ERDC/EL SR-10-X

US Army Corps of Engineers®
Engineer Research and Development Center

System-Wide Water Resources Program

Review Summary of Selected Software Packages for Ecosystem Habitat and Attribute Modeling

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December 2010

Environmental Laboratory

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Final report

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Abstract: Projects that require analyses of ecosystem response to changing flow regime and other environmental factors can depend on software technologies for modeling. Choosing the appropriate technology is a vital concern for each project. This report is designed to help managers evaluate which models would be useful for specific applications related to assessing habitat and ecosystem functions.

The report describes seven software packages that can be used to study ecosystem habitat characteristics and processes. This information can help managers evaluate models and their utility for specific applications related to assessing habitat and ecosystem functions. This report identifies the seven models and who developed them, describes target applications, and discusses data requirements, ease of use, and the form of the results.

Case studies were performed for two different species: Fremont cottonwood and Chinook salmon. Habitat conditions for Fremont cottonwood (*Populus fremontii)* seedling recruitment were evaluated using five of the models, excluding the fish models. Habitat potential was analyzed with three alternative flow regimes in the time period 1946-1994 in a selected reach of the Upper Sacramento River in Northern California. Habitat conditions related to redd-dewatering, which is a limiting population factor of fall-run Chinook salmon (*Onchohynchus tshawytscha*), were evaluated using four of the models.

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Summary

Management decisions related to ecosystem functions can benefit from models that evaluate biological habitat characteristics and simulate ecosystem processes. This review describes seven software packages that can be used to study ecosystem habitat characteristics and processes. This review can help managers evaluate models and their utility for specific applications related to assessing habitat and ecosystem functions. This short report identifies the seven models and who developed them, identifies the target applications, and discusses data requirements, ease of use, and the form of the results.

Ecosystem simulation models typically have been developed with a target application, which influences the operation of the model. The software packages were classified into two categories: 1) ecosystem relationships, and 2) environmental flows. Ecosystem relationship models simulate habitat conditions based on specific biological processes and also simulate how the habitat changes in relationship to environmental changes. Two of the models in the ecosystem relationship group were designed specifically to evaluate fish habitat. Environmental flow models analyze the changes in hydrologic flow.

For evaluating habitat quality of ecosystems, all of the models reviewed tend to be based on the thinking behind “habitat suitability indices,” where the quantitative evaluation of habitat change is ultimately based on a ranking system established by a body of scientific expertise. For the ecosystem relationship models, the habitat suitability assessment is an explicit part of the model; for the environmental flow models, the habitat suitability tends to be determined outside of the modeling effort.

In this review, case studies were performed for two different species: Fremont cottonwood and Chinook salmon. Habitat conditions for Fremont cottonwood (*Populus fremontii)* seedling recruitment were evaluated by using five of the models, excluding the fish models. Habitat potential was analyzed with three alternative flow regimes in the time period 1946-1994 in a selected reach of the Upper Sacramento River in Northern California. Because the “ecosystem relationship” models are designed for applications like examining habitat characteristics, it was easier to use the ecosystem relationship models to directly analyze the cottonwood recruitment.

Although the “environmental flow” models are not specifically designed to define ecosystem relationships, they were used to consider the cottonwood habitat analysis. Technical knowledge of cottonwood recruitment played a key role in successfully using all the models. For evaluating ecosystem response to changing environmental conditions, the definition of the relationship rules, the choice of which output to use, and the interpretation of the output all required technical knowledge of the biological system in question. Partly because similar metrics were extracted from the five models, the results of analyzing cottonwood habitat were qualitatively similar in all five cases. The Base Flow scenario resulted in the best potential habitat, followed by the Nodos and Shasta scenarios, in that order.

Habitat conditions related to redd-dewatering, which is a limiting population factor of fall-run Chinook salmon (*Onchohynchus tshawytscha*), were evaluated using four of the models. The Chinook salmon spawning habitat potential results, based on analyses of redd-dewatering, suggested that the Nodos and Shasta scenarios both provided somewhat better habitat potential than the Base Flow scenario.

Many of the models can analyze and visualize flow time series, which are data that are generally accessible and useful to a wide range of users, both expert and general. In addition, many of the models are designed to give simple output data related to ecosystem response (e.g. SacEFT, HEC-EFM). In some cases, the pre-defined output is relatively easy to interpret by a lay practitioner (e.g. SacEFT); in some cases it is not as obvious. For the environmental flow models, the choice of which indices to choose in order to reflect a defined ecosystem response requires significant technical judgment.

The process of developing relationships for environmental flow and ecosystem processes modeling software packages can be conceptualized in seven steps:

1. Analyze life history
2. Screen variability between scenarios
3. Identify and refine key ecosystem relationships
4. Develop hypotheses
5. Run model and review graphic output (visualizations)
6. Interpret output
7. Refine and revisit where necessary

Preface

Information used in preparing this report was provided by Clint Alexander and Don Robinson of ESSA Technologies, Vancouver, Canada, and by John Hickey of the Hydrologic Engineering Center (HEC), Davis, California. Program software, information, and helpful discussions with Mike Dietl, U.S. Army Corps of Engineers (USACE); Ryan Luster, The Nature conservancy; Dr. Brian Cade, U.S. Geological Survey; Dr. Jack Killgore, USACE Engineer Research and Development Center (ERDC) – are gratefully acknowledged. Dr. Jeff Opperman, The Nature Conservancy, added comments and text for the IHA consideration. Dr. Mark Gard, U.S. Fish and Wildlife Service, provided guidance on Chinook salmon modeling. Dr. Steven Ashby, USACE ERDC, provided invaluable support, comments, and guidance. Dr. Todd Swannack, USACE ERDC, provided a thorough and thoughtful review that resulted in additions and reorganization that brought clarity and substance to the manuscript.

Funding for this work was provided by the Visiting Scholar Program of the USACE HEC, Davis, California, with support and advice from Matt McPherson and Chris Dunn.

At the time of publication of this report, COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

1 Introduction

In recent years, as research groups and regulatory agencies needed to study the ecosystem impacts resulting from land-use and flow regime changes, ecosystem habitat modeling has become prominent. Modeling how flow and land-use alterations determine future effects on natural systems is critical. With the current interest in restoring environments, and with the concern that present actions may have future effects, mathematical models are a powerful and efficient way of assessing the effect on ecosystem processes of flow regulations and land-use actions. This review examines seven mathematical computer software packages that aid in evaluating ecosystem conditions resulting from flow and land-use changes.

Management decisions, regulatory issues, and restoration efforts are all aided by ecosystem modeling and visualization tools. Managers for public and non-profit agencies, private groups, consulting firms, and research groups use modeling tools for many planning purposes such as restoration design, mitigation evaluation, and cost-benefit analyses. In addition, the visualization component of the software packages is a valuable communication tool. Various tools are available that model ecosystem functions. The models studied in this review were chosen because they are potentially valuable in helping understand ecosystem processes. To one degree or another, they are publically available. Many have been developed for specific purposes, but can possibly be generalized outside the original area of concern.

The models evaluated here were classified into two broad categories: 1) models that focused primarily on "ecosystem relationships," and 2) models that focused on "environmental flows." Ecosystem relationship models simulate a biological process and how it changes in relationship to environmental changes. Ecosystem relationship models include a metric within the model that quantitatively evaluates habitat quality given various environmental situations. Environmental flow models analyze the changes in hydrologic flow and leave it up to the user, outside of the model, to interpret how this will influence ecological factors.

Any conceptualization of reality is a model. The increasing speed and utility of computers have made mathematical modeling more common, and more effective. Modeling ecosystem relationships ultimately deals with assessing biological health. Because biological health depends on the habitat in which an organism lives, habitat modeling is common. The assumption is that positive habitat will result in more life organisms. This may not always be the case, and it is important to note that most models can only model the *potential* for the abundance and health of a biological organism (i.e. the habitat), not the actual abundance or health of the organism itself.

Traditionally, an ecosystem is defined as referring to a collection of plants, animals, and microorganisms and the physical environment in which they live. A more complete and current view is that "an ecosystem is a complex of ecological communities and their environment, forming a functional whole in nature (Patten and Jørgensen 1995)." Ecosystem relationship models therefore conceptualize how a species interacts with the physical environment. Mathematical models of ecosystem processes assign numerical values to flow and habitat features. Mathematical procedures are also used to assess habitats and their suitability through procedures that are similar to "habitat suitability indices," which are used to evaluate particular habitat qualities of an ecosystem generally for a particular species or research objective. A habitat suitability index provides a quantitative evaluation of habitat change that is ultimately based on a ranking system established by a body of scientific expertise, often developed from research studies. For the ecosystem relationship models, the habitat suitability assessment is an explicit part of the model; for the environmental flow models, the habitat suitability tends to be determined outside of the modeling effort.

Environmental flow models are based on the idea that biological responses are related to the hydrologic flow regime (the inter- and intra-annual variability of flow levels and events) of a river. River management related to flow has led to the setting of "environmental flow" or "instream flow" regimes that are commonly designed to protect or enhance biological processes. The early work in this field led to a definition of a collection of simple statistical measures of a flow regime (Richter et al. 1996). In an effort to assess how much a flow regime has been altered, indices of a natural regime can be compared with the indices of an altered flow regime. Further research proposed the idea that such statistical indices naturally have a range of variability, and that managed flow regimes that remained within these ranges of variability could potentially restore or maintain river ecosystems (Richter et al. 1997). Although a great deal of technical judgment is required to choose the appropriate indicators for environmental flow models, and how to interpret the results, the actual data (observed or synthesized daily flow records) are relatively simple to obtain and input.

In addition to the technical merits of the various modeling software packages, ecosystem modeling software packages benefit from an “infrastructure” in order to survive effectively and usefully. Software support was critical to the effective use of the various packages included in this report. Such support is ideally included with the help menu of the software, is interactive, relates to the issue on the screen at the time of query (i.e. context-sensitive), and adequately resolves all issues that arise. With the rapid changes in computer hardware and software technology, updates, error fixes, and ongoing support beyond the software help menu are important. Where this climate of software support does not exist, the software becomes less effective. With the rapidly changing computing environment, computer software for ecosystem modeling can be transient. Models can be formulated but not be effectively used after their support structure does not meet user needs. Additionally, active research that explains or uses the software package is beneficial.

This short review introduces each of the models and identifies who developed the model. The report describes the target audience and applications. It also discusses data requirements, ease of use, the form of the results, support and research resources, and the typical user base. In addition, for a preliminary numerical comparison of the use of the models, case studies of two sample relationships were performed. The relationship for cottonwood recruitment was patterned after the pre-defined cottonwood recruitment relationship in one of the software packages, the Sacramento River Ecological Flows Tool (SacEFT), which was determined by a panel of experts for cottonwood seedling recruitment on the Sacramento River. The potential habitat for cottonwood recruitment was assessed for three different flow scenarios (called Base, Nodos, and Shasta; cf. Figure 23) based on various hypothetical reservoir operations on the Upper Sacramento River, again patterned after input data develop for the SacEFT (The Nature Conservancy 2008). The fall-run Chinook Salmon redd-dewatering relationship used by SacEFT and also used for the other models in the current report was based on work by the U.S. Fish and Wildlife Service on the Sacramento River (U.S. Fish and Wildlife Service 2006). The U.S. Fish and Wildlife Service developed habitat suitability criteria for redd dewatering based on depth, velocity, and bed exposed, and related those criteria to various flow regimes. These relationships were used for the case study modeling reported here.

2 Model descriptions

Choice of models/overview

Many agencies and organizations (e.g. The Nature Conservancy (TNC), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE)) have developed models in response to a need to understand how flow and land-use changes influence biotic habitat in ecosystems. For this brief review, software packages that can be used to examine ecosystem processes and that are similar and complementary to each other were identified and examined (Table 1).

The models can be classified into two main groups (Table 1). One group of models, which can be called ecosystem process (or function) models, includes a component of quantitative modeling of environmental processes. The other group focuses on flow regime analyses, and may generally be classified as environmental flow models. Some of the models include both elements. General characteristics of the seven models are listed (Tables 1 and 2). Also listed are selected research citations and appropriate resource papers (Appendix A) and a brief description of the intended and practicing user groups (Appendix B).

Description of models

Ecosystem process models

Sacramento River Ecological Flows Tool (SacEFT)

The Sacramento River Ecological Flows Tool (SacEFT) grew out of the “Sacramento River Ecological Flows Study, which was initiated by The Nature Conservancy (TNC) in collaboration with a team of ecologists, geomorphologists, and river management specialists” (The Nature Conservancy 2008). Growing out of studies conducted to understand the physical and biological processes that determine the riparian habitat of the Sacramento River, the SacEFT was developed as a tool to analyze the ecological outcomes on terrestrial and aquatic species resulting from water-planning processes that involve changes in the flow regime.

Table 1. Software packages that can be used for flow-related ecosystem response modeling: General characteristics.

			Model Name	Simulate/Purpose	Input Data	Application	Notes
1	Ecosystem Processes	General	SacEFT	Evaluates habitat changes resulting from flow-related management strategies on the Sacramento River.	• Flow time series[1] • Selected cross-section profiles[1] • Stage time series at cross sections[1]	Six defined focal species on the Sacramento River.	Pre-defined focal species. Relationships currently pre-defined. Program currently usable through internet connection.
2			HEC-EFM	Evaluates ecosystem response to changes in flow regime and channel modifications.	• Flow time series • Stage time series or rating curve • Functional ecosystem relationship	User-defined relationship based on hydrology and other factors.	Able to be generalized to any application. Accepts HEC RAS input. Outputs easily visualized in GIS.
3			RAP	Evaluates ecosystem response to changes in flow regime and channel modifications.	• Flow time series • Any defined rating curve or other time series. • Functional ecosystem relationship	Allows definition of any relationship.	ERM is also designed as a visualization tool to communicate with stakeholders.
4		Fish	SAM	Evaluates fish response to bank armoring changes on the Sacramento River.	• Bank slope • Floodplain inundation ratio • Bank substrate size • Instream structure • Aquatic vegetation • Overhanging shade at different flow quantities	Evaluation of bank protection actions on selected fish species on the Sacramento River.	For selected Sacramento River fish species.
5			EnviroFish	Evaluates flood plain habitat for fish species.	• Flow time series • Stage time series • Area-stage for different species	For floodplain fish.	For Mississippi Valley floodplain fish.
6	Flows		IHA	Evaluates hydrograph changes due to water management projects.	• Flow time series	Instream flow evaluation. EFC for evaluating flow-ecology relationships.	Produces hydrologic indices. General for flows. Includes EFC[2] for flow-ecology linkage.
7			HIP/HAT	Evaluates environmental flows.	Flow time series Stream designation Stream classification system	Instream flow evaluation.	Produces hydrologic indices. General for flows. Possibly uses internal stream classification system.

[1]These data are not required by the user, but are pre-supplied by the software. Future versions will allow user input. [2] 'EFC" are "environmental flow components."

Table 2. Software package availability and use information.

	Model Name	Developing Agency/Group	Years Available[1]	Availability	Website	Within-program Menu Support	External Support
1	SacEFT	The Nature Conservancy/ESSA Technologies.	Version 1, 2009 to present.	Public; free.	http://www.essa.com/tools/EFT/download.html User will be asked to register, and then once approved, user will receive access to the SacEFTReader installation file.	Internet access only. Under development. Currently not context sensitive.	Version 1 supported by TNC and ESSA Technologies.
2	HEC-EFM	USACE	2008 to present; but previously used.	Public; free.	http://www.hec.usace.army.mil/software/hec-efm/index.html	Quick start guide, context sensitive.	Phone support, for USACE personnel mainly. Training courses publically available.
3	RAP	eWater CRC (Australia)	2002-2006.	Public; free.	http://www.toolkit.net.au/Tools/RAP	Context sensitive; but slightly out of date.	Minimal, through eWater.
4	SAM	USACE	2005 to present.	Not public?	Not available.	Not within program.	Unknown.
5	EnviroFish	USACE/ERDC	Beta 2009; but previously used.	Not yet public.	In draft review version only. Contact Killgore, Jack ERDC-EL-MS [Jack.Killgore@usace.army.mil]	Not within program.	Beta. Program and support not yet public.
6	IHA	The Nature Conservancy	Early 1990's to present.	Public; free.	http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html	Interactive. Context sensitive.	Online training courses publically available. Public training courses also available.
7	HIP/HAT	USGS	2006 to present.	Public; free.	http://www.fort.usgs.gov/Products/Software/NJHAT/ OR http://www.fort.usgs.gov/Products/Software/NATHAT/	Interactive. Context sensitive.	USGS.

[1]In many cases, the programs were in use before the technical date of public release.

"The Sacramento River Ecological Flows Tool (SacEFT) is a database centered software system for linking flow, gravel and channel management actions to changes in the physical habitats for the following six focal species of concern: Chinook salmon, Steelhead, Green sturgeon, Bank swallow, Western pond turtle, and Fremont cottonwood. SacEFT is [currently] a viewer of run results. [Future versions plan to be fully operational.] Users cannot create new scenarios or edit existing scenarios. To view results for most of the scenarios, users must run the model for each scenario they wish to use. [Some of the scenarios have results already produced.] The Ecological Flows Study treats flow as the "master" variable regulating the form and function of riverine habitats."[1]

The tool is web-based and currently requires accessing the database operated by ESSA Technologies. The interface is easy to understand, and it should be easy for managers and non-technical users to accomplish runs. The modeling tool is currently specific to the Sacramento River, and the flows, focal species, and relationships are all pre-defined and can be viewed in the tool. Future plans include users being able to modify or define relationship parameters in SacEFT V2. For user input in SacEFT V1, the user must currently choose "output" in the "output choices" offered on the program screen (Figure 1). When "Output choices" is selected, the user must choose from three different groups: 1) scenarios, 2) performance measures, and 3) years (Figure 1). The "scenarios" group consists of pre-defined flow regime time series of daily flows. The "performance measures" consists of performance measures chosen and encoded in the software that represent defined aspects of ecosystem response to flow. The "years" are the possible years available for modeling.

When the "Output viewer" button (see Figure 1) on the user interface screen is selected, the output shown in Figure 2 is made available. Model run default output shows an "annual" view and a "rollup" view, both of which are based on a good-fair-poor ranking system shown with green, yellow, and red colors. The example output (Figure 2) shows the output for three test flow regimes and the pre-defined relationship for cottonwood recruitment that are described later in this report. For some of the pre-defined performance measures, like Fremont cottonwood seeding initiation, reports can be generated through the interface on the "Finished reports" button (Figure 1). The metrics that are used to determine the default output (the

[1] http://www.essa.com/downloads/saceft/help/

poor-fair-good ranking) are recorded in the reports, and can possibly be used for further analysis. An example of these reports is given in Appendix C.

SacEFT is designed for water-management decision-makers to evaluate the effects of flow regime changes on ecosystem processes of selected species. The program is easy to use by non-experts and can effectively give qualitative (i.e. good, fair, poor) judgments based on relationships that have been defined for the Sacramento River by a panel of experts. Version 1 software is currently specific to the Sacramento River ecosystem relationships.

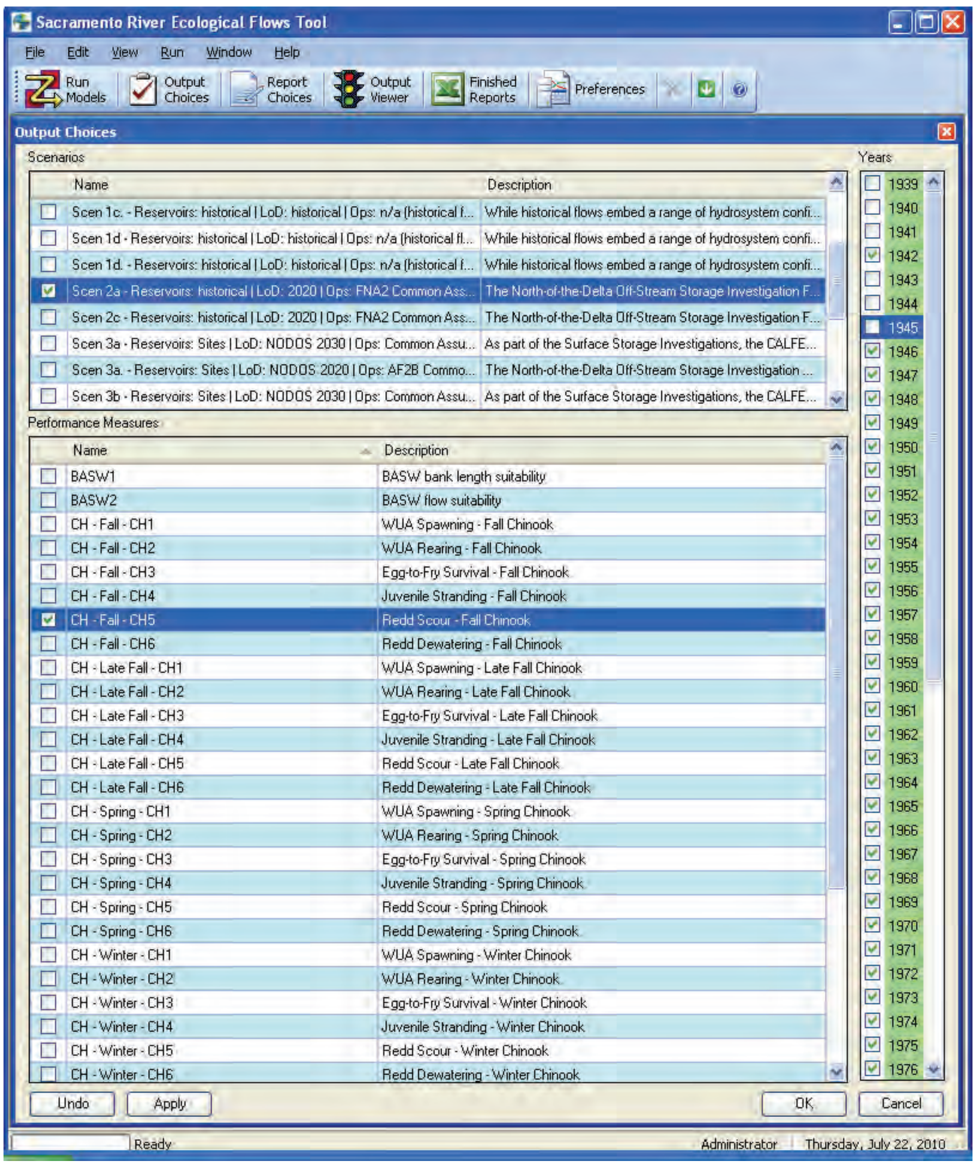


Figure 1. User interface screen with "Output choices" (These are essentially pre-defined input variables that a user may choose.)

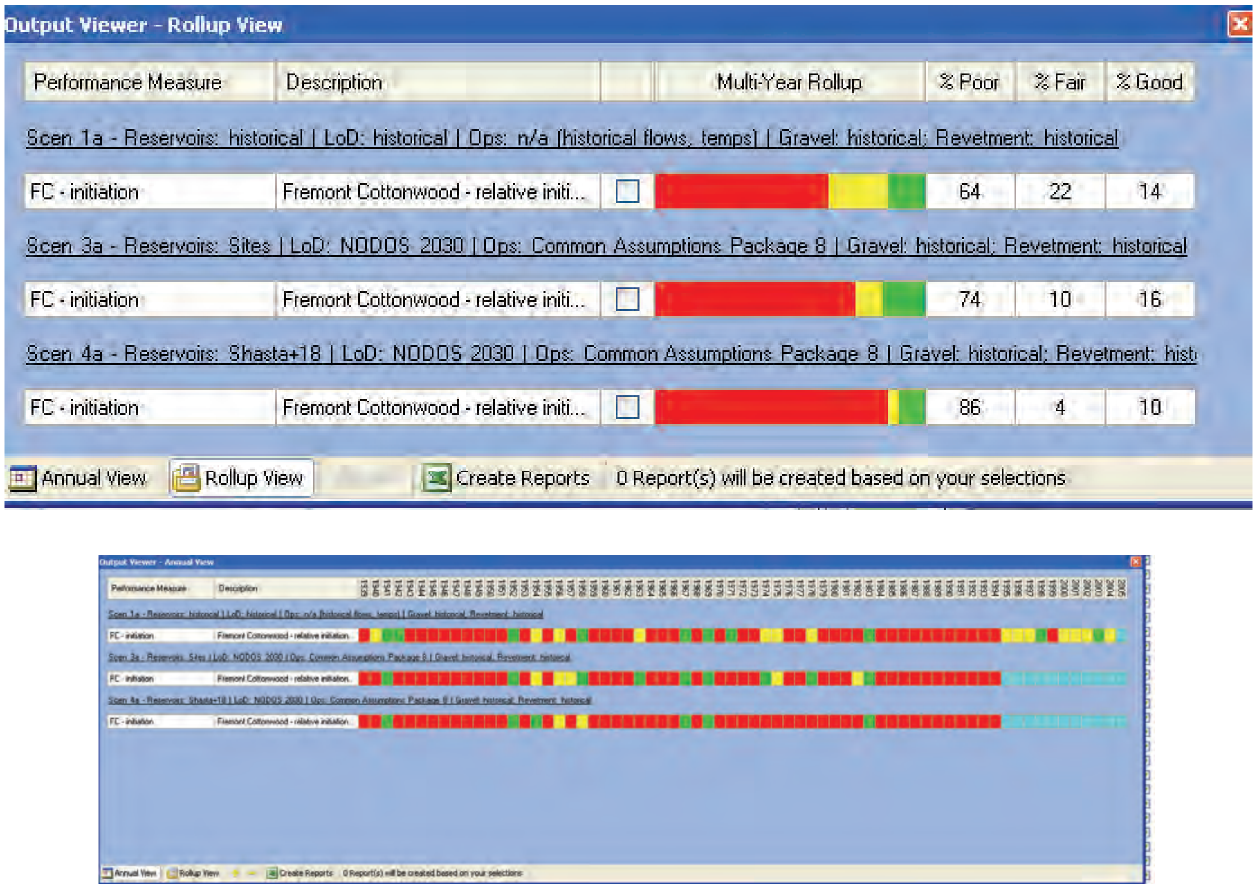


Figure 2. SacEFT rollup (top) and annual (bottom) view of output.

Hydrologic Engineering Center Ecosystem Functions Model (HEC-EFM)

The Hydrologic Engineering Center Ecosystem Functions Model (HEC-EFM) grew out of a need to understand the complex relationships between river flow (and stage) and elements of the ecosystem. The model has its roots in the Sacramento-San Joaquin Rivers Comprehensive Study initiated in 1997 by the US Army Corps of Engineers (USACE 2002). Based on an input of flow and stage time-series, which is configured on the first tab of the user interface (Figure 3), the model analyzes scenarios using “functional relationships." Once the flow time series is input, the four basic criteria for the functional relationships (which are accessed by way of the second tab on the user interface) that are analyzed are 1) season, 2), flow duration, 3) rate of change, and 4) flow frequency (Figure 4).

Once the flow and stage time series are input into the model, the user defines the ecosystem relationship of interest in terms of the four basic criteria described above. For example, in the cottonwood recruitment relationship that is used in the case studies for this report, 1) the season is defined as April 15 to June 21, 2) the duration is defined as 1 day, 3) the rate of change is defined as 0.19 ft in 2 days, and 4) the flow frequency is defined to be the flow that occurs once in 10 years (Figure 4). Relationships may be defined for aquatic or terrestrial species of plants and/or animals.

The default output (Figure 5), which appears on the third tab (Tables), once the "recalculate" button on the user interface screen is pressed, gives a single number for stage or flow. In the case of cottonwood recruitment, it gives the stage and flow at which recruitment is successful, based on recession rate (i.e. #3 above: rate of change) and seasonal timing criteria (#1 above: season). The output data can be used for further analysis and can be used to develop spatial visualizations in GIS.

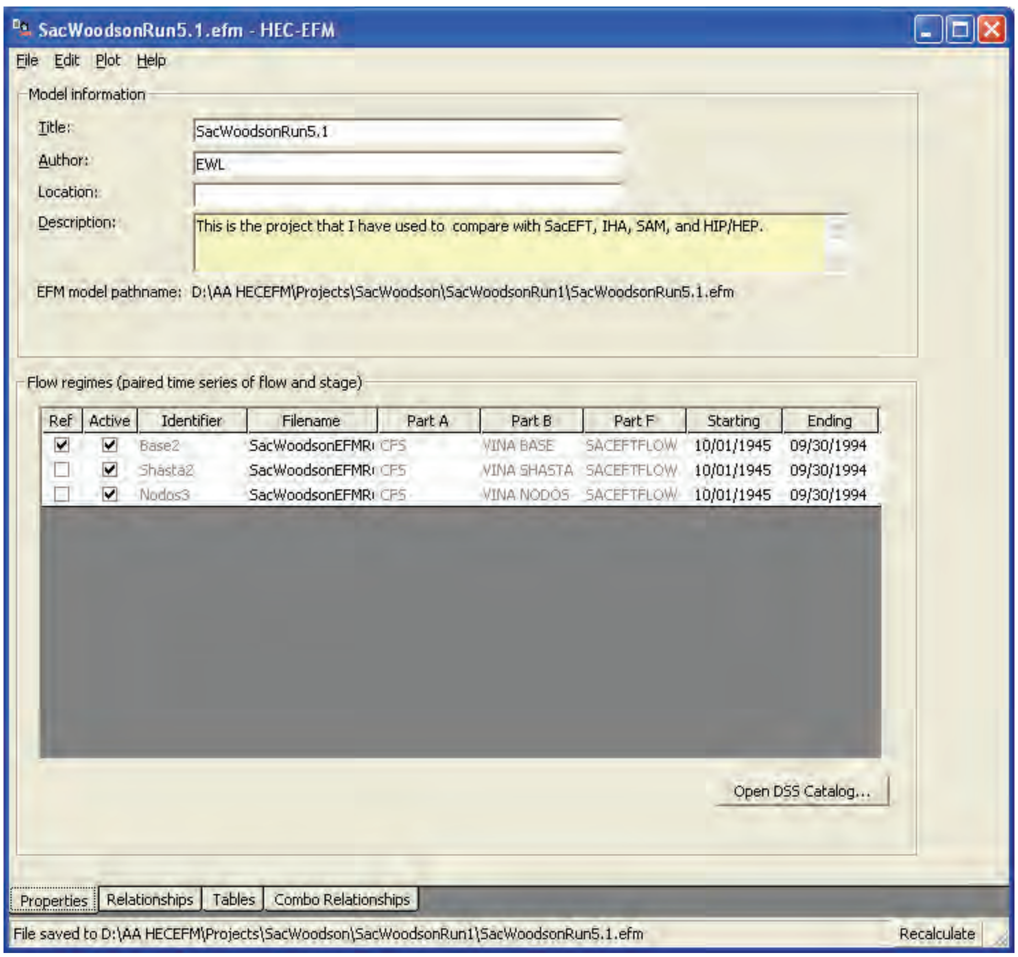


Figure 3. Flow time series input data screen shot for HEC-EFM.

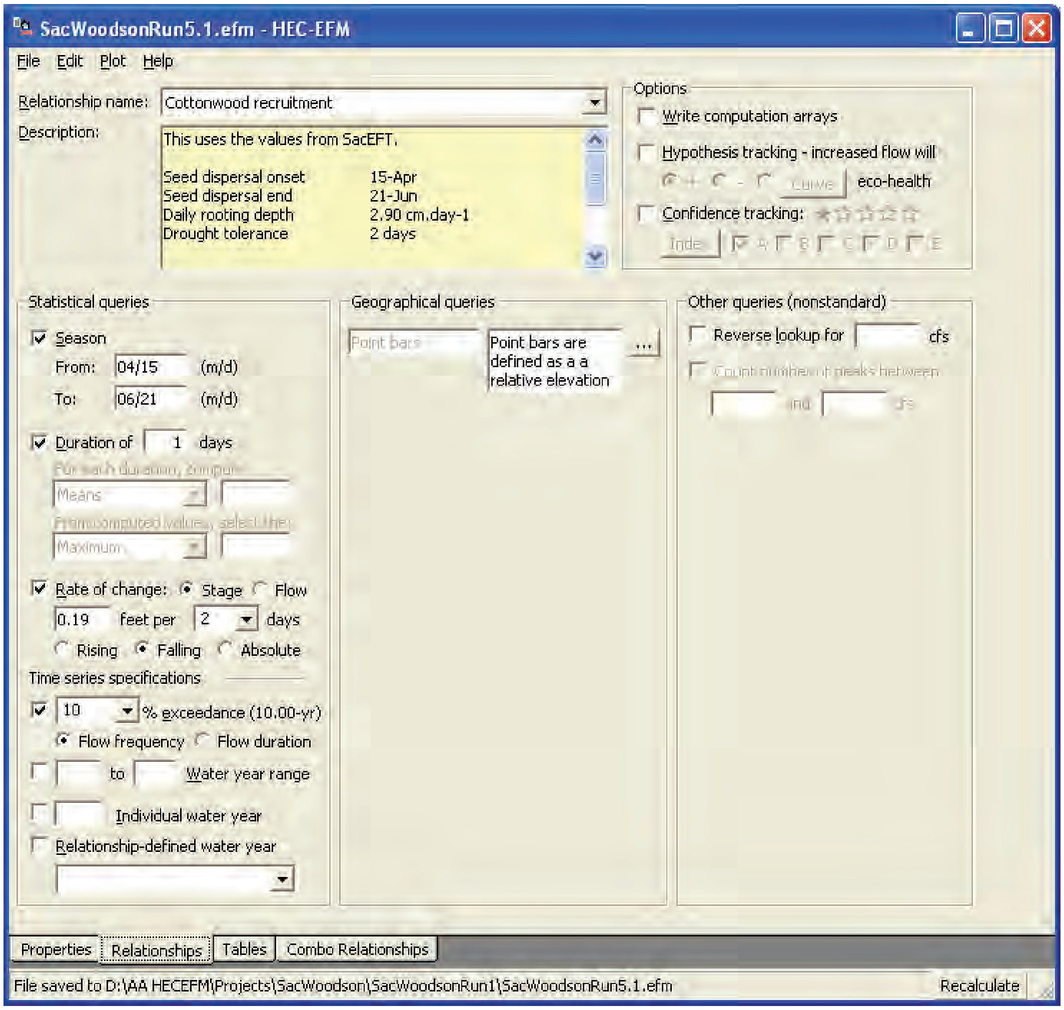
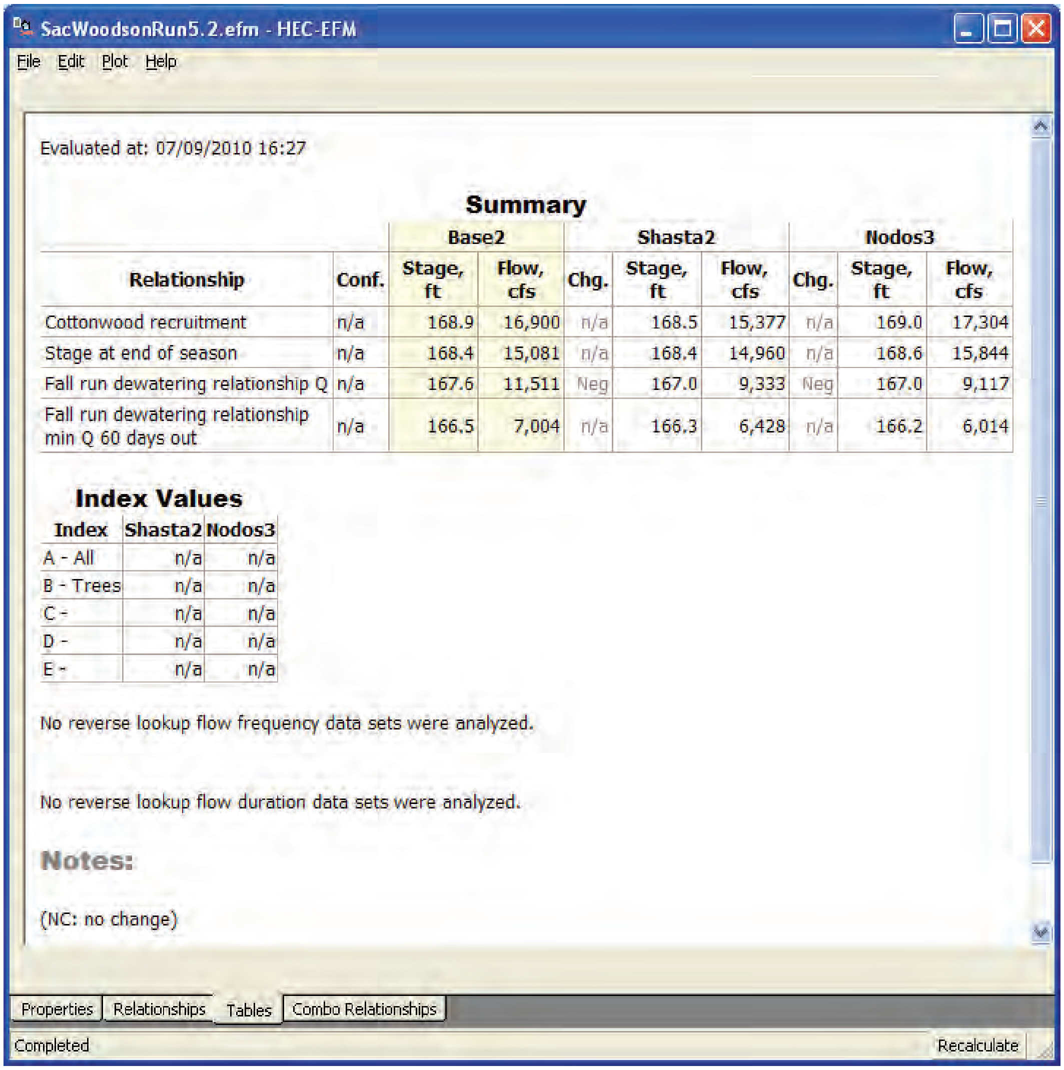


Figure 4. “Relationships” screen shot for HEC-EFM.

EFM also has a plotter (Figure 6), accessed from the menu under “plot,” that helps users quickly visualize and interpret the data and the output from the EFM software. This streamlines manipulation of the data. There are standard graphs and an option to create custom graphs.

HEC-EFM is a free USACE software package available through HEC. It is actively supported and undergoes regular updates. It is currently being used for USACE projects, as well as by consultants and researchers. EFM is highly versatile, allowing user-defined relationships. Using the output tables and EFM plotter, an experienced user can then define a set of output values that further clarify ecosystem relationships such as tree recruitment success. Expert knowledge is required to define the relationships, and to interpret the results.



Relationship	Conf.	Base2 Stage, ft	Base2 Flow, cfs	Chg.	Shasta2 Stage, ft	Shasta2 Flow, cfs	Chg.	Nodos3 Stage, ft	Nodos3 Flow, cfs
Cottonwood recruitment	n/a	168.9	16,900	n/a	168.5	15,377	n/a	169.0	17,304
Stage at end of season	n/a	168.4	15,081	n/a	168.4	14,960	n/a	168.6	15,844
Fall run dewatering relationship Q	n/a	167.6	11,511	Neg	167.0	9,333	Neg	167.0	9,117
Fall run dewatering relationship min Q 60 days out	n/a	166.5	7,004	n/a	166.3	6,428	n/a	166.2	6,014

Index	Shasta2	Nodos3
A - All	n/a	n/a
B - Trees	n/a	n/a
C -	n/a	n/a
D -	n/a	n/a
E -	n/a	n/a

Figure 5. HEC-EFM sample summary output table.

eWater Cooperative Research Centre River Analysis Package (RAP)

The River Analysis Package (RAP) is a suite of software packages that assesses the environmental consequences of flow and channel changes. Four modules fall under the umbrella of the system. Two modules, Time Series Analysis (TSA) and Time Series Management (TSM), are used for manipulating and analyzing time series data. The Hydraulic Analysis module (HA) utilizes HEC-RAS data and is able to manipulate it. The fourth module, Ecological Response Model (ERM), *"is a tool for collating and organizing existing knowledge of environmental requirements (e.g. flow, hydraulic habitat) of biota or ecosystem processes in a rules database. It can predict habitat change in response to altered flow conditions … and it enables the user to run scenarios and evaluate the likely impact of changes*

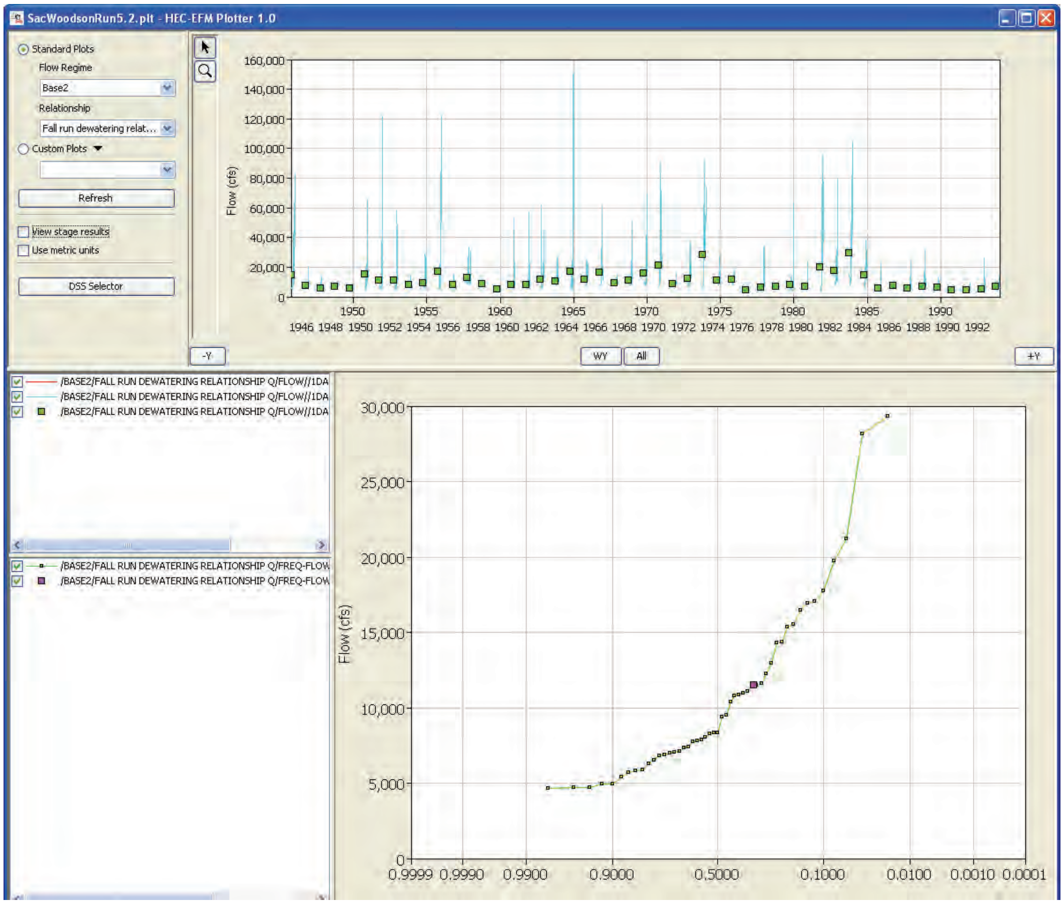


Figure 6. HEC-EFM Plotter.

to the flow regime on pre-defined habitat components of ecological importance to species' or ecosystem processes."[1]

The TSA module is used to manipulate the flow time series data. For example, in evaluating the cottonwood recruitment potential, the TSA was used to analyze and display fall rates during the defined recruitment season. The ERM is the "expert panel" component of the RAP process, where more complex relationships can be defined. Although an early version of the ERM is capable of a range of interactive trials and visualizations that would benefit decision-making processes, the ERM is no longer offered as a download on the web site.

The interface for this software package, exemplified by the TSA interface (Figure 7), is user-friendly and intuitive to use. The tree structure for the TSA in the program interface (Figure 7), along with the context-sensitive

[1] RAP Version 2.0.4 ERM Help menu.

help menu, makes the software easy to use. The interactive help menu is, in some cases, slightly out of date. The program was developed in Australia, and required changing the operating systems date format to English (Australian) and formatting the dates in the flow input data in the Australian format (ddmmyyyy). Once this was discovered (it is not mentioned in the user guide), the program was useable. It is not clear whether there is active support or research related to this program.

The input consists of flow time series and a number of user-defined options (e.g. Figure 7). The output includes options to see a table (Figure 8, upper), different types of visualizations (see output section of menu tree in Figure 7), and different methods of viewing the frequency of the flow (Figure 8, lower).

Only interactive help is available for the ERM; there is no user's guide. Apparently there is not a way to save a model run in the TSA module, and therefore it is necessary to reload the data and analysis choices each time the module is used. Output was easily saved to a format that was directly usable in a spreadsheet.

RAP is a software package with great flexibility in defining relationships, and it is easy to use, with the interactive help guidance. There is only limited support for RAP, which seems to have become inactive since some time in 2006. In addition to the user reference manual (Marsh et al. 2003) there is a limited body of research literature that supports or has utilized the software package (e.g. Navarro et al. 2007; Humphries et al. 2008; Smakhtin and Eriyagama 2008).

Fish Models

Standard Assessment Methodology (SAM)

"The Standard Assessment Methodology (SAM) (USACE 2006) was developed by the U.S. Army Corps of Engineers to address specific habitat assessment and regulatory needs for bank protection actions in the Sacramento River Bank Protection Project (SRBPP) planning area. The SAM was designed to provide a tool to systematically evaluate the impacts and compensation requirements of bank protection projects based on the needs of listed fish species. … SAM integrates species life history and flow-related variability in habitat to generate species responses to project actions over time. In general, the SAM quantifies

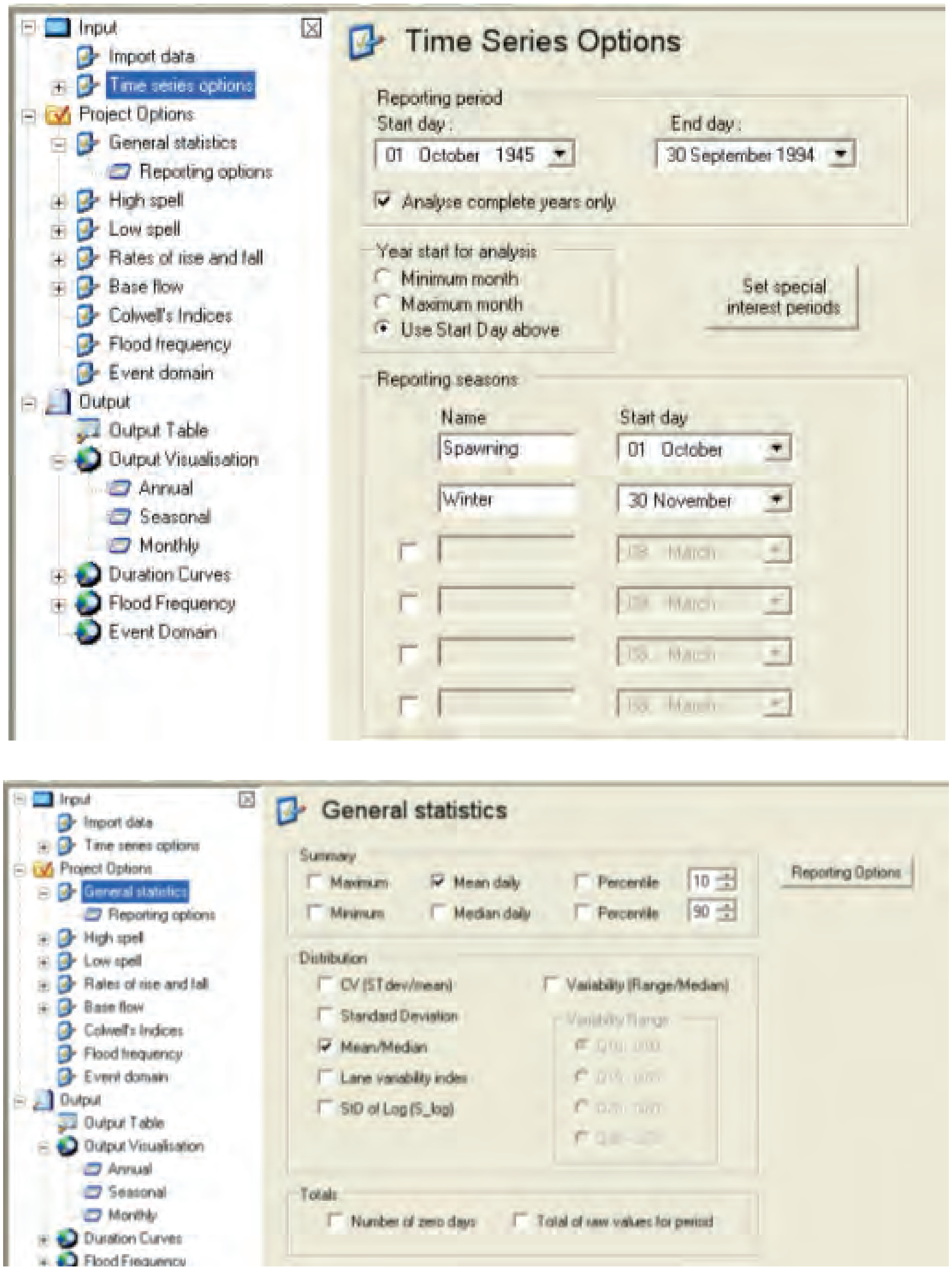
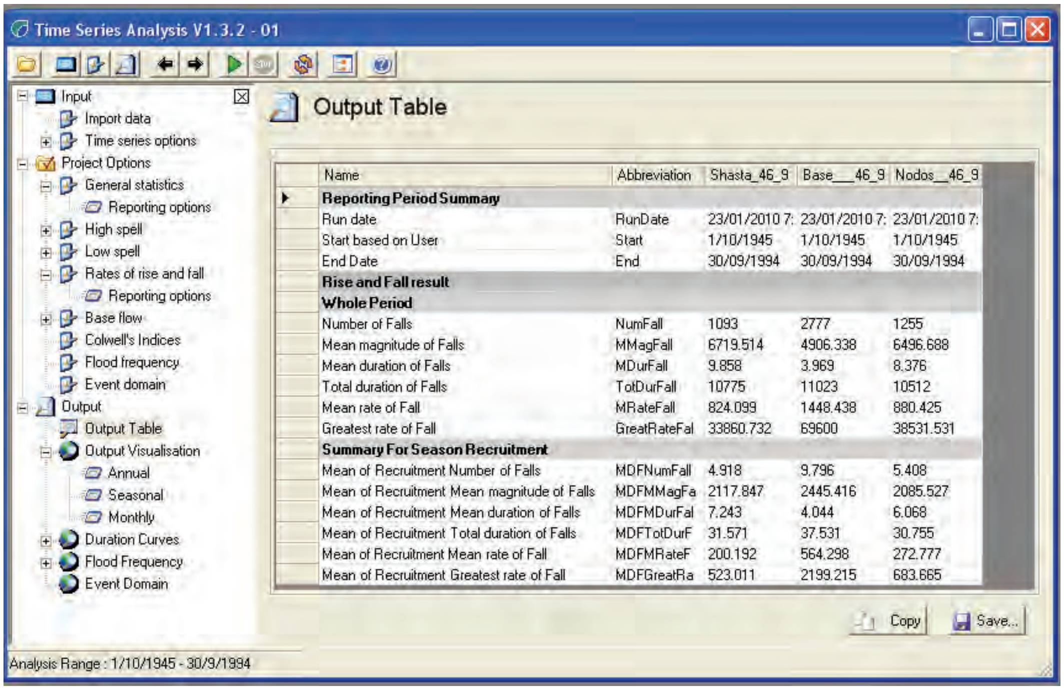


Figure 7. Time series (upper figure) and general statistics (lower figure) options tables for the RAP time series analysis (TSA) module.



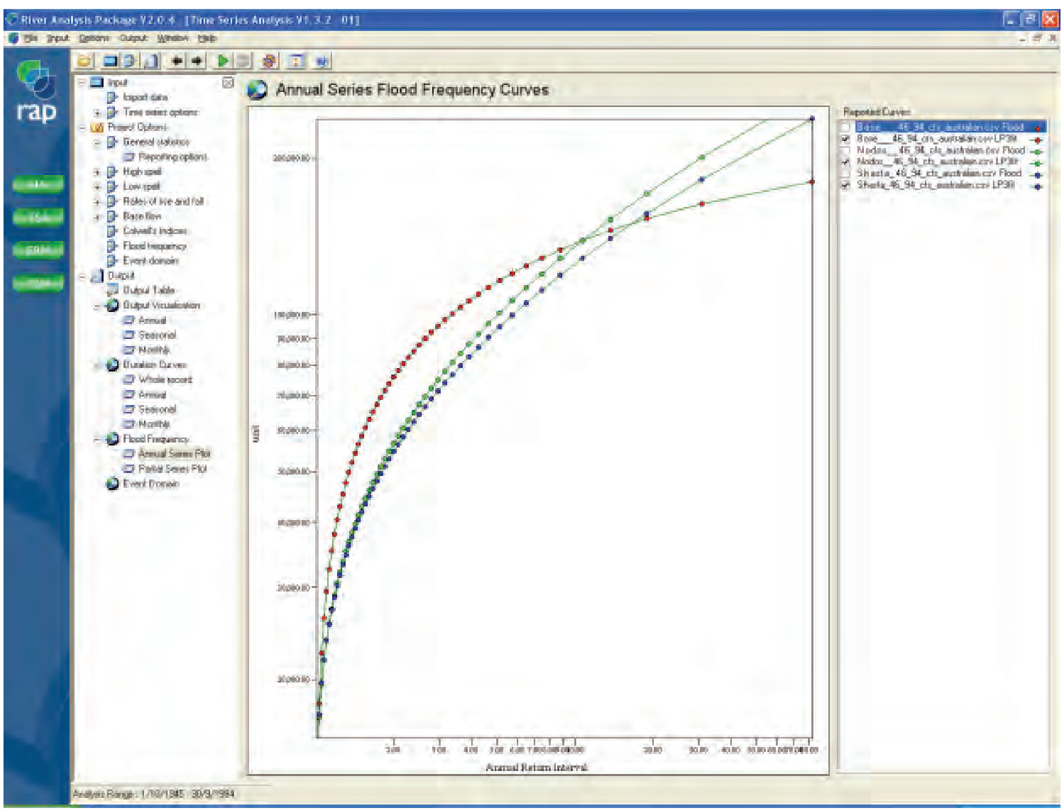


Figure 8. Output table (top figure) and annual series plot (bottom figure) for the RAP time series analysis (TSA) module. Discharges are given in cubic feet per second.

habitat values in terms of bank line- or area-weighted species responses that are calculated by combining habitat quality with quantity for each season, target year, and relevant species/life stage. … The response indices vary from 0 to 1, representing conditions for survival, growth, and/or reproduction. For a given site and scenario, the SAM uses these relationships to determine the response of individual species and life stages to the measured or predicted values of each variable for each season and target year, and multiplies these values together to generate an overall response index. This index is then multiplied by the area or linear feet of bank to which it applies to generate the weighted species response. These values provide a common metric that can be used to quantify habitat values over time, compare project alternatives to baseline conditions, and evaluate the effectiveness of onsite and offsite mitigation actions."[1]

The SAM is performed by means of an Electronic Calculation Template (ECT) (Figure 9), which carries out all the calculations and tabulates the results. The data requirements for the SAM are a set of cross sections from which bank shape characteristics can be calculated. This will be available for the original target purpose of the program, which is an evaluation of bank restraint scenarios on the Sacramento River. For other users, it requires data that are similar to those required by HEC-RAS, which require cross section bed topography and stage-discharge relationships at defined flows (for calibration). HEC-RAS runs are also necessary to develop the input data for conditions at different flow rates. SAM was designed to assess changes in fisheries habitat resulting from possible bank revetment scenarios on the Sacramento River. SAM is currently in limited public use, and tends to be used by a small group of "in-house" trained users.

The user interface is easy to use, and the user's manual gives step-by-step instructions, which are prompted and performed through the Access-based user interface (Figure 9). Required input data for the SAM ECT are illustrated in Figure 10. This example shows the data in an Excel spreadsheet that have been prepared in the input data format for a "with-project" design where the construction design alters the alternative input values. For example, see bank slope and bank substrate size and how they change over time. In the SAM ECT, six response curves (bank slope, floodplain inundation ratio, bank Substrate Size, instream structure, aquatic

[1] Jones and Stokes Draft review memo October 2005

vegetation, and shade) are supplied or can be developed by the user. A sample response curve from the ECT is shown in Figure 11.

Another run parameter requires defining a season of interest, which can be done with the life-history timing table (Figure 12).

The results are shown in both length- and area-weighted values; sample output data for length-weighted values are shown in Figure 13.

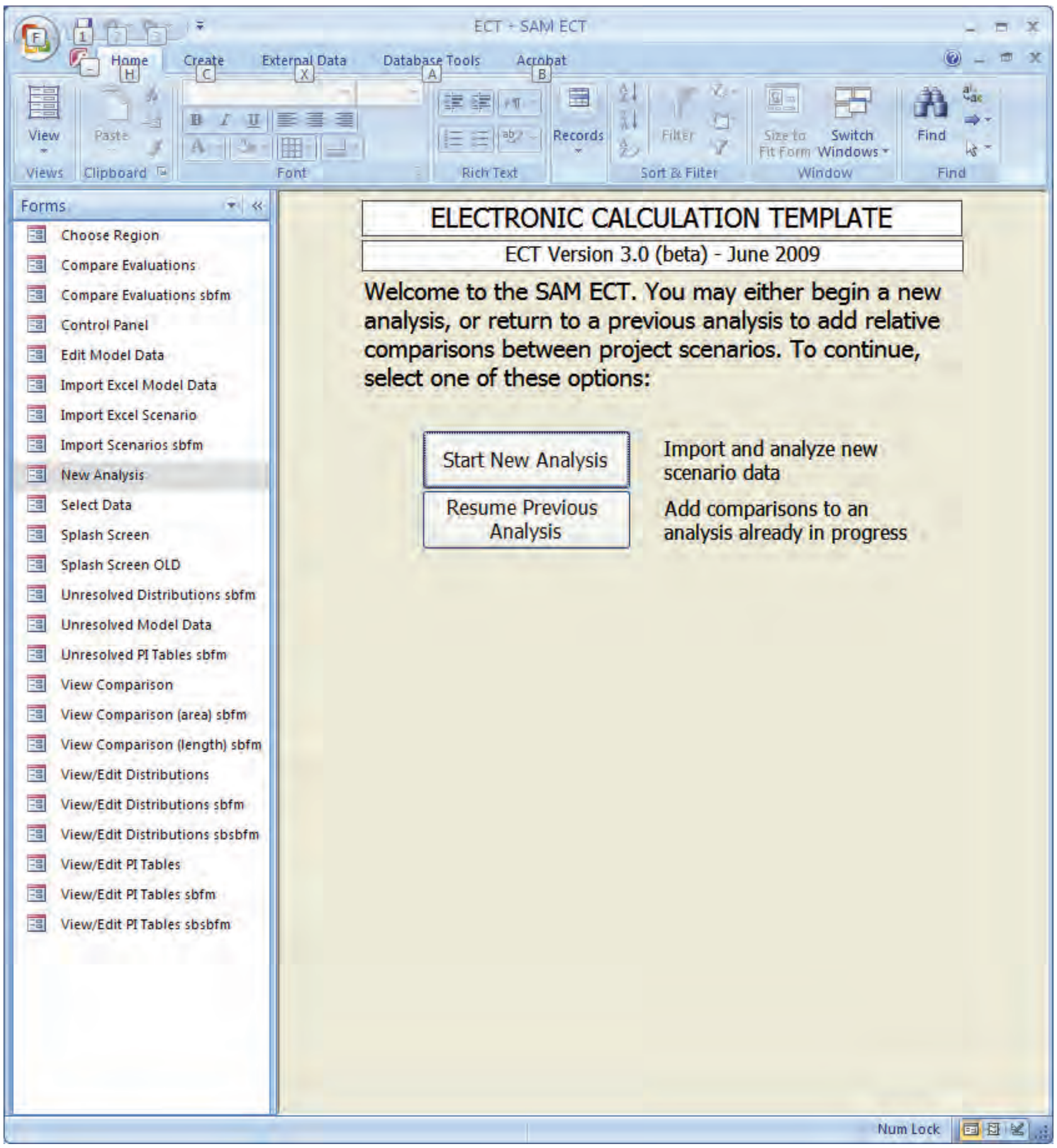


Figure 9. User interface for SAM Electronic Calculation Template (ECT).

		Seasonal Values			
Habitat Parameter	WY	Fall	Winter	Spring	Summer
Water Surface Elevation (feet)	2005	59	62	62	61
	2060	59	62	62	61
Wetted Area (square feet)	2005	116,721	120,773	120,040	118,904
	2060	116,721	120,773	120,040	118,904
Shoreline Length (feet)	2005	1,065	1,064	1,066	1,065
	2060	1,065	1,064	1,066	1,065
Bank Slope (dH:dV)	2005	1	1	1	2
	2011	2	10	10	2
	2060	2	10	10	2
Floodplain Inundation Ratio (AQ2:AQavg)	2005	1	2	2	1
	2060	1	2	2	1
Bank Substrate Size (D50 in inches)	2005	0	0	0	10
	2011	10	0	0	10
	2060	10	0	0	10
Instream Structure (% shoreline)	2005	26	26	26	50
	2011	50	50	50	50
	2060	50	50	50	50
Vegetation (% shoreline)	2005	13	38	38	0
	2011	0	25	50	0
	2015	0	88	88	0
	2025	0	88	88	0
	2035	0	88	88	0
	2060	0	88	88	0
Shade (% shoreline)	2005	78	20	59	20
	2011	20	6	18	20
	2015	20	18	55	20
	2025	100	25	75	100
	2035	100	25	75	100
	2060	100	25	75	100

Figure 10. SAM sample data summary showing a "with-project" design at Sacramento River Mile 152.7R (SAM sample data, Personal Communication Mike Dietl, U.S. Army Engineer District, Sacramento).

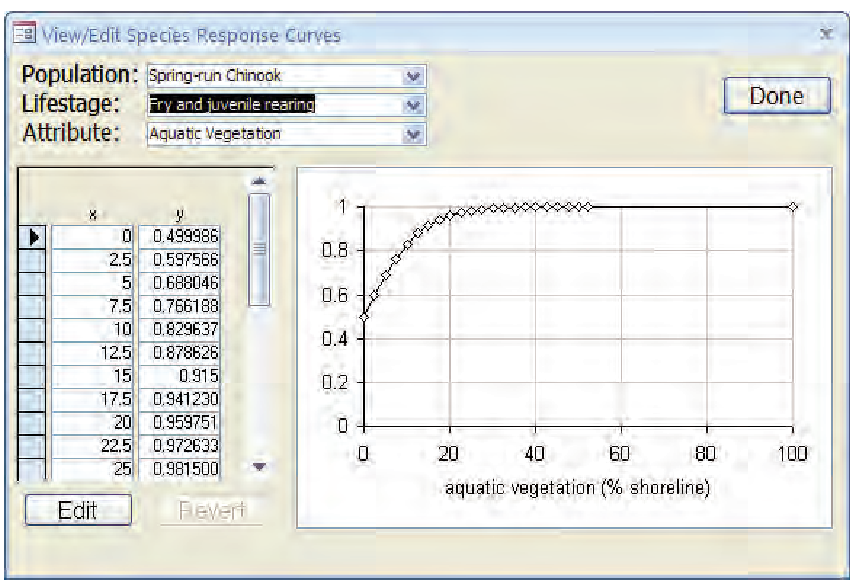


Figure 11. Sample SAM response curve.

Figure 12. Sample Life history timing table.

Bankline weighted relative response (feet)
Comparison existingProjectTest3
Alternative Scenario: EWLSac152.7R_Project!EWLSac152.7R_Project
Baseline Scenario: EWLSac152.7R_Existing!EWLSac152.7R_Existing

	Fall (September–November)					Winter (December–February)					Spring (March–May)					Summer (June–August)				
Focus Fish Species and Water Year	Adult migration	Spawning and egg incubation	Fry and juvenile rearing	Juvenile migration	Adult residence	Adult migration	Spawning and egg incubation	Fry and juvenile rearing	Juvenile migration	Adult residence	Adult migration	Spawning and egg incubation	Fry and juvenile rearing	Juvenile migration	Adult residence	Adult migration	Spawning and egg incubation	Fry and juvenile rearing	Juvenile migration	Adult residence
Fall-run Chinook																				
2005	0.0		0.0					0	0		0			0		0				
2006	-1.7		1.5					7	4		-1			10		-21				
2007	-3.4		2.5					14	7		-3			20		-21				
2008	-5.1		2.7					21	11		-4			30		-21				
2009	-6.9		2.4					28	14		-5			39		-21				
2010	-8.6		1.5					35	17		-6			49		-21				
2011	-10.3		0.2					41	19		-8			59		-21				
2012	-11.8		-1.1					48	24		-8			69		-21				
2013	-13.0		-2.0					54	32		-8			78		-21				
2014	-13.8		-2.8					60	41		-7			87		-21				
2015	-14.5		-3.4					67	52		-5			95		-21				
2016	-14.9		-3.8					73	63		-4			103		-21				
2017	-15.0		-4.0					78	72		-2			110		-20				
2018	-14.7		-4.0					83	79		-1			115		-20				
2019	-14.1		-3.8					87	86		0			120		-19				
2020	-13.4		-3.6					90	92		1			124		-18				
2021	-12.6		-3.2					94	98		2			128		-16				
2022	-11.6		-2.8					97	102		3			131		-15				
2023	-10.5		-2.3					100	107		4			134		-14				
2024	-9.3		-1.8					102	111		4			136		-13				
2025	-8.0		-1.2					105	115		5			139		-11				
2026	-6.8		-0.6					107	118		6			141		-10				
2027	-5.7		-0.1					109	121		7			142		-9				
2028	-4.6		0.4					111	124		7			144		-7				
2029	-3.7		0.8					113	127		8			146		-6				
2030	-2.8		1.2					115	129		8			147		-5				
2031	-2.0		1.6					116	131		9			149		-4				
2032	-1.3		1.9					118	134		9			150		-4				
2033	-0.6		2.2					119	135		9			151		-3				
2034	0.0		2.5					120	137		10			152		-2				
2035	0.6		2.8					121	139		10			153		-1				
2036	1.2		3.1					122	140		10			154		-1				

Figure 13. SAM sample output data.

EnviroFish

EnviroFish is a software package developed by the USACE Engineer Research and Development Center (ERDC) that can be used to "*estimate [the] value of floodplain habitat suitable for fish reproduction under a given set of hydrologic and hydraulic conditions. EnviroFish can be used to calculate habitat units for specific floodplain habitats, with each habitat providing different values for spawning and rearing fishes. In order of least to most preferred habitats, are agricultural fields, fallow fields, bottomland hardwood forests, and permanent waterbodies. Area can be weighted using a Habitat Suitability Index (HSI), which reflects the biological value of a land use for fish reproduction. Habitat units are computed by multiplying the average daily flooded area (ADFA) by the associated HSI value.*

EnviroFish was initially developed for flood control projects in the lower Mississippi River Valley. However, the approach is applicable to any alluvial river system where floodplain fish spawning habitat is being managed, mitigated, or restored, by determining applicable land use categories and HSIs for representative fish species."[1] *"Over 100 species of fish are represented in the current framework of EnviroFish, so this technique has applicability to a broad range of warmwater fish assemblages".*[2]

The user interface for EnviroFish will be familiar to, and easy to use, for those who have used the U.S. Army Corps of Engineers' Hydrologic Engineering Center Data Storage System, or *HEC-DSS* (USACE 2009). The input data are in the form of a DSS file with elevation-area data. "Habitat constraints" are set on the main screen and are separated into spawning, season, and rearing constraints (Figure 14).

The output is generated by selecting "calc summary" from the "model" pull-down menu, which can be saved to a user-defined output path. Sample output, saved to Excel, is shown in Figure 15.

[1] User manual v 1.0

[2] System-Wide Water Resources Program Brochure USACE

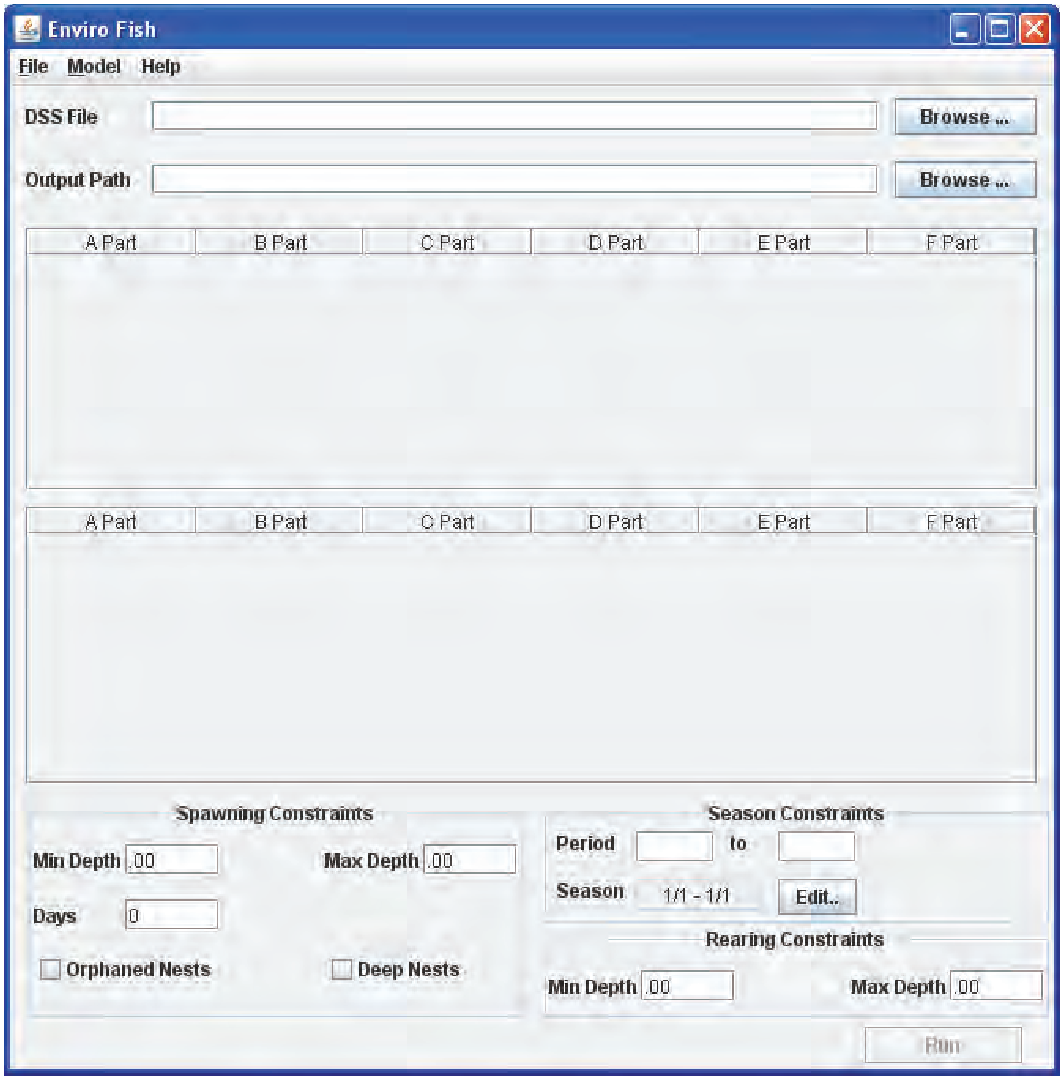
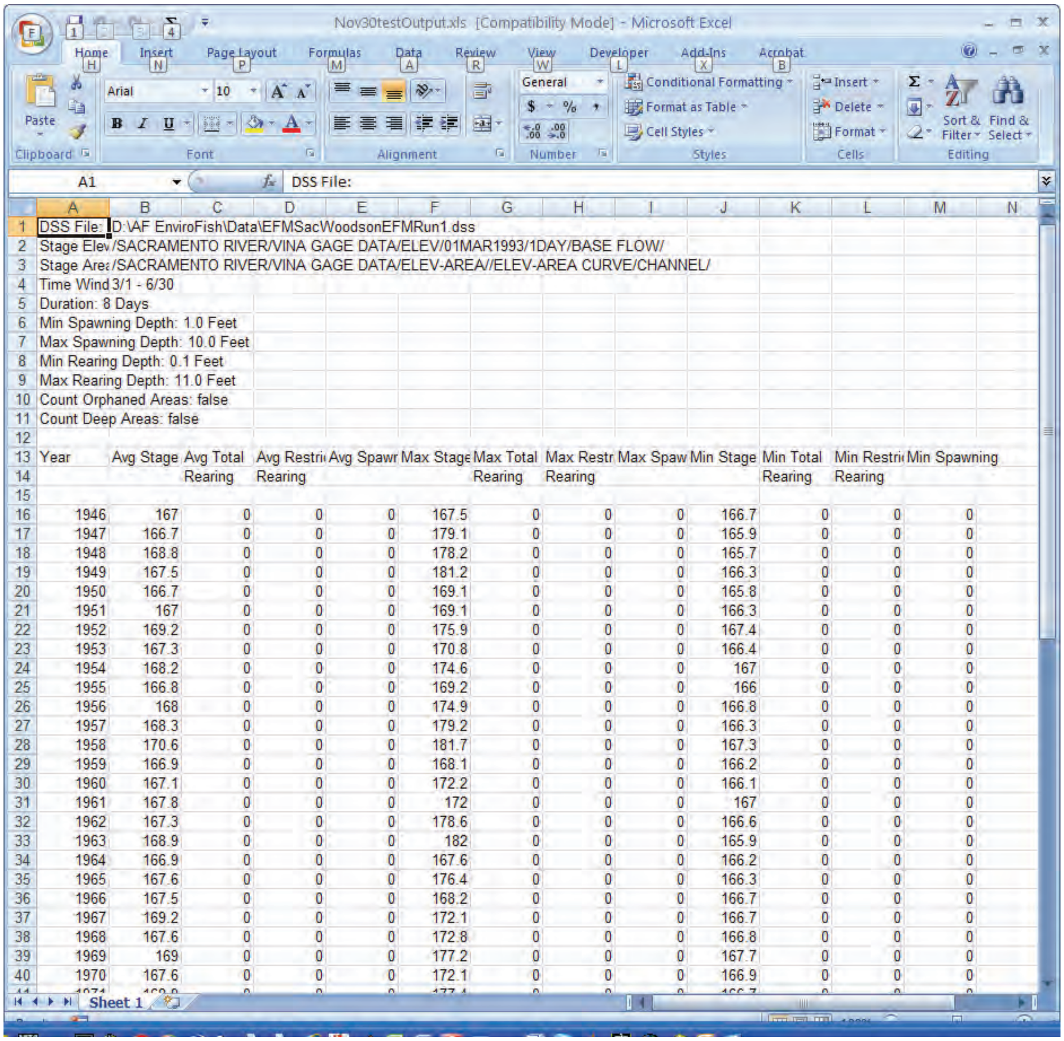


Figure 14. EnviroFish user interface.

EnviroFish is currently in a testing phase, and does not accept flow data from the most current version of Data Storage System (HEC-DSS; USACE 2009). It is not appropriate for riparian tree species, and was not tested using this test relationship. The fall-run Chinook salmon relationship did not fit into the floodplain fish categories of EnviroFish. Currently, this program is in the first phases of development and is only used in limited applications by “in-house” users.



Year	Avg Stage	Avg Total Rearing	Avg Restri Rearing	Avg Spawr	Max Stage	Max Total Rearing	Max Restr Rearing	Max Spaw	Min Stage	Min Total Rearing	Min Restri Rearing	Min Spawning
1946	167	0	0	0	167.5	0	0	0	166.7	0	0	0
1947	166.7	0	0	0	179.1	0	0	0	165.9	0	0	0
1948	168.8	0	0	0	178.2	0	0	0	165.7	0	0	0
1949	167.5	0	0	0	181.2	0	0	0	166.3	0	0	0
1950	166.7	0	0	0	169.1	0	0	0	165.8	0	0	0
1951	167	0	0	0	169.1	0	0	0	166.3	0	0	0
1952	169.2	0	0	0	175.9	0	0	0	167.4	0	0	0
1953	167.3	0	0	0	170.8	0	0	0	166.4	0	0	0
1954	168.2	0	0	0	174.6	0	0	0	167	0	0	0
1955	166.8	0	0	0	169.2	0	0	0	166	0	0	0
1956	168	0	0	0	174.9	0	0	0	166.8	0	0	0
1957	168.3	0	0	0	179.2	0	0	0	166.3	0	0	0
1958	170.6	0	0	0	181.7	0	0	0	167.3	0	0	0
1959	166.9	0	0	0	168.1	0	0	0	166.2	0	0	0
1960	167.1	0	0	0	172.2	0	0	0	166.1	0	0	0
1961	167.8	0	0	0	172	0	0	0	167	0	0	0
1962	167.3	0	0	0	178.6	0	0	0	166.6	0	0	0
1963	168.9	0	0	0	182	0	0	0	165.9	0	0	0
1964	166.9	0	0	0	167.6	0	0	0	166.2	0	0	0
1965	167.6	0	0	0	176.4	0	0	0	166.3	0	0	0
1966	167.5	0	0	0	168.2	0	0	0	166.7	0	0	0
1967	169.2	0	0	0	172.1	0	0	0	166.7	0	0	0
1968	167.6	0	0	0	172.8	0	0	0	166.8	0	0	0
1969	169	0	0	0	177.2	0	0	0	167.7	0	0	0
1970	167.6	0	0	0	172.1	0	0	0	166.9	0	0	0

Figure 15. EnviroFish sample output.

Flow alteration models

Indicators of Hydrologic Alteration (IHA)

Indicators of Hydrologic Alteration (IHA) is a statistical analysis and viewing package that calculates hydrologic indices from flow time series. The program itself can provide statistical descriptions of a given flow regime or quantitatively describe the degree of difference between two flow data sets. These can include analysis of a single time series of river hydrology with a "before and after" scenario (such as a river's flow regime before and after the construction of a dam) and Version 7.1 allows for input of two time series. Using two time series allows for additional comparisons such as reservoir inflow versus outflow, managed flows versus simulated natural flows, or comparisons between a reference river and an altered river. These comparisons can provide a basis for asking questions and formulating hypotheses about how flow alterations may be affecting the river processes and outputs. The statistical descriptions and comparisons can provide insight to those engaged in processes to define environmental flows. Users can analyze changes in these indices as a basis to explore potential changes in river processes. Thirty-three indices are calculated automatically, and graphical and tabular output can be selectively chosen, saved, and exported. Recently IHA, which was primarily a statistical analysis of flow regime data, added the capability of calculating an additional 34 “environmental flow components” (EFC), which are aimed at informing the flow-ecology relationship more directly (Mathews and Richter 2007).

The input for IHA consists of daily flow data that can be input in a number of formats (Figure 16). Once a project has been defined, the main user interface includes two tabs, one for the project basic definition (Figure 17 upper) and one for the list of analyses that can be defined by the user (Figure 17 lower). Once an analysis has been defined, and calculated, the “view results” tab on the bottom of the interface (Figure 17 lower) provides a method to create new graphs and to view graphs that have been previously created and saved (e.g. Figure 18).

IHA is one of the oldest of the software packages reviewed, having roots in the early work of Richter et al. (1996). It is widely used, and is supported by TNC staff.

In applying IHA to the cottonwood recruitment problem, different weighted combinations of selected indices were tested for cottonwood seedling recruitment output. Ultimately, one single index seemed most applicable. IHA allows the creation of a number of graphs, and also allows access to all the data from which the graphs are made. In order to get the quantity of mean fall rate in the season of interest, a graph was defined, created, and used to read off the desired number (Figure 18). As with every model in this review, technical knowledge of both the model and the species of concern, and carefully defined assumptions, were useful to define and interpret cottonwood-specific results.

Hydroecological Integrity Assessment Process / Hydrologic Assessment Tool (HIP/HAT)

The Hydroecological Integrity Assessment Process (HIP), which was developed and is maintained by the USGS, originally consisted of four computer software tools that together compute statistics that are designed

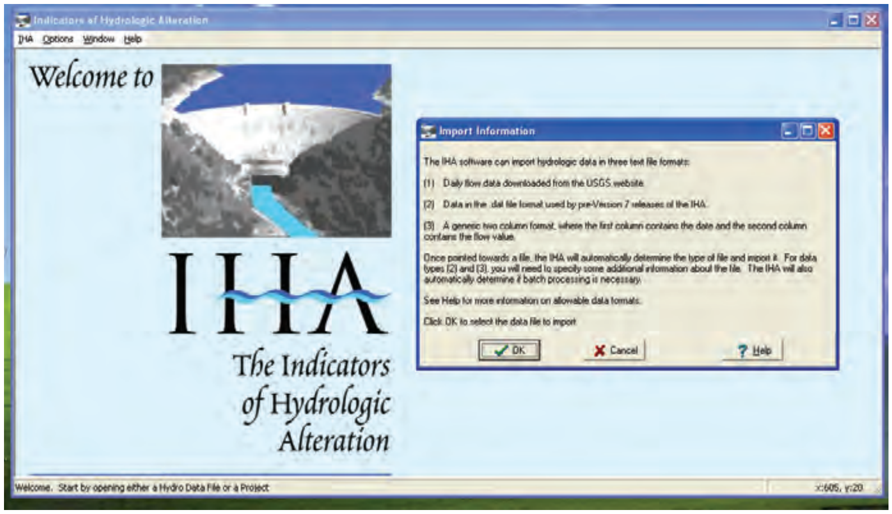


Figure 16. IHA user interface for data input.

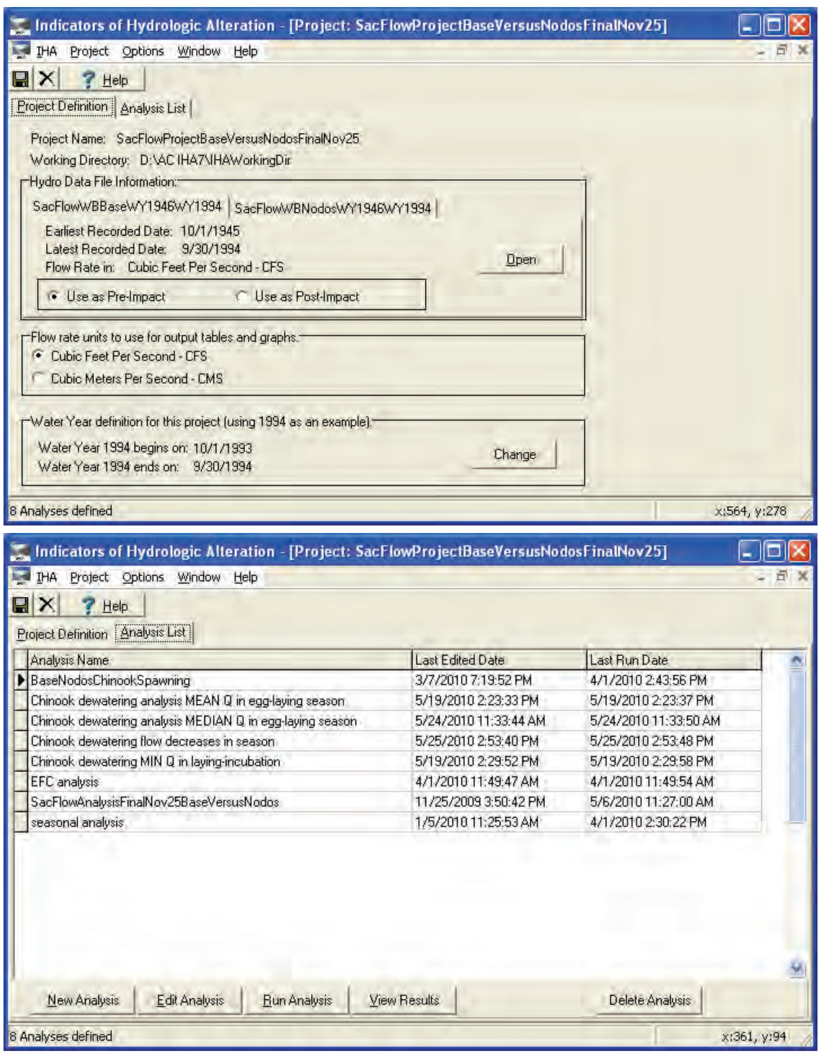


Figure 17. IHA project definition (upper) and analysis list (lower) user interfaces.

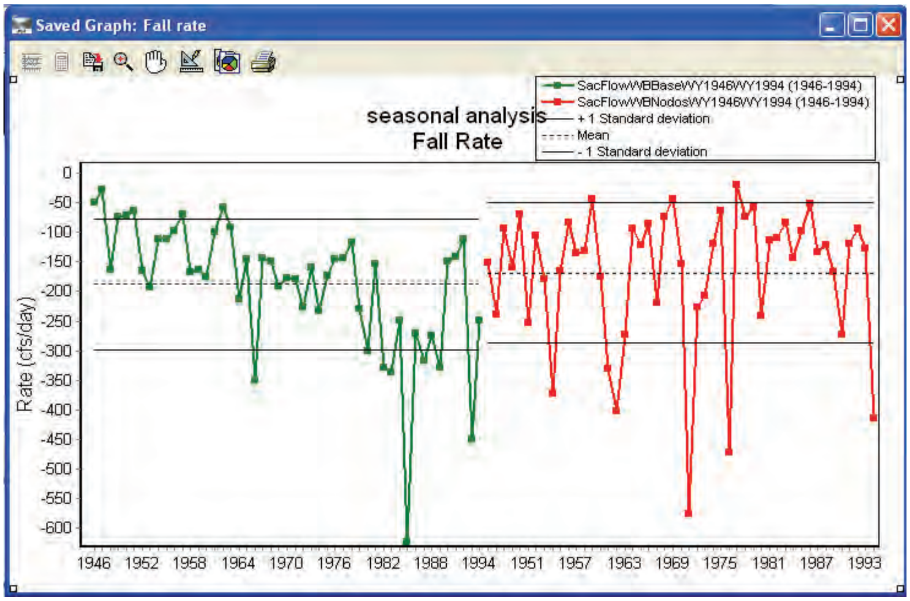


Figure 18. IHA seasonal analysis of mean fall rate (Note: the data used for cottonwood recruitment assessment were taken from the dotted lines, the mean fall rate in the recruitment season).

to be related to the physical make-up of rivers. Currently, the HIP process for general use is entirely contained in the National Hydrologic Assessment Tool (NATHAT) or more simply HAT. The software suite, developed by the USGS, was originally applied in New Jersey, for which there is a specific tool (New Jersey Hydrologic Assessment Tool NJHAT). The HIP process was designed to utilize hydrologic indices of flow regimes, and to define which indices were specifically appropriate for specific stream types. Stream type classifications were researched and codified for New Jersey, but not specifically for other areas. Recently a similar site-specific HAT application was developed for Missouri streams (Kennen et al. 2009); this application is called MOHAT.

HAT was designed for use in general settings outside New Jersey or Missouri. HAT (NATHAT) is useable as a single program, but requires the user to define the indices of interest. Essentially, the “stream classification” is left to the user. The basic steps in this tool are 1) use daily and peak flow records (from USGS records) to calculate 171 indices of hydrologic performance, 2) having performed a stream classification, establish indices for the magnitude, frequency, duration, timing, and rate of change. This is accomplished through 10 specific indices chosen, according to stream class, from 171 indices defined in step 1, 3) with the HAT, establish environmental flow standards, and assess changes in stream flow characteristics due to changes in environmental factors.

The user interface is controlled by buttons at the top of the screen (Figure 19), which control defining a project, importing data, and viewing data analyses. There are a number of pre-defined ways to view and graph the data, all controlled by “radio” buttons on the lower part of the “graph data set” option (Figure 20). Based on the data sets entered, and the pre-defined indices that are automatically calculated from the data, a graph comparing hydrologic indices, which can be the default indices or manually selected ones, is produced (Figure 21).

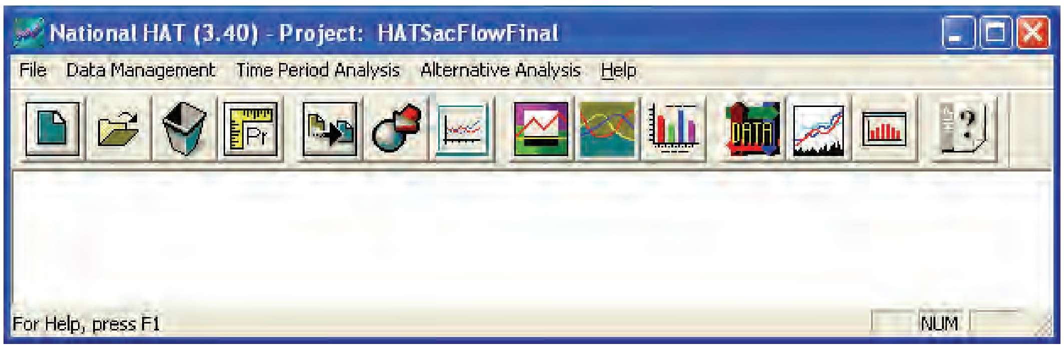


Figure 19. HAT user interface.

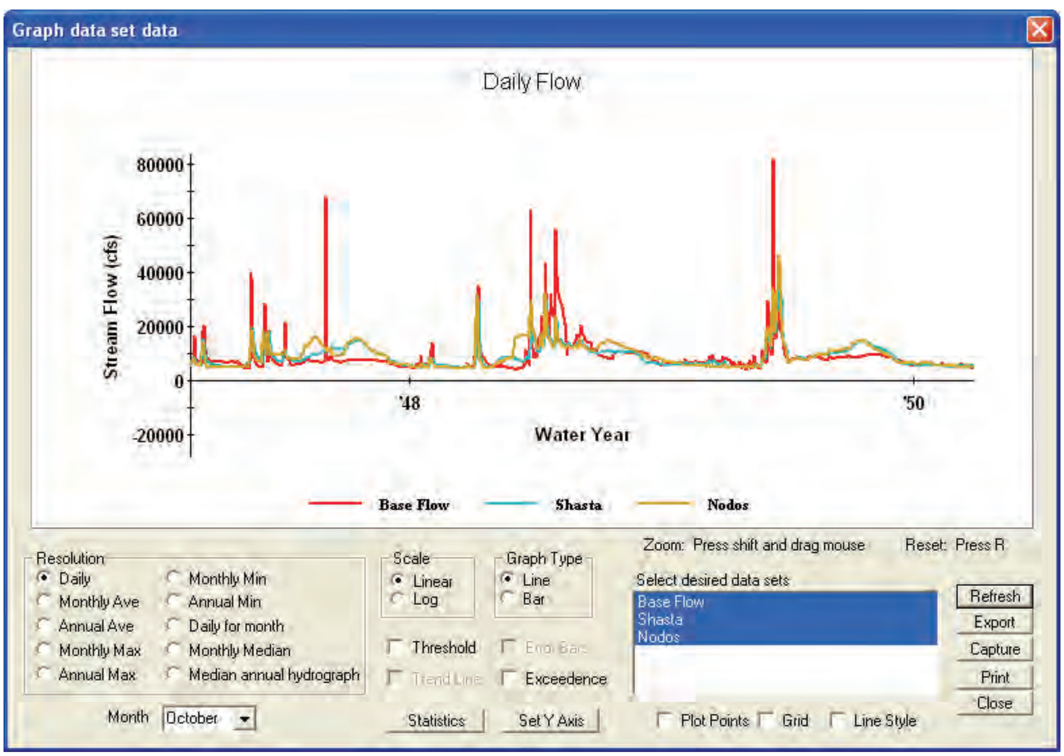


Figure 20. HAT graph data set option user interface.

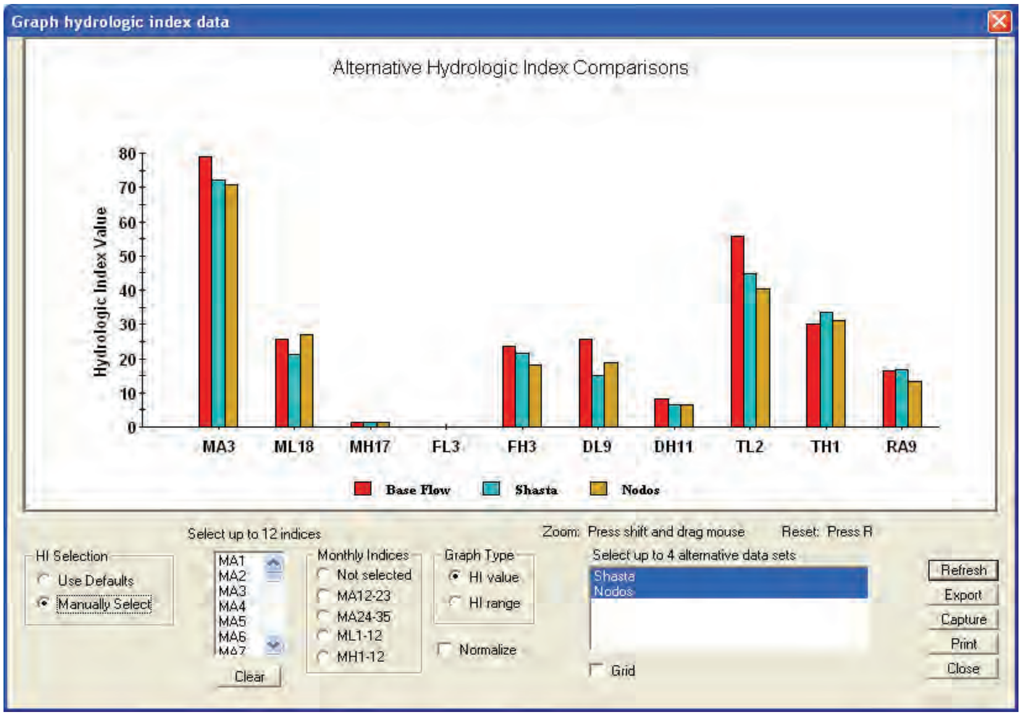


Figure 21. HAT hydrologic indices user interface.

Another feature of this program is that the comparison of hydrologic indices can be selected manually if the default ones don't meet the needs of the defined project. This implicitly applies a stream classification for the subject stream. The main analytic task is defining a specific ecosystem process in a way that can be informed by the analyses that are available. This is probably best done as is recommended for IHA, with a group of experts who work together on defining which indicators will reveal meaningful results about the change in habitat due to change in flow.

The software is used to calculate statistical indices of hydrologic alteration and allows the user to compare indices of a base condition with altered conditions. Once a generic stream type is picked (HAT offers a limited selection), the program displays a default set of 10 non-redundant indices that have been shown to adequately characterize the five major components of the flow regime (magnitude, frequency, duration, timing, and rate of change (Olden and Poff 2003). It is also possible for the user to define which indices are chosen for analysis and viewing.

Like the other software packages, HAT is also effective and useful for analyzing and visualizing flow data. The flow analysis portion is fairly intuitive, easy to use, and is useful for viewing and analyzing time series of flow data.

3 Case studies

In order to evaluate software usage, two sample ecological relationships were chosen: Fremont cottonwood seedling initiation, and fall-run Chinook salmon redd-dewatering. The relationship for cottonwood recruitment was patterned after the Sacramento River Ecological Flows Tool (SacEFT) pre-defined cottonwood recruitment relationship, which was determined by a panel of experts for cottonwood seedling recruitment on the Sacramento River (The Nature Conservancy 2008). In short, the relationship defines the recruitment season as occurring between April 15 and July 21, and requires a specified drawdown rate not to be exceeded in the recruitment season or the seedlings will dry out. The potential habitat for cottonwood recruitment was assessed for three different flow scenarios (Base [also called 1a], Nodos [3a], and Shasta [4a]; Figure 23) based on different hypothetical reservoir operations on the Upper Sacramento River, California between Redbluff and Colusa (Figure 22), again patterned after input data develop for the SacEFT (The Nature Conservancy 2008).

The fall-run Chinook salmon redd-dewatering relationship that was used by SacEFT and that was also used for the other models in the current report was based on work on the Sacramento River by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service 2006), who developed habitat suitability criteria for redd-dewatering based on depth, velocity, and bed exposed; and related those criteria to different flow regimes. A conceptual model of the link between redd-dewatering and population impacts follows. Eggs may be laid at any flow during the spawning period. Correlated with the flow when spawning occurs is an area of the bed in which the eggs are laid. Reductions in flows result in reductions of the bed surface area that is covered by water and also in reductions in water depth and velocity. As areas become dewatered, or have critically reduced flows, the eggs die (U.S. Fish and Wildlife Service 2006). Based on the difference between the flow at egg laying, and the flow at post-laying reduction in flow, the USFWS developed curves that give the percent redd dewatered. These curves are used in the analyses reported herein.

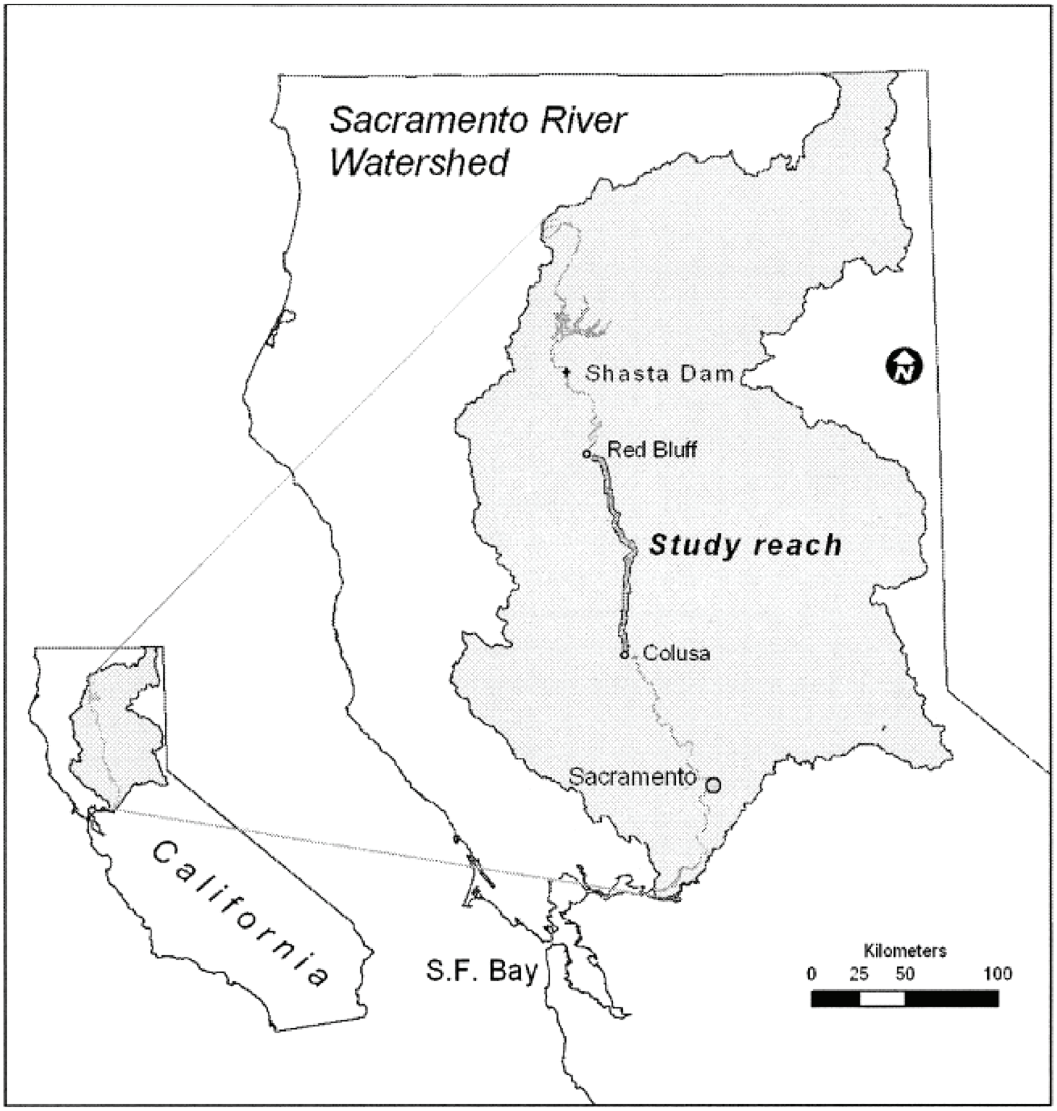


Figure 22. Sacramento River study area.

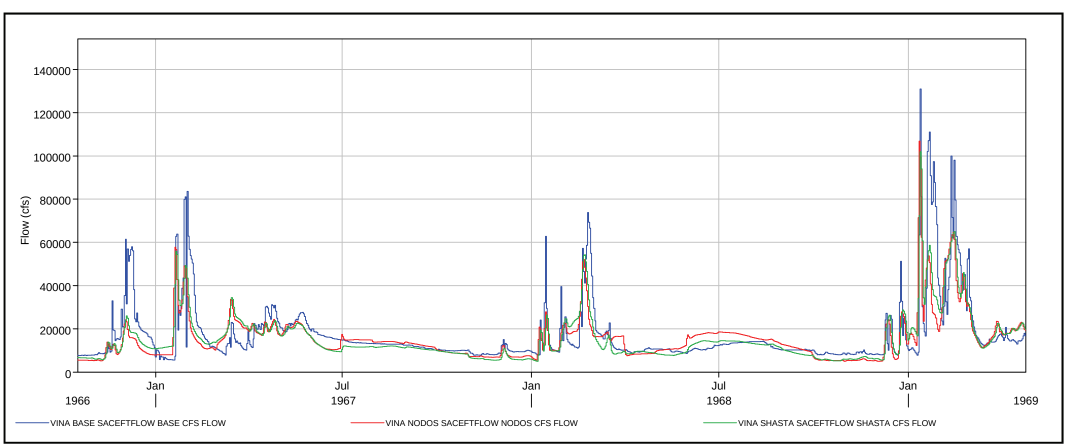


Figure 23. Base, Nodos, and Shasta flows; a sample of data from 1966 to 1998.

Case studies of these two relationships were performed using some of the software packages. Neither of the two fish-specific software packages was used for the cottonwood seedling initiation modeling. Because SAM is configured to evaluate response to changes in channel banks, and because the six response curves in the SAM ECT (bank slope, floodplain inundation ratio, bank substrate size, instream structure, aquatic vegetation, and shade) cannot be configured to evaluate redd-dewatering (cf. Figure 12), SAM was not used to evaluate fall-run Chinook salmon redd-dewatering. EnviroFish was also not used for the salmon analysis, because EnviroFish is designed primarily for analyses of floodplain habitat and is not applicable to salmon redd-dewatering. In addition, RAP was not used to examine the Chinook salmon redd-dewatering. RAP could be used to calculate statistics similar to those calculated in IHA, but more precisely than in IHA because the period of interest could be specified in RAP. Technical problems linked with lack of software support were the main reason for not using RAP for the redd-dewatering analysis.

Sacramento River Ecological Flows Tool (SacEFT)

Cottonwood seedling initiation

In developing metrics to compare the SacEFT with the other models, the default poor-fair-good output metrics of SacEFT were not used in the final analysis. The cottonwood initiation model is currently defined in the program software such that there are three cross sections that are intended to represent the entire area of concern. Arbitrary nodes are defined across each cross section and each node is considered with respect to the criteria for seedling establishment. The nodes satisfying the criteria that allow cottonwood seeds to establish and successfully grow are counted, summed, and tabulated. For the default output, good-fair-poor ratings are established (Figure 24) using defined criteria.

For the current study, a more detailed analysis was performed using data from the reports that were provided in the software package to document the default results. From the data in those reports (Appendix C) a sum of total number of appropriate nodes from 1946 to 1994 was used as the metric for comparisons with other software packages. These are the data from which the poor-fair-good ratings were derived; the raw data were used in a different way in the current study to summarize the total number of nodes for the analysis in this report (Figure 25). The results for total number of nodes were used for the final comparison with other software packages (Figure 38). In the final analysis, all the values were non-dimensionalized; the number of nodes in each scenario was divided (non-dimensionalized) by the total number in the Base scenario.

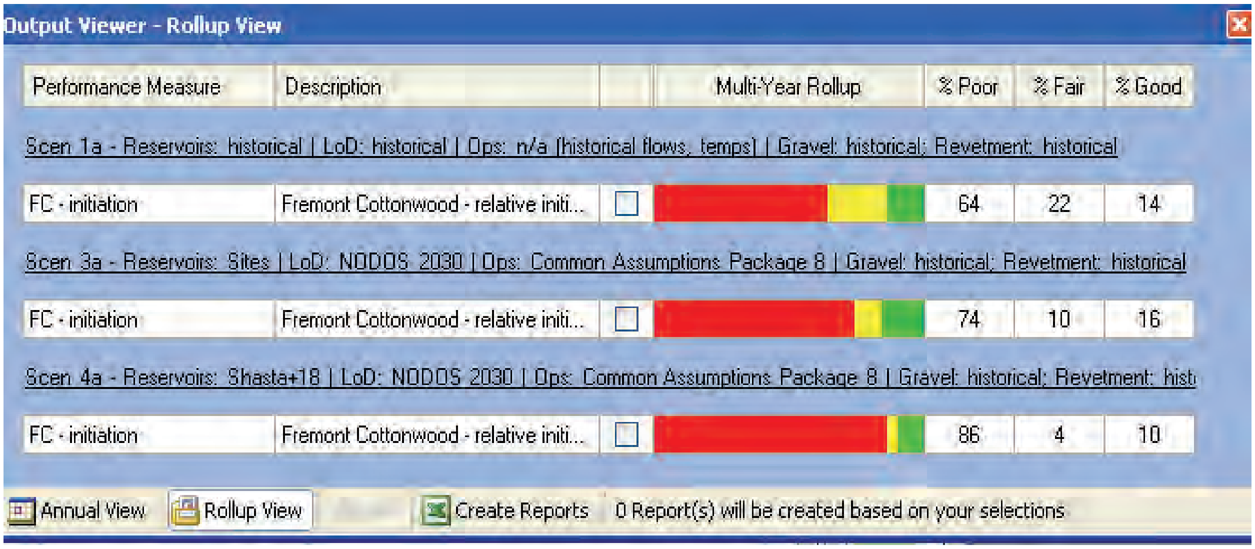


Figure 24. SacEFT multi-year "rollup" view output.

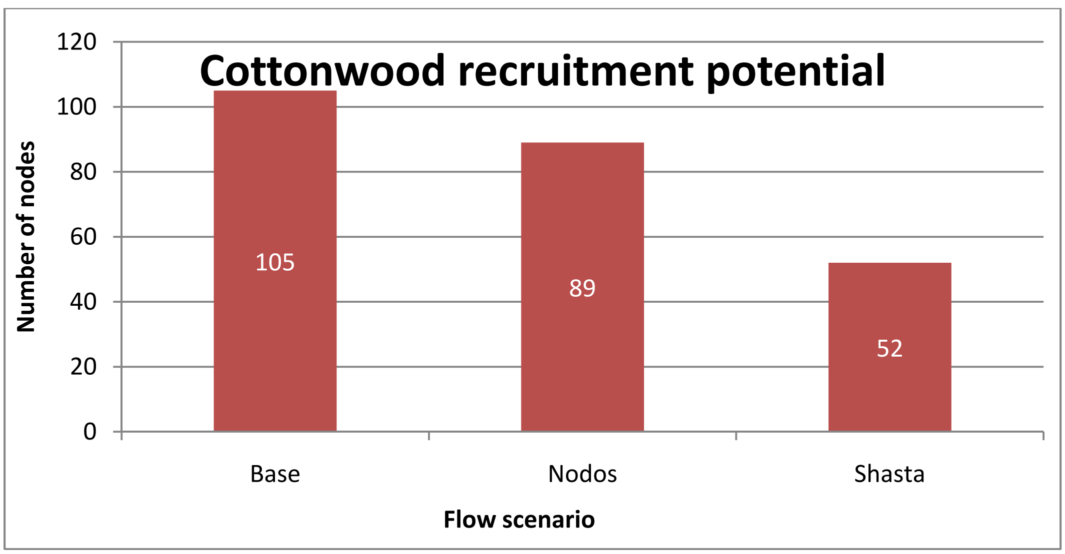


Figure 25. Number of potential cottonwood recruitment nodes in SacEFT run.

Fall-run Chinook salmon redd-dewatering

For fall-run Chinook salmon redd-dewatering, the final "roll-up" results for the SacEFT analyses are shown in Table 3. These data show that the Base flow scenario has the most "poor" potential habitat; all three scenarios have almost the same percent "good" habitat. The Nodos flow scenario has the most "fair" habitat.

Table 3. EFT "rollup" results for fall-run Chinook Salmon

Chinook salmon EFT dewatering			
Flow Type	% Poor	% Fair	% Good
Base flow	33	29	38
Nodos flow	12	51	37
Shasta flow	27	34	39

In order to compare these results with the output from the other models, a non-dimensional rating system was developed similar to the one used for the cottonwood, where the values for all three flow scenarios were non-dimensionalized by the base value. Different combinations of the "Good" (G) and "Fair" (F) were calculated. For example, in Figure 26, the 1.0 for the (G+F) Base flow scenario is (38+29)/(38+29) = (G +F)Base/(G+F) Base; the Nodos value is (37+51)Nodos /(38+29)Base = (G +F)Nodos/(G+F) Base. Three combinations (G, G+F, and 2G+F) were used (Figure 26) to compare with the results from the other software packages (Figure 39).

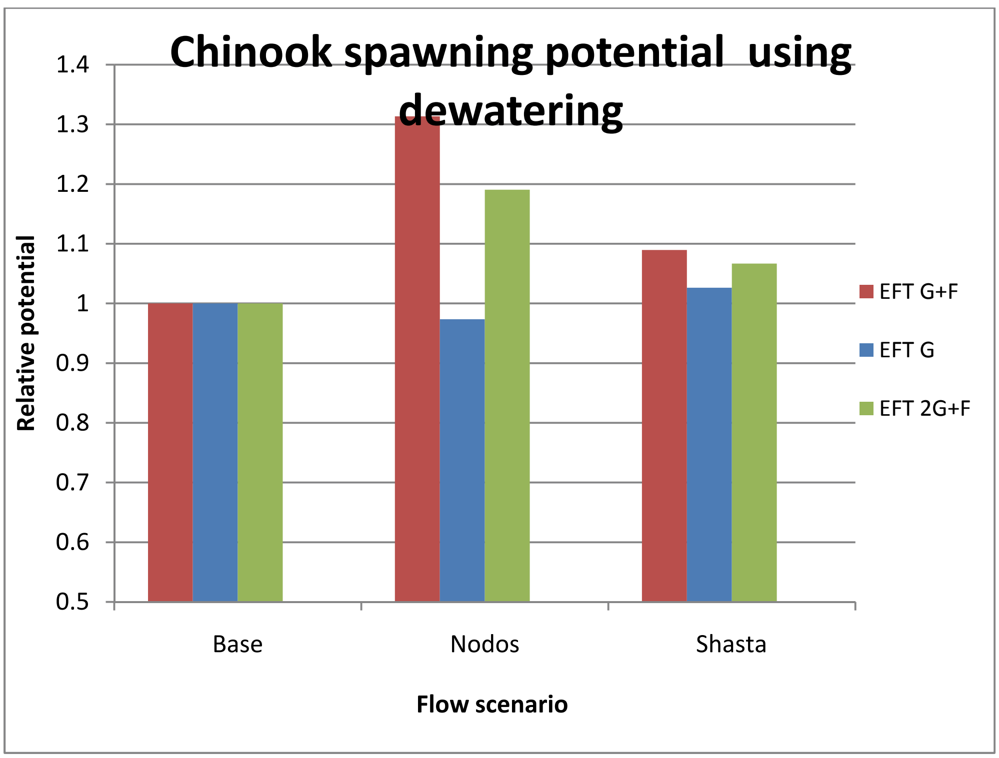


Figure 26. Chinook spawning potential non-dimensional comparison for EFT results.

Hydrologic Engineering Center Ecosystem Functions Model (HEC-EFM)

Cottonwood seedling initiation

HEC-EFM focuses on flow and stage changes, and the default output gives a single number for stage and a single number for flow. In the case of cottonwood recruitment, it gives the stage (that occurs once in 10 years) at which recruitment is successful, based on recession rate and seasonal timing criteria. The program allows for hypotheses to be formulated, but this feature is not illustrated in the current figures. For example, one hypothesis is that a higher value (10-year recurrence interval flow, or stage) is better than a lower 10-year flow. Based on the relationship definitions, the output showed the stage and flow that satisfied the cottonwood seedling establishment rules on the average once in 10 years (Table 4). In the case of the cottonwood relationship, these default outputs are difficult to interpret. For example, it is not clear whether a higher 10-year flow (stage) indicates better or worse habitat conditions.

Table 4. HEC-EFM sample summary output table.

	Base		Shasta		Nodos	
Relationship	Stage, ft	Flow, cfs	Stage, ft	Flow, cfs	Stage, ft	Flow, cfs
Cottonwood recruitment	168.9	16,900	168.5	15,377	169.0	17,304
Stage at end of season	168.4	15,081	168.4	14,960	168.6	15,844

Another way to compare the output is to assume that there is no recruitment after the end date of the season. Without doing further analysis, which is possible (for example, one can import the existing output data into GIS, and calculate areas inundated), one can use the tables that are available to do further analyses. The area available for seedling recruitment would be proportional to the difference in stage between the first day of successful recruitment and the stage on the last day of the season. The stage differences between successful recruitment initiation and end of season for the cottonwood relationship for the three different flows are shown in Table 5.

Table 5. HEC-EFM results for cottonwood seedling recruitment.

Stage difference (ft)		
Base flow	Nodos flow	Shasta flow
0.5	0.4	0.1

These results were compared to the results of the other software packages (Figure 38), where non-dimensionalizing the results allows a comparison where the base case is represented by 100% in all the models.

Fall-run Chinook salmon redd-dewatering

In EFM, the redd-dewatering relationship was defined in the following way. The flow in each single day of the egg-laying season was chosen. This season was defined as October 1 to December 31. Then, from each individual day, the minimum flow that occurred anytime in the interval 60 days after the eggs were laid was identified. This results in two numbers that can be inserted into the dewatering lookup table. Each combination of flows returns a percent dewatered. The conceptual model assumes that eggs can be laid in gravels that become exposed, or dewatered, to such an extent that the reduced flows cannot support the egg survival. A number of statistics can be used to establish the resulting discharges. Three were used in this study: the 20% exceedance, 50% exceedance (5-year and 2-year recurrence intervals), and the mean.

Table 6. HEC-EFM Chinook fall run dewatering output analysis results.

	20% exceedance (5-yr flow)			50% exceedance (2-yr flow)			Mean		
Description	Base	Nodos	Shasta	Base	Nodos	Shasta	Base	Nodos	Shasta
Q in egg-laying season	15330	12623	12870	8347	8514	8175	10,708	9,696	9,816
Minimum in egg-incubation	7869	8046	6775	6283	5653	5407	6,432	6,075	6,484
Percent of redds dewatered	30.3%	19.2%	27.0%	7.3%	12.7%	12.3%	24%	14.4%	18.3%

The inverse of the percent dewatered was non-dimensionalized, plotted, and the different methods were compared to each other (Figure 27), and used in the final comparison (Figure 39). The inverse was used because the more dewatered, the less the good habitat, and the final metric was chosen to represent the good habitat.

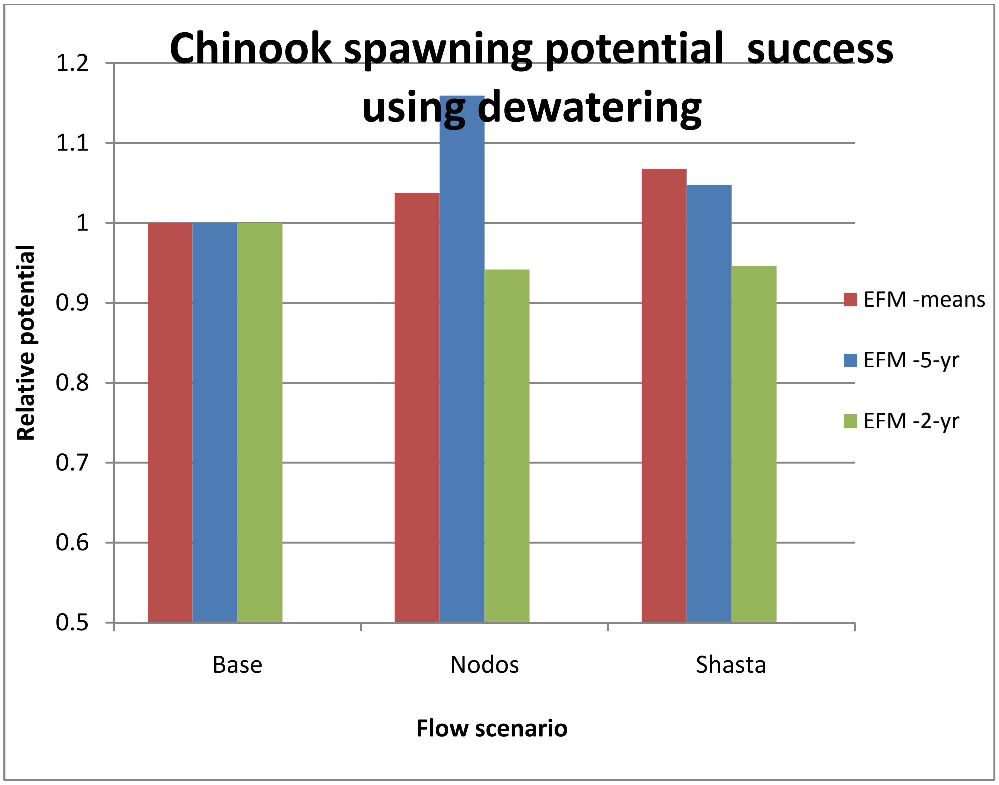


Figure 27. HEC EFM Chinook fall run dewatering output using different flow frequencies.

eWater Cooperative research Centre River Analysis Package (RAP)

Cottonwood seedling initiation

It was a simple matter in the Time Series Analysis (TSA) module in RAP to calculate and output the mean fall rate during the recruitment season and to use this as a metric for cottonwood recruitment (Figure 28).

OutputTable				
Name	**Abbreviation**	**Base___46_94_cfs _australian.csv**	**Nodos__46_94_cf s_australian.csv**	**Shasta_46_94_cfs _australian.csv**
Reporting Period Summary				
Run date	RunDate	23/01/2010 11:29	23/01/2010 11:29	23/01/2010 11:29
Start based on User	Start	1/10/1945	1/10/1945	1/10/1945
End Date	End	30/09/1994	30/09/1994	30/09/1994
Rise and Fall result				
Whole Period				
Mean rate of Fall	MRateFall	1448	880	824
Summary For Season Recruitment				
Mean of Recruitment Mean rate of Fall	MDFMRateFallRecruitment	567	274	203
Median of Recruitment Mean rate of Fall	MedMRateFallRecruitment	382	175	123
CV of Recruitment Mean rate of Fall	CVMRateFallRecruitment	0.95	0.896	1.029
Variability of Recruitment Mean rate of Fall	VarMRateFallRecruitment	3.025	4.053	4.248

Figure 28. RAP output for mean rate of fall during the recruitment season.

Taking the mean of the mean rate of fall, dimensionless ratings were developed as they were for the other software package results, yielding the relationships in Figure 29, which were used in the overall comparison of all models.

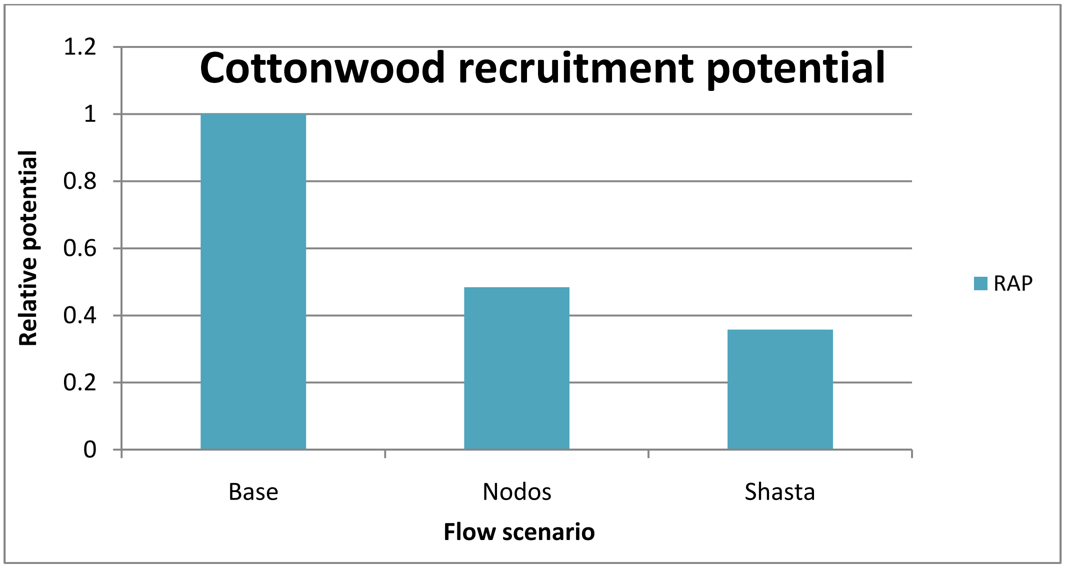


Figure 29. Rap cottonwood seedling recruitment potential flow scenarios compared.

The Ecological Response Model (ERM) module in RAP could be used to further define ecosystem relationship rules for cottonwood recruitment, but learning time for defining relationships in the software is significant, and an ERM analysis was not done for the current study. Additionally, it is not clear whether the ERM is still supported or offered as part of the RAP system.

Indicators of Hydrologic Alteration (IHA)

Cottonwood seedling initiation

The same three flow scenarios used in the previous software package applications were used in applying IHA to the cottonwood recruitment problem. A set of IHA indices were applied to various weighted combinations to evaluate cottonwood seedling recruitment habitat. Three different hypotheses were considered: 1) the faster the flow recedes, the better for habitat suitability (because a faster recession rate will expose more area for recruitment), 2) the recession rate in season has to be less than a certain amount (derived from the stage discharge curve), and 3) the fewer reversals in the season, the better.

A composite index was formed (Equation 1). The first "a" component addresses the hypothesis that the faster the mean fall rate, the better. The "*mean seasonal scenario fall rate*" is the mean rate of flow fall in the seasons of interest for a selected scenario (i.e. Base, Nodos, or Shasta), and the "*mean seasonal Base fall rate*" is the mean rate of flow fall during the season of interest for the Base case scenario. The "b" component addresses the issue that if the stage drops at a certain rate, it will kill the seedlings. As a crude approximation, the number of "killing" fall rates have been counted (where "killing" is defined as the number of rates that are greater than 2.9 cm/day.) In order to make an index that positively weights the minimization of killing rates, the number of killing rates in a specific scenario were subtracted from the sum of killing rates in all scenarios, and non-dimensionalized by the sum in all scenarios. The "c" component is composed of the number of flow reversals.

$$\begin{aligned} Index &= a\left(\frac{(mean\ seasonal\ scenario\ \ fallrate)}{(mean\ seasonal\ Base\ \ fallrate)}\right) \\ &+b\left(\frac{(sum\ of\ \#of\ \ rates\ greater\ than\ "killing"\ in\ all\ scenenarios - \#in\ scenario)}{(sum\ of\ \#of\ \ rates\ greater\ than\ "killing"\ in\ all\ scenarios)}\right) \\ &+c\left(\frac{(sum\ of\ \#of\ \ reversals - \#in\ scenario)}{(sum\ of\ \#of\ \ reversals)}\right) \end{aligned} \qquad (1)$$

Table 7 shows the raw data derived from the IHA graphs and data, and Table 8 shows the results using different values of the weighting factors. It is reasonable that factors *b* and *c* have less weight than factor *a*. Two indices were ultimately used: 1) the *a* component alone (the fall rate of the hydrograph during the season of interest) and 2) with a=0.75, b=0.20, and c= 0.05. This represented a portion of the cottonwood recruitment relationship that was originally defined. It does not completely account for fall rates that are too fast, which would "dry out" the seedlings. An assumption was made that the faster the mean seasonal fall rate, the more area would be available. For example, a fall rate of 188 cfs/day is better than 171 cfs/day. This is a crude assumption, and even with the other criteria in weighting factors *b* and *c*, the criteria that a drawdown rate that is too fast will desiccate and kill the seedlings (a model requirement that was included in the HEC-EFM criteria) is not adequately modeled. IHA allows the creation of a number of graphs, and also allows access to all the data from which the graphs are made. In order to get the quantity of mean fall rate in the season of interest, a graph was defined, created, and used to determine the desired number.

Table 7. IHA statistics for evaluating Cottonwood recruitment potential.

Factor	Description	Base flow	Nodos flow	Shasta flow
a	Mean seasonal fall rate (cfs/day)	188	171	99
b	Number of seasonal rates below standard deviation of Base	2	4	0
c	Number of reversals in the recruitment season	11	4	3

Table 8 IHA Composite index of Cottonwood recruitment potential

Graph name	Weighting factors			Composite Index value		
	a	b	c	Base	Nodos	Shasta
IHA	1	0	0	1.00	0.91	0.53
IHA2	0.75	0.2	0.05	1.00	0.87	0.71

Figure 30 shows the results of the two composite indices that were used. Qualitatively the results are the same, and show that the Base flow scenario potentially provides more habitat, with the Nodos and Shasta following in that order. For the final comparison of the results from all software packages, the simple metric with a=1 (the fall rate of the hydrograph during the season of interest) was used (i.e. IHA on the bar graph).

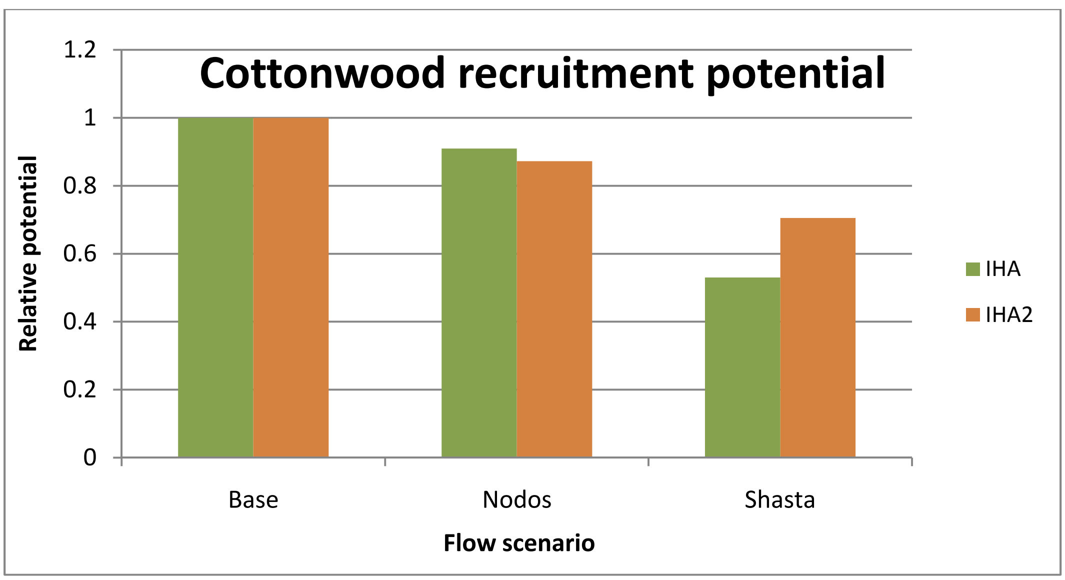


Figure 30. Cottonwood recruitment potential.

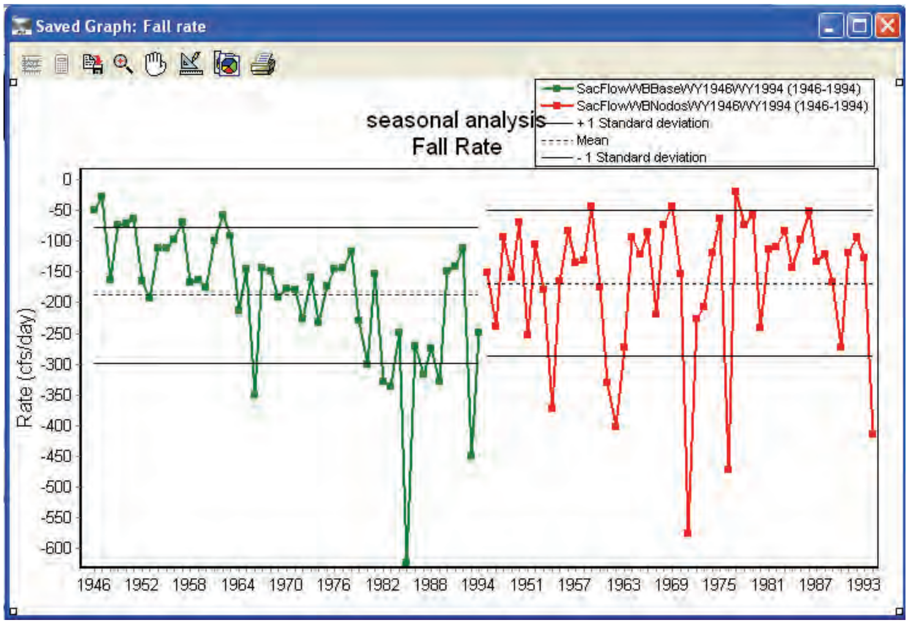


Figure 31. IHA Seasonal analysis of mean fall rate (for Base and Nodos) (Note: the data used for cottonwood recruitment assessment were taken from the dotted lines, which represent the mean fall rate in the recruitment season.)

Fall-run Chinook salmon redd-dewatering

IHA is useful as a tool to analyze the changes in flow from one operational schedule to another. This is often in the form of pre- and post-dam flow regimes, or other changes to flows. IHA is also effective as “a screening tool,” which can be used to screen for possible limiting factors. IHA was used in three ways, 1) to screen for possible high flows, which could scour the redds; 2) to analyze flow decreases for changes in habitat that could cause redd dewatering; and 3) to examine general indices that might relate to the dewatering. The tabular data, processed with some additional mathematical steps, were used to develop the dewatering table. For the third method, standard IHA indices were used and a parameter that could measure flow decrease was sought, because redd dewatering increases monotonically with higher flow decreases.

The same life-history conceptual relationship used in the previous cases was used for this analysis. The first part of the IHA analysis examined the average flow in the season for the egg laying (October 1 to December 31). Next, flow decreases following the egg-laying were examined. From the relationship between the flow at which the eggs are laid, and how far it tends to drop sometime in the next 60 days, the redd-dewatering curve (Appendix E) was used to estimate the percent dewatered with that particular flow drop. Ideally, a program could calculate the percent of habitat dewatered for each day during the spawning season. Such a procedure would sequentially examine each day during the spawning season by recording the daily discharge of a “spawning day” and then identifying the minimum daily flow within the subsequent 60 days. The difference between the spawning day and the 60-day minimum would indicate the proportion of eggs laid on the spawning day that become dewatered. This procedure would be conducted for each spawning day, yielding a cumulative total for the entire season.

However, this procedure cannot be followed within IHA. Thus, a statistical measure (the mean and the median of the entire 49-year record) of the flow in the egg-laying season was used to characterize the egg-laying flow. This is the same statistical value calculated in EFM. Following this step, the data in IHA were used to get a statistical measure of the minimum in the “incubation” season, which was defined as October 1 to March 1, a season that would include any of the days in which eggs could be dewatered. This value differed from the one derived in EFM, which was more particularly derived from the minimum that occurred sometime in the 60 days after the specific date of egg-laying.

Both the mean value of each of the egg-laying Q’s and the incubation period minimum were used; and then the median. Based on the values of the Q’s, the look-up table in Formation was entered and the percent of redds dewatered was caluculated.

Table 9. IHA redd dewatering.

	Mean			Median		
Criteria	Base	Nodos	Shasta	Base	Nodos	Shasta
Q in egg-laying season	9267	8509	8728	7250	6446	6425
Minimum in egg-incubation	6093	5910	6611	5780	5105	5380
Percent of redds dewatered	14.1%	10.5%	7.6%	5.3%	4.5%	3.4%

IHA indicators that represent flow decreases were searched for. One possibility was the “low-flow” pulses. A pulse is defined as a daily mean flow that falls below a selected threshold; in this case it is the number of daily mean flows less than the 25th percentile over the period of record.

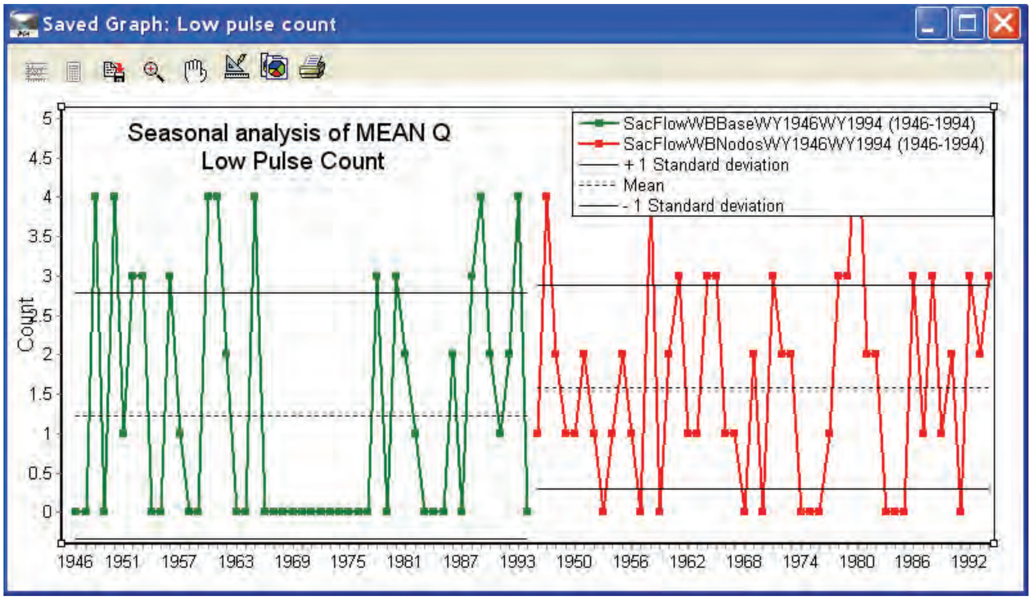


Figure 32. IHA low pulse count.

Table 10. IHA seasonal low-flow pulses over 49 years.

Base	60
Nodos	78
Shasta	64

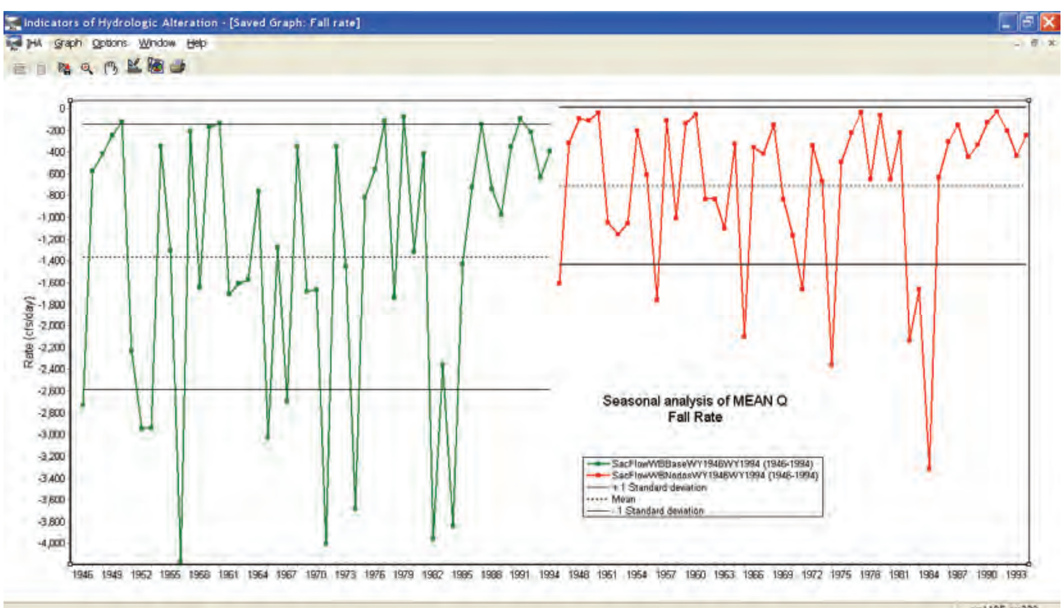


Figure 33. IHA seasonal fall rate.

Table 11. IHA sum of fall rate over years of record.

Base	-13144
Nodos	-6458
Shasta	-6646

Looking at all the results for the IHA parameters considered, there are very similar results for the two analyses that use the weighted useable area (WUA) curves for dewatering. The Shasta scenario is the best, followed by Nodos and then Base. The low-flow pulses suggest that the Base is the best with the others somewhat less. The fall rate suggests that Nodos and Shasta are similar and both are better than the Base case. In order to compare all the measures, they were non-dimensionalized. Because more dewatering means less habitat, the inverse of the non-dimensional number was used for comparisons.

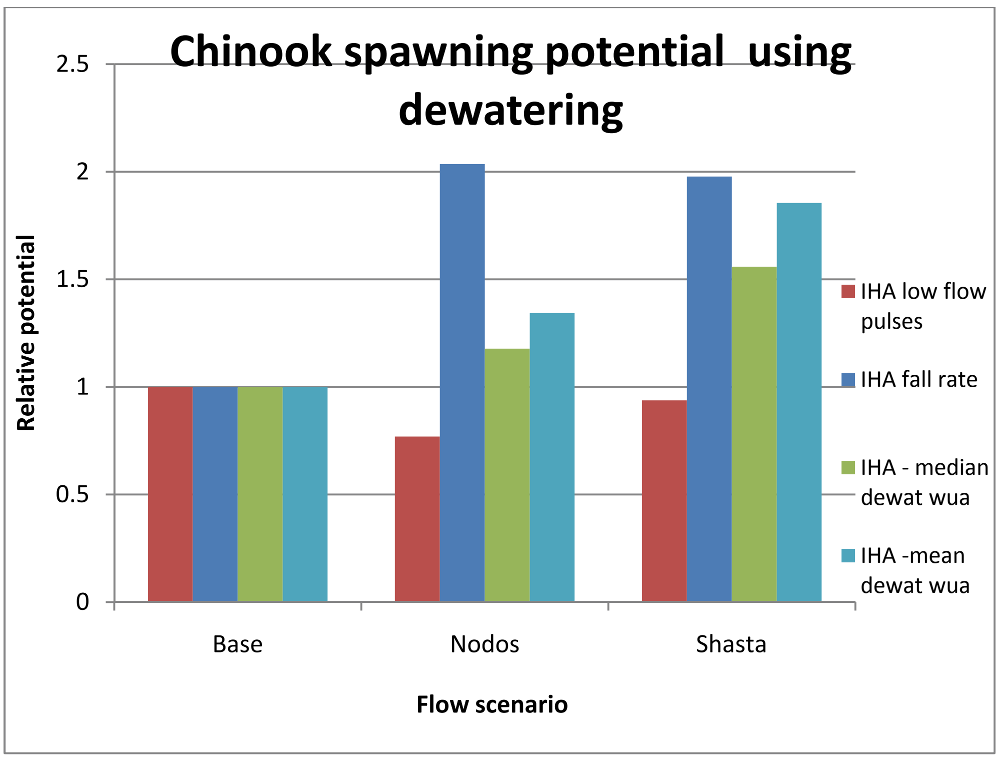


Figure 34. IHA dewatering analysis.

Hydroecological Integrity Assessment Process / Hydrologic Assessment Tool (HIP/HAT)

Cottonwood seedling initiation

In applying the HAT to the cottonwood recruitment example scenario, it was necessary to study the definitions of the indices and to choose one, or a combination of, indices that seemed applicable to the problem. After experimenting with different combinations, a single index seemed the most appropriate, which was the mean rate of flow fall for those days when the flow reduces (Figure 35). This is almost identical to the approach used with IHA, but it is less versatile and less precise than the IHA approach, because it does not have a way to use an average limited to the recruitment season.

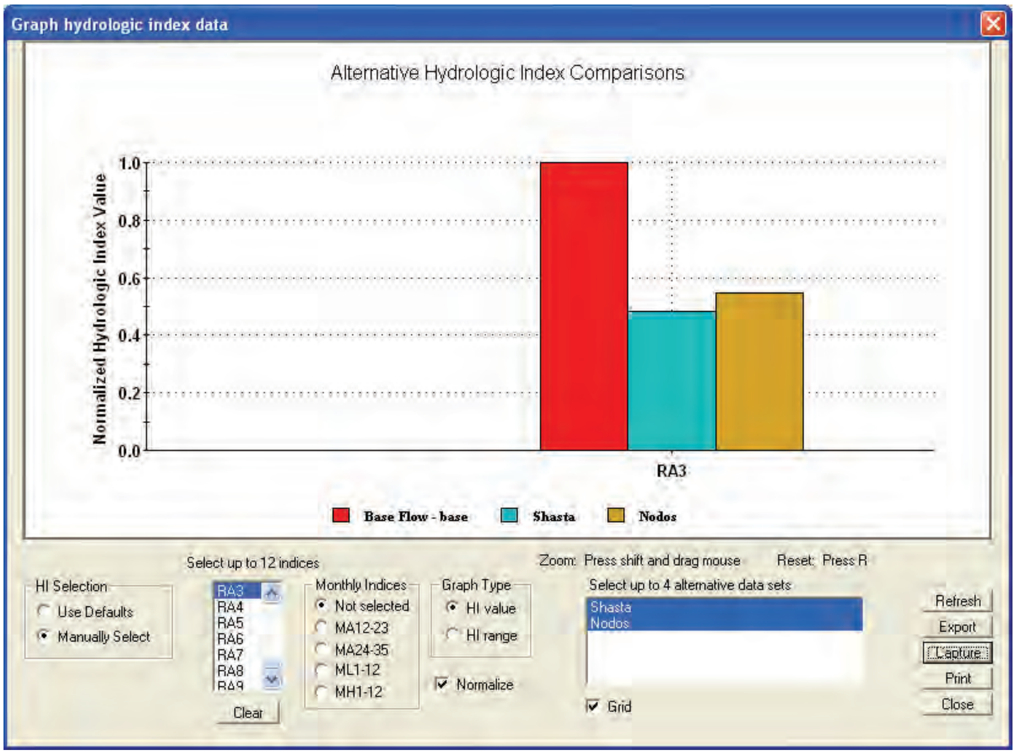


Figure 35. HAT output showing the hydrologic index for mean rate of flow fall for those days when the flow reduces.

Fall-run Chinook salmon redd-dewatering

The pre-defined indices that best represent the dewatering phenomenon both relate to the fall rate of the flows. As with IHA, there is no method to limit the calculations to the season in question, so the indices represent the entire flow year. Two indices were chosen.

RA3 (fall rate) "compute[s] the change in flow for days in which the change is negative for the entire flow record. RA3 is the mean (or median – Use Preference option) of these values (cubic feet/second/day). RA7 (change of flow) compute[s] the log10 of the flows for the entire flow record. [RA7] computes the change in log of flow for days in which the change is negative for the entire flow record. RA7 is the median of these log values (cubic feet/second/day)."[1]

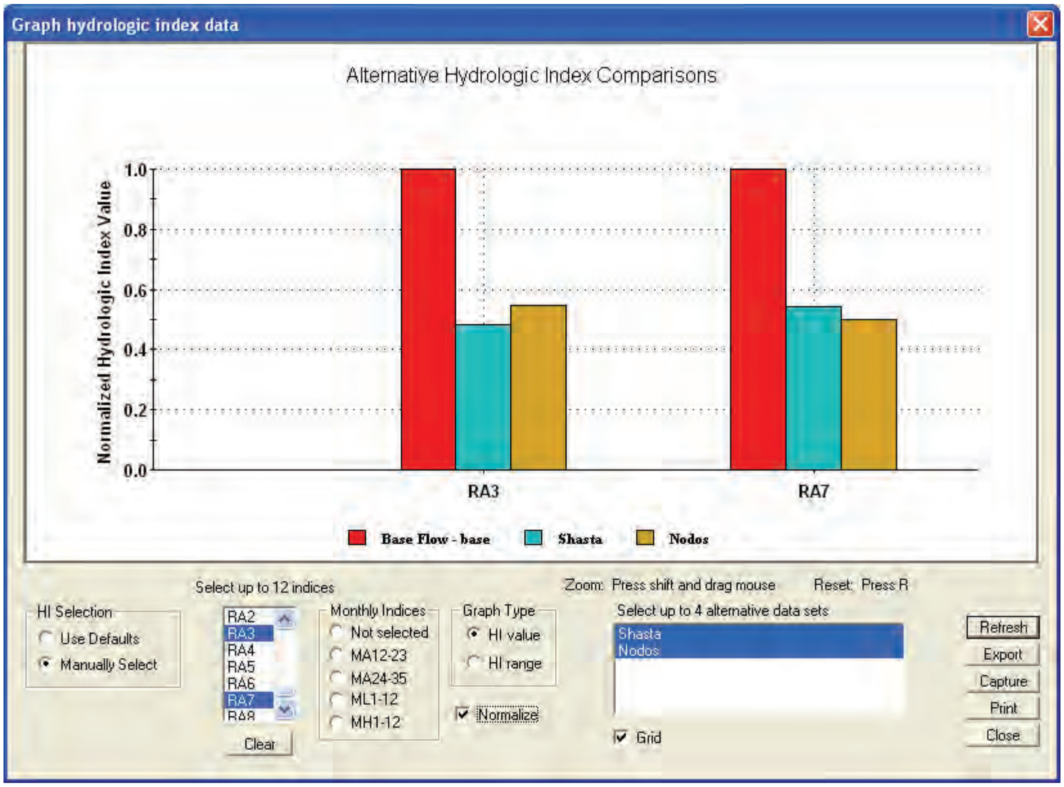


Figure 36. HIP/HAT indices.

Table 12. HIP/HAT indices.

Index	Base	Nodos	Shasta
RA3	1	0.548	0.483
RA7	1	0.5	0.542

In order to compare all the measures, they were non-dimensionalized. Because more dewatering means less habitat, the inverse of the non-dimensional number was used for comparisons.

[1] RAP interactive help.

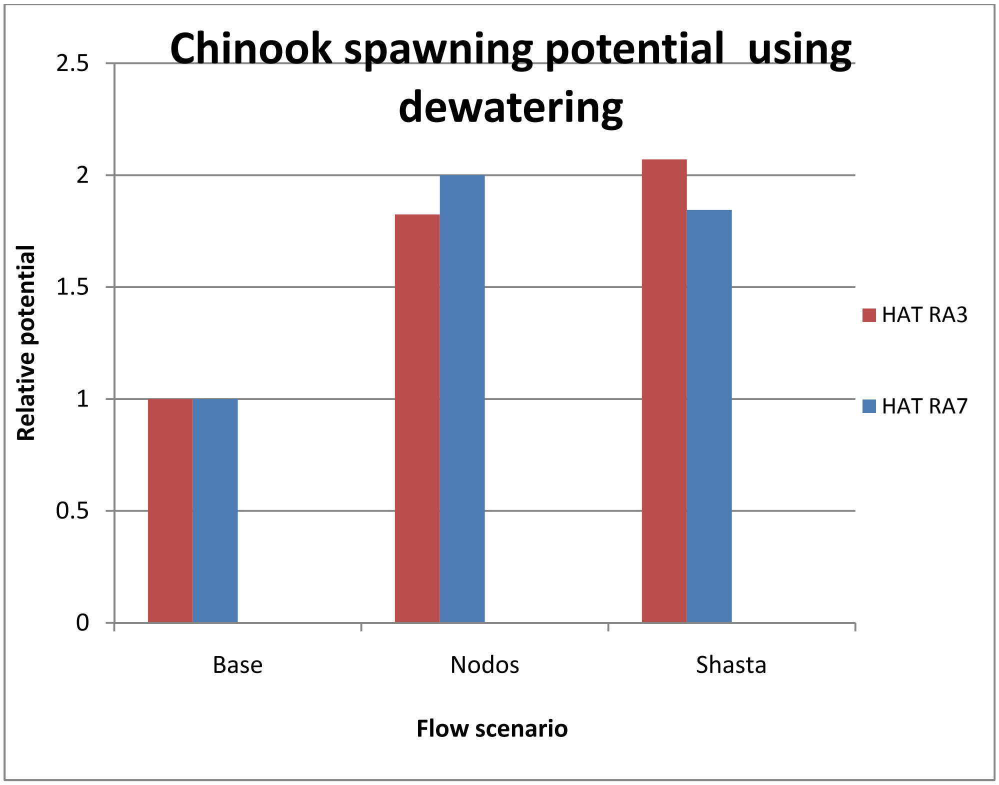


Figure 37. HAT dewatering results.

4 Summary and discussion

Choosing an appropriate software package for a specific application related to modeling ecosystem functions requires knowledge of the capabilities of the software packages being considered. When faced with a problem that requires ecosystem modeling, decision makers often do not have the resources to explore a range of software packages. This review examined seven software packages that can be applied to evaluate habitat changes in response to hydrologic changes. The goal of the review was to make it easier for a manager or decision-maker to decide which software package(s) would be appropriate for a specific application.

The models evaluated here were classified into two categories: 1) models that focused primarily on "ecosystem relationships," and 2) models that focused on "environmental flows." Ecosystem relationship models simulate habitat conditions based on specific biological processes and how the habitat changes when the environmental conditions change. Two of the models that are included in the ecosystem relationship group are designed specifically to evaluate fish habitat. Environmental flow models analyze the changes in hydrologic flow. This type of model was specifically designed to analyze flow alterations. If the defined sample problems — which were defined as the ecological functions of cottonwood seedling recruitment and salmon redd dewatering — had instead been related to developing indices of flow regime alteration, the environmental flow models would have been more direct and easier to apply than the ecosystem relationship models.

For evaluating habitat quality of ecosystems, all of the models reviewed tend to be based on the thinking behind "habitat suitability indices." This means that the quantitative evaluation of habitat change is ultimately based on a ranking system established by a body of scientific expertise, often developed from research studies. For the ecosystem relationship models, the habitat suitability assessment is an explicit part of the model; for the environmental flow models, the habitat suitability tends to be determined outside of the modeling effort.

The two environmental flow software packages (IHA, HIP/HAT) are similar to each other and produce a similar array of flow regime indices. Both software packages are oriented to evaluating "instream flow" requirements, which is an important and prominent issue in river management. The ability to assess ecosystem functions in the “environmental flow paradigm” is implicitly embedded in the assumption that a “natural” flow regime tends to satisfy the flow required to create suitable habitat for species in an ecosystem. These software packages were not specifically designed to simulate the habitat, or to address the biological processes that depend on the habitat. Although not specifically designed for habitat assessment, these indices of hydrologic conditions can be used to consider such questions. As illustrated by the simple examples used here (assessing habitat for cottonwood seedling recruitment and examining the habitat quality defined by redd-dewatering for the fall-run Chinook salmon), defining the indices (or combination of them) that correlate with habitat quality is the key step, and requires technical knowledge. A study comparing the utility of these two programs for use in the Texas Instream Flow Program concluded that “IHA, as its name implies, is best suited to assess hydrologic alteration and to quantify the effects of dam construction and other such water management development projects on the flow regime via two-period analyses and the Range of Variability Approach. HAT, as its name implies, is focused on characterizing streamflow, particularly in the context of a regional analysis of factors that influence streamflow properties” (Hersh and Maidment 2006). Neither software package was directly suitable for the Texas program; both required modifications for the needs of the instream flow program. The study concluded that there was little difference between the two software packages for characterizing streamflow hydrographs.

“One of the logical problems encountered when trying to use the flow indices, either environmental flow components (EFC's) in IHA or the indices in HIT/HAT, comes in thinking about rules for evaluating impacts or conserving species based on analyzing multiple flow indices as done in most applications. A good example is current work on analyses of HIP/HAT flow indices and trout abundance in Missouri streams (Kennen et al. 2009). When using rules like 25th to 75th percentiles in HIP/HAT or mean plus or minus 1 standard deviation as Richter proposed, one rapidly runs into the issue of how to obtain such intervals simultaneously across multiple flow indices. There will always be tradeoffs in one group of flow indices versus another group or two. The only way to resolve these tradeoffs in flow indices would seem to require information on how biological components (e.g., fish species) or ecological processes are related to the flows, and which ones are deemed more important in a given analysis. So although avoiding direct linkages with important biological components and ecological processes may make it easier to get started with an analysis using IHA or HIP/HAT, the issue of which flow indices are related to which biological components/ecological processes will always return in some form when trying to interpret outputs from these flow index approaches. And establishing meaningful relationships between the flow indices and some biological measure is not easy nor will such relationships ever have strong relationships with narrow intervals of responses. People are just barely beginning to explore these issues with the flow indices. None of the issues will be a surprise to anyone who has worked with terrestrial habitat suitability models for many years.”[1]

Of the programs reviewed here, three have specific target fish species (Table 13). The table shows the partial overlap of the selected fish species of the software packages. EnviroFish is specific to the Mississippi River region and includes approximately 100 in-channel and floodplain fish.

Table 13. Fish relationships “common” to SacEFT, SAM ECT (Version 3.0), and EnviroFish.

EnviroFish1	SacEFT	SAM ECT
	Chinook salmon	Chinook salmon (Oncorhynchus tshawytscha) Central Valley spring-run Central Valley fall-run Central Valley late fall-run Sacramento River winter-run
	Steelhead	Central Valley steelhead DPS (*Oncorhynchus mykiss*) Threatened
		Delta smelt (*Hypomesus transpacificus*) Threatened
Shovelnose sturgeon	Green sturgeon	Green sturgeon southern DPS (*Acipenser medirostros*)

[1]EnviroFish currently applies to about 100 species of Mississippi River in-channel and floodplain fish; only one is shown here.

Two of the software packages, which were designed to be used for fish species (SAM and EnviroFish), are currently limited to the target locale and application for which they were designed. EnviroFish was designed for floodplain fisheries of the Mississippi River basin. SAM was designed to be used to assess changes in fisheries habitat resulting from possible bank revetment scenarios on the Sacramento River. Both are currently in limited public use, and tend to be used by a limited group of “in-house” trained users related to the USACE. Review of these two packages was limited to a

[1] This paragraph was contributed by Brian Cade of the USGS.

description; they were not used with a sample data set, as were the other packages. There were two main reasons for this. First, the sample problems were framed as flow-change problems, with a time series of discharges and stages used as the variable that changed between scenarios. These input data – flow time series – are not standard input data for SAM or EnviroFish. Second, for EnviroFish, the sample fish problem is a Sacramento River species whose spawning and rearing behavior is limited to the main channel; EnviroFish focuses on Mississippi River species with floodplain life history behaviors.

A useful development, for both the environmental flow and ecosystem relationship software packages, is a peer-reviewed library of relationships to assess specific habitats. This is similar to the extensive library of habitat suitability indices (HSI) that exists (USGS 2010). For the environmental flow example, research studies could be performed that correlate a specific combination of indices with specific habitat quality; then that index or weighted group of indices could be used confidently by various groups to evaluate the specified habitat. Likewise, with the ecosystem relationships group of programs, if the habitat requirements were defined by research groups, and research results were peer-reviewed, then one could refer to the research to use a defined relationship. A library of relationships could then be established that users could call upon for specific applications.

One related effort for standardizing such information is TNC's Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al. 2010), whose goal is evaluating environmental flows when detailed site-specific information is not available. The ELOHA framework, and particularly the ELOHA Toolbox,[1] has a detailed collection of information and references related to the use of environmental flows to assess ecologically significant hydrologic alteration at a regional scale.

In using specific ecosystem relationships (cottonwood seedling recruitment and salmon redd dewatering) in the course of this review, technical knowledge of the biological life history played a key role in successfully using the software packages. Some of the software packages are designed to give simple output data related to ecosystem response (e.g. SacEFT, HEC-EFM, HIT/HAT). In some cases, the pre-defined output is relatively easy to interpret by a lay practitioner (e.g. SacEFT); in some cases it is not. In

[1] http://conserveonline.org/workspaces/eloha

general, for evaluating ecosystem response to changing environmental conditions, the definition of the relationship rules, the choice of which output to use, and the interpretation of the output all require technical knowledge of the biological system in question. For the environmental flow programs, the choice of which indices to choose in order to reflect a defined ecosystem response also requires significant technical knowledge.

Many of the software packages can analyze and visualize flow time series, which is output data that are generally accessible and useful to a wide range of users, both expert and general. But this is essentially a visualization of the input data, and not a metric of habitat suitability.

In utilizing similar criteria for the cottonwood seedling recruitment in five of the software packages (excluding the fish-only ones) the results were qualitatively similar (Figure 38). The scale of the quantitative metrics differed in each case; therefore, the results for the different programs were non-dimensionalized, with each value presented as a percentage of the Base flow scenario case. All programs showed that the Base flow case had the most habitat potential, the Nodos case had the second-most potential, and the Shasta case had the least habitat potential in all cases. The results are similar for IHA, HAT, and RAP probably because a very similar metric was chosen to represent the recruitment model.

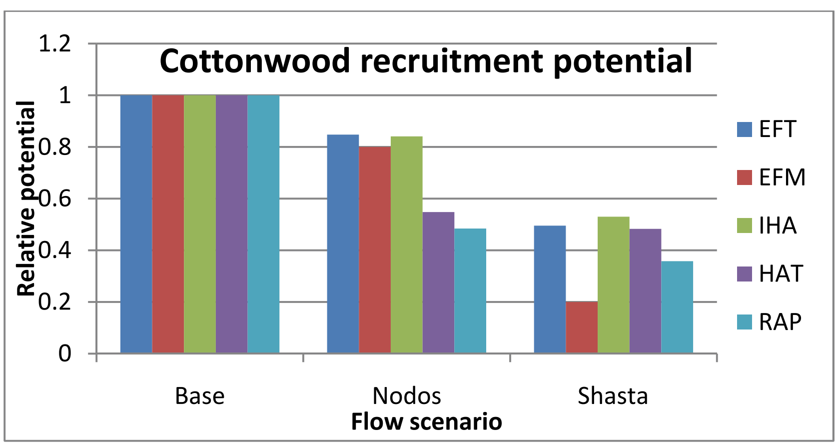


Figure 38. Cottonwood recruitment potential with different flow scenarios as modeled by five software packages.

For the Chinook salmon habitat potential, based on the limiting factor of redd-dewatering, multiple indices were developed for four of the models. Each of those indices, non-dimensionalized by the Base flow value, was plotted (Figure 39). On the average, the Nodos and Shasta scenarios show potentially better habitat for the salmon, based on the redd-dewatering relationship.

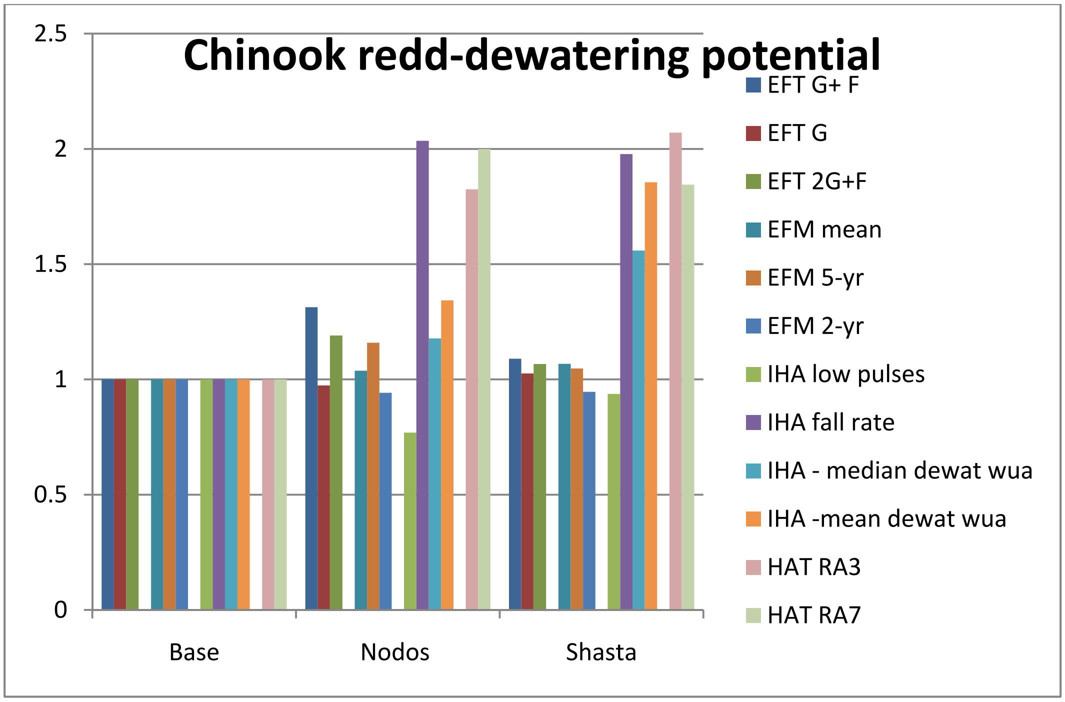


Figure 39. Chinook redd-dewatering potential with various flow scenarios as modeled by four software packages.

The process of utilizing an ecosystem functions and flow modeling approach is similar to the Range of Variability approach (Richter et al. 1997; Richter and Richter 2000), which is effective for setting quantitative flow-management goals.

The process of developing relationships for ecosystem flow models and other analysis tools like environmental flow tools is illustrated in Figure 40.

1. The process begins with examining individual life stages of a species in question (step 1).
2. Once these life stages are conceptually described, a simple initial screening can be performed to see if the life stage process is sensitive to the environmental changes in the project being considered (step 2).
3. The habitat preferences for each life stage and how habitat preference is linked to flow is then reconsidered (step 3).
4. Based on that, the process differs slightly for the two types of models that have been considered. The ecosystem functions models use life stage-

habitat-flow linkages and a defined relationship to develop hypotheses (step 4).

The environmental flow models use the linkages to identify specific environmental flow components or indicators that influence the life-stage habitat preference (e.g. Mathews and Richter 2007). The RVA approach can be a subset of step 2 in the flow chart below.

5. An Ecosystem functions model like EFM then has internal review capabilities (Vue) where the flow-process linkage (step 1), relationship dynamics (step 3), and hypotheses (step 4) can be visualized. This visualization and review (step 5) can be an important juncture where stakeholder communication and input are valuable.
6. Based on this analysis, interpretation of output results and hypotheses testing (step 6) can be the result of technical advisory meetings based on the presentation of the visual output.
7. Decisions may be made to refine some of the preceding steps (step 7), until a working set of results is agreed upon.

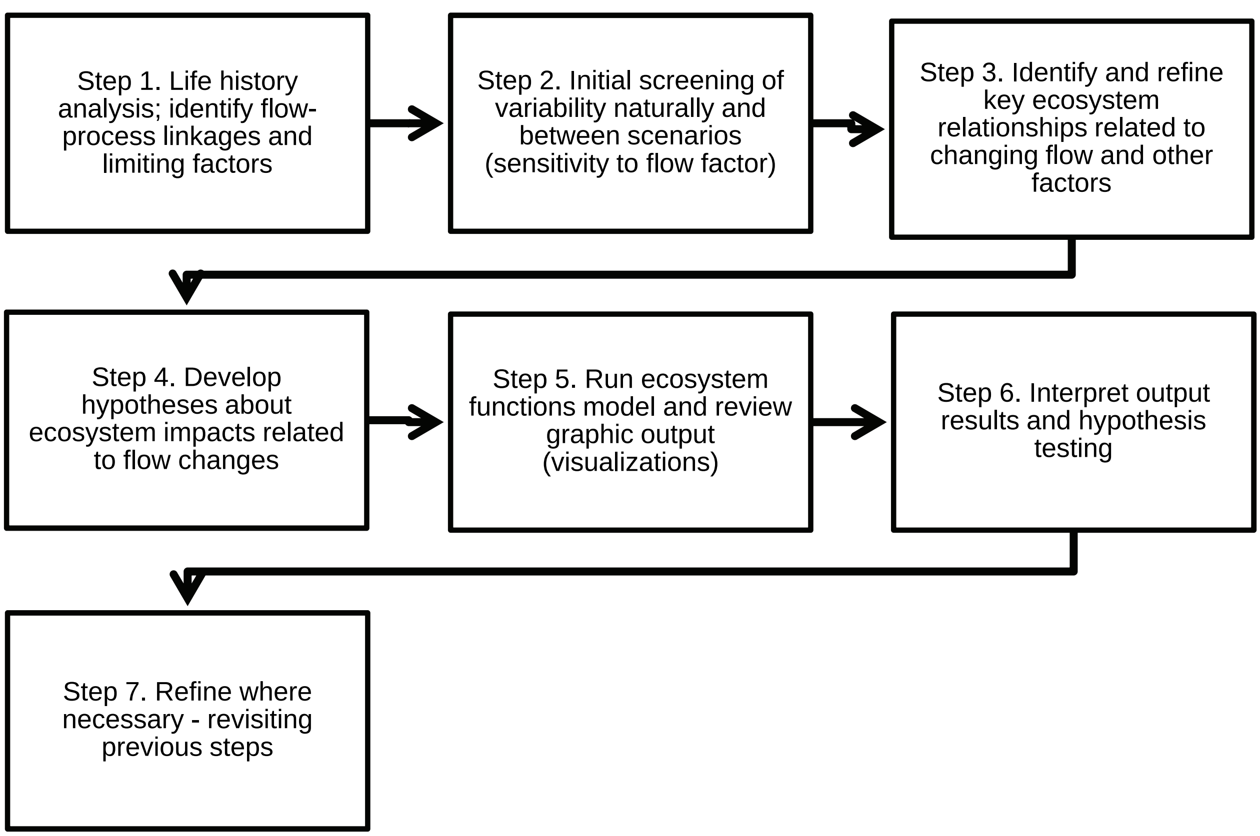


Figure 40. Conceptual stages in using ecosystem modeling to inform management decisions.

For the majority of the software packages, the most important aspect of ecosystem modeling is establishing and using a panel of experts to define the ecosystem relationship to be used, determine which metrics will be used to assess the change in habitat resulting from a change in the environment, and define how the results are to be interpreted. SacEFT and SAM differ because the “expert panel” was used to develop the relationships, which are then embedded in the software packages. In that sense, these two packages could be the most easily used by non-experts. Currently, HEC-EFM and RAP ERM have the most flexibility in terms of user-defined relationships; both of these software packages could be used for a wide range of ecosystem habitats and ecosystem relationships. Both of them accept HEC RAS data. HEC-EFM is easily extended to produce GIS visualization of its results. RAP appears to not be widely used, is not well supported, and is apparently not cited in research papers. HIT/HAT and IHA are essentially “environmental flow” software packages that produce similar indices of flow regimes. Currently IHA is widely used and is cited in numerous research studies. HIT/HAT tends to be used by USGS-specific projects.

Projects that require analyses of ecosystem response to changing flow regime and other environmental factors can depend on software technologies for modeling. Choosing the appropriate technology is a vital concern for each project. This review aims to help managers evaluate which models would be useful for specific applications related to assessing habitat and ecosystem functions.

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Appendix A: Citations and resource papers for the software packages

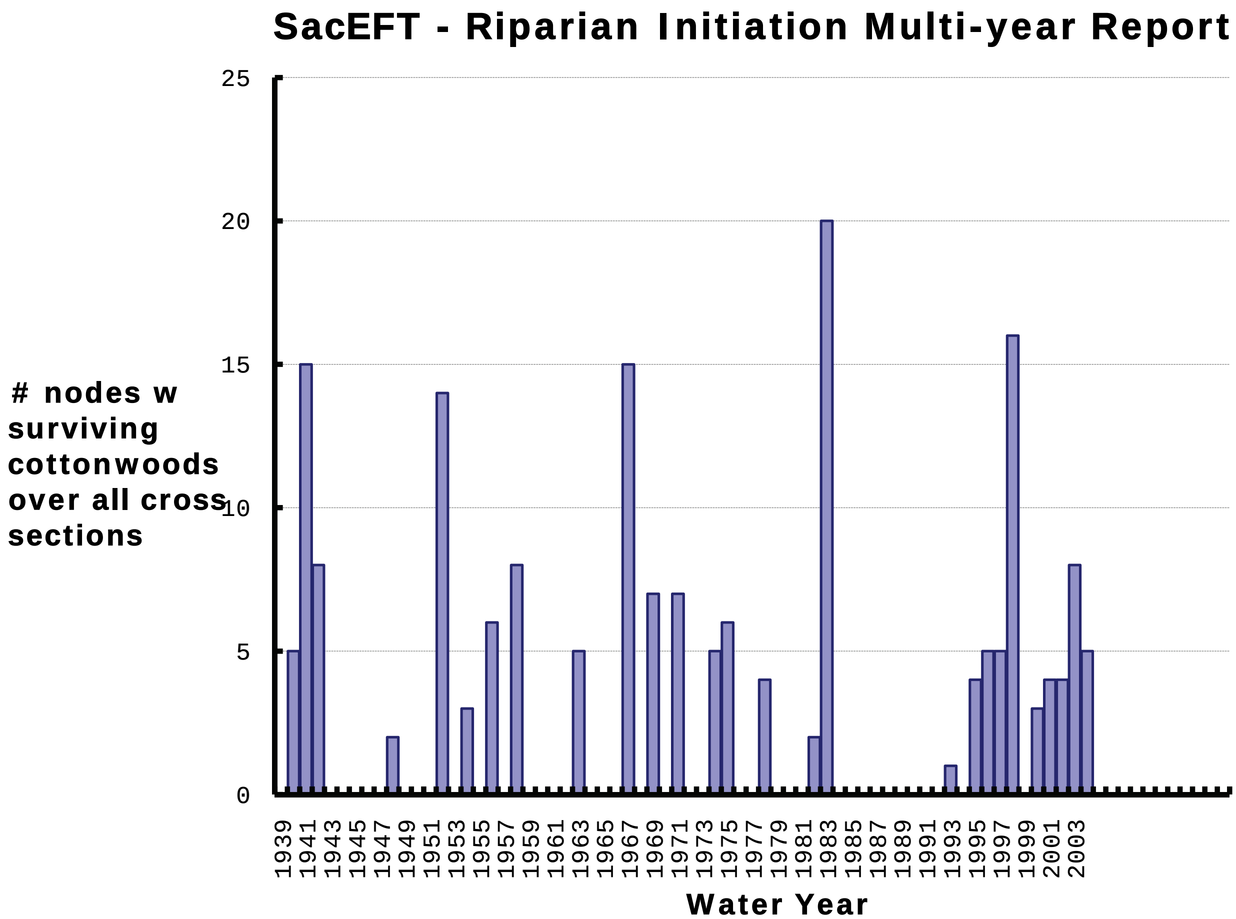
	Software package Name	Selected Citations/Resource papers
1	SacEFT	The Nature Conservancy, Stillwater Sciences and ESSA Technologies. 2008. Sacramento River Ecological Flows Study: Final Report. Prepared for CALFED Ecosystem Restoration Program. Sacramento, CA. 72 pp. Stillwater Sciences. 2007. Linking biological responses to river processes: Implications for conservation and management of the Sacramento River—a focal species approach. Final Report. Prepared by Stillwater Sciences, Berkeley for The Nature Conservancy, Chico, California. ESSA Technologies Ltd. 2005. Sacramento River Decision Analysis Tool: workshop backgrounder. Prepared by ESSA Technologies Ltd., Vancouver, British Columbia for The Nature Conservancy, Chico, California. Available at: www.delta.dfg.ca.gov/erp/sacriverecoflows.asp ESSA Technologies Ltd. 2007. Sacramento River ecological flows tool (SacEFT): design & guidelines (v.1.00.018). Prepared by ESSA Technologies Ltd., Vancouver, British Columbia for The Nature Conservancy, Chico, California. Available at: www.delta.dfg.ca.gov/erp/sacriverecoflows.asp ESSA Technologies Ltd. 2008. Appendix F. SacEFT Analysis Results. Prepared by ESSA Technologies, Vancouver, B.C. for The Nature Conservancy, Chico, California. (http://www.delta.dfg.ca.gov/erp/sacriverecoflows.asp)
2	HEC-EFM	Jones and Stokes. (2000). *Final functional relationships for the Ecosystem Functions Model*, Sacramento and San Joaquin River Basins Comprehensive Study, Sacramento, CA. A. H. Arthington, R. J . Naiman, M. E. Mcclain and C. Nilsson (2009) *Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities;* Freshwater Biology doi:10.1111/j.1365-2427.2009.02340.x U.S. Army Corps of Engineers (USACE). 2009. HEC-EFM – Ecosystem Functions Model. Quick Start Guide. Hydrologic Engineering Center, Davis, CA. Shafroth, P. B., A. C. Wilcox, et al. (2010). "Ecosystem effects of environmental flows: modelling and experimental floods in a dryland river." Freshwater Biology 55(1): 68-85. U.S. Army Corps of Engineers (USACE) and Reclamation Board, State of California (Rec Board). 2002. Ecosystem Functions Model - Technical Studies Documentation, Appendix G. Sacramento and San Joaquin Rivers Basin Comprehensive Study, Sacramento, CA. Hutzinger, Hickey, and Walker. 2008. *How Much Water Do Stream-Dependent Species Need?* Southwest Hydrology July/August 2008. Hickey. 2007. *Models and Software for Supporting Ecologically Sustainable Water Management.* Water Resources IMPACT July 2007.
3	RAP	Marsh, Nick. 2004. River Analysis Package - Users Guide. CRC for Catchment Hydrology, Australia 2004. http://toolkit.ewater.com.au/Tools/RAP/documentation.

	Software package Name	Selected Citations/Resource papers
4	SAM	U.S. Army Corps of Engineers, Sacramento District. 2004. Standard Assessment Methodology for the Sacramento River Bank Protection Project, Final. Prepared by Stillwater Sciences and Dean Ryan Consultants, Sacramento AC. DACW05-99-D-00066. Task Order 0017.30 July. http://www.stillwatersci.com/resources/2004SAMfinalreport.pdf
5	IHA	Richter, B. D., Baumgartner,J.V.,Powel,J.,Braun,D.P. (1996). "A Method for Assessing Hydrologic Alteration within Ecosystems." Conservation Biology 10(4): 1163-1174. Richter, B. D., Baumgartner,J.V.,Wigington,R. (1997). "How Much Water Does a River Need?" Freshwater Biology **37**: 231-249. Richter, B. D., Baumgartner,J.V.,Braun,D.P.,Powell,J. (1998). "A Spatial Assessment of Hydrologic Alteration Within A River Network." Regulated Rivers: Research & Management **14**: 329-340. Mathews, R. and B. D. Richter (2007). "Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting." JAWRA Journal of the American Water Resources Association **43**(6): 1400-1413.
6	HIP/HAT	Olden, J.D., and N.L. Poff. 2003. *Redundancy and the choice of hydrologic indices for characterizing streamflow regimes.* River Research and Applications 19:101-121. Poff, N.L. 1996. *A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors*. Freshwater Biology 36:71-91. Henriksen J.A., Heasley J., Kennen J.G. & Nieswand S. (2006) Users' Manual for the Hydroecological Integrity Assessment Process Software (Including the New Jersey Assessment Tools). Open-File Report 2006-1093. U.S. Geological Survey, Fort Collins Science Center, Fort Collins, CO. Kennen J.G., Henriksen J.A. & Nieswand S.P. (2007) Development of the Hydroecological Integrity Assessment Process for Determining Environmental Flows for New Jersey Streams. Scientific Investigations Report 2007- 5206. US Geological Survey, New Jersey Water Science Center. Available at: http://pubs.er.usgs.gov/usgspubs/sir/sir20075206 Kennen, J. G., J. A. Henriksen, et al. (2009). Application of the Hydroecological Integrity Assessment Process for Missouri Streams Open-File Report 2009-1138 U. S. D. o. t. Interior and U. S. G. Survey: 57.
7	EnviroFish	Killgore, K. J., et al. 2009. EnviroFish Version 1.0 User Manual (Draft). System Wide Research Program ERDC/EL TR-08- . http://www.mvm.usace.army.mil/stjohns/2009_update/Model_Certfication_Documents/4_Envirofish/EnviroFish_User_Manual_19_Mar_09.pdf

Appendix B: User Base for the Software Packages

Number	Software package Name	User base
1	SacEFT	Version 1. Targeted user base consists of managers and decision makers related to water-planning efforts on the Sacramento River.
2	HEC-EFM	USACE managers. Environmental and engineering consultants.
3	RAP	The target audience was defined as: Water resource managers Consultants Scientists River management community groups Expert Panels Currently, the program does not appear to be actively used or supported.
4	SAM	USACE for bank protection mitigation and evaluation.
5	IHA	Widely used. http://www.nature.org/initiatives/freshwater/files/iha_apps.pdf provides a 20-page list of known applications.
6	HIP/HAT	
7	EnviroFish	BETA. Previous use: Yazoo Delta projects in Mississippi during the late 1990's. Previously used for Mississippi River flood-control projects. Current version not yet in public use.

Appendix C: EFT data available in detailed reports



Water Year	Total Live Nodes (count)
1939	
1940	5
1941	15
1942	8
1943	
1944	
1945	
1946	
1947	
1948	2
1949	
1950	
1951	
1952	14
1953	
1954	3
1955	
1956	6
1957	
1958	8
1959	
1960	
1961	
1962	
1963	5
1964	
1965	
1966	
1967	15
1968	
1969	7
1970	
1971	7
1972	
1973	
1974	5
1975	6
1976	
1977	
1978	4
1979	
1980	
1981	
1982	2
1983	20
1984	
1985	
1986	
1987	
1988	
1989	
1990	
1991	
1992	
1993	1
1994	
1995	4
1996	5
1997	5
1998	16
1999	
2000	3
2001	4
2002	4
2003	8
2004	5

Appendix D: IHA 33 basic indices

Table I. Summary of hydrologic parameters used in the RVA, and their characteristics

General group	Regime characteristics	Streamflow parameters used in the RVA	Examples of ecosystem influences
1: Magnitude of monthly discharge conditions	Magnitude, timing	Mean discharge for each calendar month	Habitat availability for aquatic organisms Soil moisture availability for plants Availability of water for terrestrial animals Availability of food/cover for fur-bearing mammals Reliability of water supplies for terrestrial animals Access by predators to nesting sites Influences water temperature, oxygen levels, photosynthesis in water column
2: Magnitude and duration of annual extreme discharge conditions	Magnitude, duration	Annual maxima one-day means Annual minima one-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means Number of zero-flow days 7-day minimum flow divided by mean flow for year ('base flow')	Balance of competitive, ruderal, and stress-tolerant organisms Creation of sites for plant colonization Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology and physical habitat conditions Soil moisture stress in plants Dehydration in animals Anaerobic stress in plants Volume of nutrient exchanges between rivers and floodplains Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments Distribution of plant communities in lakes, ponds, floodplains Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3: Timing of annual extreme discharge conditions	Timing	Julian date of each annual one-day maximum discharge Julian date of each annual one-day minimum discharge	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats during reproduction or to avoid predation Spawning cues for migratory fish Evolution of life history strategies, behavioral mechanisms
4: Frequency and duration of high/low flow pulses	Magnitude, frequency duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year	Frequency and magnitude of soil moisture stress for plants Frequency and duration of anaerobic stress for plants Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain Soil mineral availability Access for waterbirds to feeding, resting, reproduction sites Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5: Rate/frequency of hydrograph changes	Frequency, rate of change	Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values No. of flow reversals	Drought stress on plants (falling levels) Entrapment of organisms on islands, floodplains (rising levels) Desiccation stress on low-mobility stream edge (varial zone) organisms

Richter et al. 1998.

Appendix E: USFWS redd dewatering table

Table 14. Fall-run Chinook redd-dewatering relationship (U.S. Fish and Wildlife Service 2006).

	3500	3750	4000	4250	4550	4750	5000	5250	5500	6000	6500	7000	7500	8000	9000	10000	11000
30000																	
27000																	
25000																	
23000																	
21000																	
10000																	
17000																	
15000																	
14000																	
13000																	
12000																	
11050																	
10000																	0.9%
9000																2.2%	5.5%
8000															2.6%	6.6%	11.5%
7500														0.8%	4.4%	9.1%	14.1%
7000													0.9%	2.0%	6.6%	11.5%	17.3%
6500												1.3%	2.6%	4.2%	9.8%	15.6%	21.1%
6000											1.2%	2.8%	4.8%	6.5%	12.9%	19.7%	25.8%
5500										1.4%	3.2%	5.4%	7.7%	10.3%	17.6%	24.9%	31.0%
5250									0.7%	2.1%	4.2%	6.8%	9.4%	12.3%	19.8%	27.2%	33.1%
5000								0.7%	1.3%	3.2%	5.6%	8.6%	11.6%	14.7%	22.6%	30.2%	36.0%
4750							0.8%	1.6%	2.5%	4.8%	7.6%	10.8%	14.2%	17.6%	25.8%	33.2%	38.8%
4500						0.8%	1.7%	2.8%	4.0%	6.9%	10.4%	14.2%	18.2%	22.1%	30.9%	38.8%	44.2%
4250					0.8%	1.6%	2.7%	4.0%	5.4%	8.9%	13.0%	17.2%	21.6%	25.8%	34.9%	42.8%	48.0%
4000				0.9%	1.7%	2.8%	4.1%	5.7%	7.3%	11.4%	15.8%	20.3%	24.8%	29.0%	38.0%	45.7%	50.7%
3750			0.9%	1.6%	2.6%	3.9%	5.5%	7.3%	9.2%	13.5%	18.4%	23.1%	28.0%	32.4%	41.5%	48.7%	53.6%
3500		1.0%	2.1%	3.2%	4.6%	6.2%	8.1%	10.1%	12.2%	11.2%	22.2%	27.4%	29.2%	37.0%	45.9%	52.8%	57.3%
3250	1.0%	2.0%	3.4%	4,8%	6.6%	8.4%	10.6%	12.9%	15.3%	20.5%	26.2%	31.7%	37.0%	41.5%	50.2%	56.3%	60.4%

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YYYY)*** December 2010	**2. REPORT TYPE** Final report	**3. DATES COVERED** ***(From - To)***
4. TITLE AND SUBTITLE Review Summary of Selected Software Packages for Ecosystem Habitat and Attribute Modeling		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Eric Larsen		**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Hydrologic Engineering Center 609 Second Street Davis, CA 95616-4687		**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/EL SR-10-XX
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, U.S. Army Corps of Engineers Washington, DC 20314-1000		**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Projects that require analyses of ecosystem response to changing flow regime and other environmental factors can depend on software technologies for modeling. Choosing the appropriate technology is a vital concern for each project. This report is designed to help managers evaluate which models would be useful for specific applications related to assessing habitat and ecosystem functions.

The report describes seven software packages that can be used to study ecosystem habitat characteristics and processes. This information can help managers evaluate models and their utility for specific applications related to assessing habitat and ecosystem functions. This report identifies the seven models and who developed them, describes target applications, and discusses data requirements, ease of use, and the form of the results.

Case studies were performed for two different species: Fremont cottonwood and Chinook salmon. Habitat conditions for Fremont cottonwood (*Populus fremontii)* seedling recruitment were evaluated using five of the models, excluding the fish models. Habitat potential was analyzed with three alternative flow regimes in the time period 1946-1994 in a selected reach of the Upper Sacramento River in Northern California. Habitat conditions related to redd-dewatering, which is a limiting population factor of fall-run Chinook salmon (*Onchohynchus tshawytscha*), were evaluated using four of the models.

15. SUBJECT TERMS

Attribute modeling	Ecosystem functions	Fremont cottonwood
Chinook salmon	Ecosystem habitat modeling	Habitat functions
	Flow regime	

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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