in parallel to EFM's current capabilities. This scalability, where applications of these software can be statistical analyses of flow regimes or also map habitat or simulate population dynamics, allows modeling to be customized per the needs of different projects and offers opportunities to engage study teams and stakeholders by producing results at each level of application.

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