MODELING RESPONSE TO FLOW CHANGES FOR COTTONWOOD INITIATION AND CHINOOK SALMON REDD DEWATERING ON THE UPPER SACRAMENTO RIVER WITH ENVIRONMENTAL FLOW AND ECOSYSTEM PROCESSES MODELING SOFTWARE PACKAGES

Eric W. Larsen

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2nd Street
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Eric W. Larsen
University of California
Department of Environmental Design
Landscape Architecture Program
One Shields Avenue
Davis, California
Phone: (530) 752-8336
E-mail: ewlarsen@ucdavis.edu

ABSTRACT

The management decision-making process benefits from ecosystem process models that evaluate biological habitat characteristics under a range of scenarios. Due to the large scale of ecosystems and of the planning objectives related to ecosystem management, these models tend to integrate knowledge across phenomenalistic and mechanistic approaches, have complex internal relationships and numerous output metrics and results. Understanding the advantages and limitations of applying these models is important for managers aiming to understanding system biotic response to river alterations.

In this paper, we compared the structure and results of four software packages. The software packages were classified into two categories: 1) ecosystem relationships and 2) environmental flows. Ecosystem relationship models simulate biological habitats and how habitats change in relationship to environmental changes, and the habitat suitability assessment is an explicit part of the model. Environmental flow models analyze the changes in the hydrologic flow regime, producing metrics of the flow regime, and the habitat suitability tends to be determined outside of the modeling effort.

This paper applied four software packages to potential habitat modeling for seedling establishment of Fremont cottonwood (*Populus fremontii*) and redd-dewatering of fall-run Chinook salmon (*Onchohynchus tshawytscha*), both of which is are limiting population factors for the respective species. Habitat potential was analyzed with three alternative flow regimes (called Base, Nodos, and Shasta) in the time period 1946-1994 in a selected reach of the Upper Sacramento River in Northern California.

The cottonwood seedling establishment potential habitat results were qualitatively the same for all of the models: the Base flow case had the best habitat with a non-dimensional ranking of 1.0; the Nodos scenario was second with a ranking of approximately 0.8 for all but one model; and the Shasta scenario ranked third with approximately 0.5 for all models but one. These quantitative rankings probably do not reflect the quantitative amount of habitat for each flow scenario, but do suggest that the Base flow scenario provides the most potential habitat, the Shasta scenario provides the least, and the Nodos scenario is somewhere in-between. 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.

Technical knowledge of both cottonwood and salmon life histories played a key role in successfully using all the models. Some models are designed to give simple output indices 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. 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 environmental flow models tended to be most effective as “screening tools,” which allows users to quickly assess generalized patterns, but are not able to be strictly defined in terms of ecosystem processes.

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Introduction

In recent years, as research groups and regulatory agencies have studied 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 that were affected in the past, and with the concern that our current actions may have future effects, mathematical models are a powerful and efficient way of assessing the effect of flow regulations and land-use actions. This review examines four 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 is valuable as a 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. They are publically available. Some have been developed for specific purposes, but can possibly be generalized outside the original area of concern.

A 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.

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 different environmental situations; therefore the habitat suitability assessment is an explicit part of the model. “Environmental flow” models analyze the changes in hydrologic flow and leave it up to the user, outside of the model, to assess habitat suitability and interpret how this will influence ecological factors.

Ecosystems generally refer to a collection of plants, animals, and micro organisms and the physical environment in which they live. 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. 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.

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 flows” 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 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 1997). For environmental flow models, although there is a great deal of technical judgment required to choose the appropriate indicators, and how to interpret the results, the actual data, which are 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. In using the various packages included in this report, updates, error fixes, and an ongoing software support was critical to using them effectively. Additionally, active research that explains or uses the software package is beneficial. For example, we initially used the River Analysis Package (RAP) model (add ref) from Australia, which was potentially a useful model for ecosystem simulations, but adequate software support and documentation was not available.

This paper first introduces each of the models and identifies who developed the model. The appendices list selected references and resource papers for each model and a simple description of the user base. Each of the models is applied to modeling habitat requirements for cottonwoods and Chinook salmon, and the changes in potential habitat with three different flow regimes are analyzed.

Models

Many agencies and organizations (e.g. TNC, USGS, 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 functions) 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 models are listed (Table 1 and Table 2). Selected research citations and appropriate resource papers (Appendix 1) and a brief description of the intended and practicing user groups are also listed in Appendix 2.

		Model Name	Simulate/Purpose	Input data	Application	Notes
1	**Ecosystem Processes**	SacEFT	Evaluates habitat changes resulting from flow-related management strategies on the Sacramento River.	• Flow time series* • Selected cross section profiles* • Stage time series at cross sections*	Six defined focal species on the Sacramento River	Pre-defined focal species. Relationships currently pre-defined. Program only 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	Allows definition of any relationship	Able to be generalized to any application. Accepts HEC RAS input. Outputs easily visualized in GIS.
3	**Flows**	IHA	Environmental flows.	• Flow time series	Instream flow evaluation. EFC for evaluating flow-ecology relationships	Produces hydrologic indices. General for flows. Includes EFC[+] for flow-ecology linkage.
4		HIP/HAT	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.

Table 1 Software packages: general characteristics

These software packages can be used for flow-related ecosystem response modeling: general characteristics. *These data are not required by the user, but are pre-supplied by the software. Future versions plan to allow user input. [+] EFC are “environmental flow components.”

	Model Name	**Developing agency/group**	**Years available for public use**	**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	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	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.
4	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.

Table 2 Software packages: use information

Software packages use availability and use information. [*]In many cases, the programs were in use before the technical date of public release.

Sacramento River Ecological Flows Tool (SacEFT)

The Sacramento River Ecological Flows Tool (SacEFT) grew out of a "*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 that were done to understand the physical and biological processes that determine the riparian habitat of the Sacramento River, the SacEFT was developed as a tool to integrate ecological information about terrestrial and aquatic species with water-planning processes that involve changes in the flow regime.

"*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 logging into the database operated by ESSA technologies. The interface is easy to understand, and should be very easy for managers and non-technical users to accomplish runs. It is currently specific to the Sacramento River, and the flows, focal species, and relationships are all pre-defined and can be viewed in the model. Future plans include users being able to modify or define relationship parameters. 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. More detailed data are available for the cottonwood relationship with tables that can be defined and retrieved from the main menu. The metrics that led to the poor-fair-good ranking are recorded in the tables, and can be used for further analysis. SacEFT is a new model and has not had time to develop a track record of use, research

SacEFT is designed for water-management decision makers to evaluate the effects of flow regime changes on ecosystem processes of selected species. Although the program is in the first phase of use and will be changed, it is easy to use by a non-expert 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. The Version 1 software is currently specific to the Sacramento River ecosystem relationships.

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

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, the model analyzes scenarios using “functional relationships." Once the flow time series is input, the four basic criteria for the functional relationship that are analyzed are 1) season, 2), flow duration 3) rate of change, and 4) flow frequency.

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. Relationships may be defined for aquatic or terrestrial species of plants and/or animals. The default output gives a single number for stage or flow. In the case of cottonwood recruitment, it gives the stage (defined to be the flow that occurs once in 10 years, which is #2 above: flow frequency) at which recruitment is successful, based on recession rate (i.e. #4 above: rate of change) and seasonal timing criteria (#1 above: season).

EFM also has a plotter that helps users quickly visualize and interpret the data and the output from the EFM software. This streamlines quick manipulation of the data. There are standard graphs and an option to create custom graphs. HEC-EFM is one of the USACE free software packages available through the HEC center. It is actively supported and undergoing regular updates. It is currently being used for USACE projects, as well as by consultants.

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

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 to be related to the physical make-up of rivers. Currently, the HIP process for general use is entirely contained in 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, Henriksen et al. 2009) called MOHAT.

HAT has been designed to be used in general settings outside New Jersey or Missouri. HAT (NATHAT) is useable as a single program, but requires the user to define which indices are 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 assesses changes in stream flow characteristics due to changes in environmental factors.

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 of the indices are chosen for analysis and viewing.

Like the other software packages, HAT is 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.

Methods

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 else 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]; **Error! eference source not found.**) based on different hypothetical reservoir operations on the Upper Sacramento River, California between Redbluff and Colusa (), again patterned after input data develop for the SacEFT (The Nature Conservancy 2008).

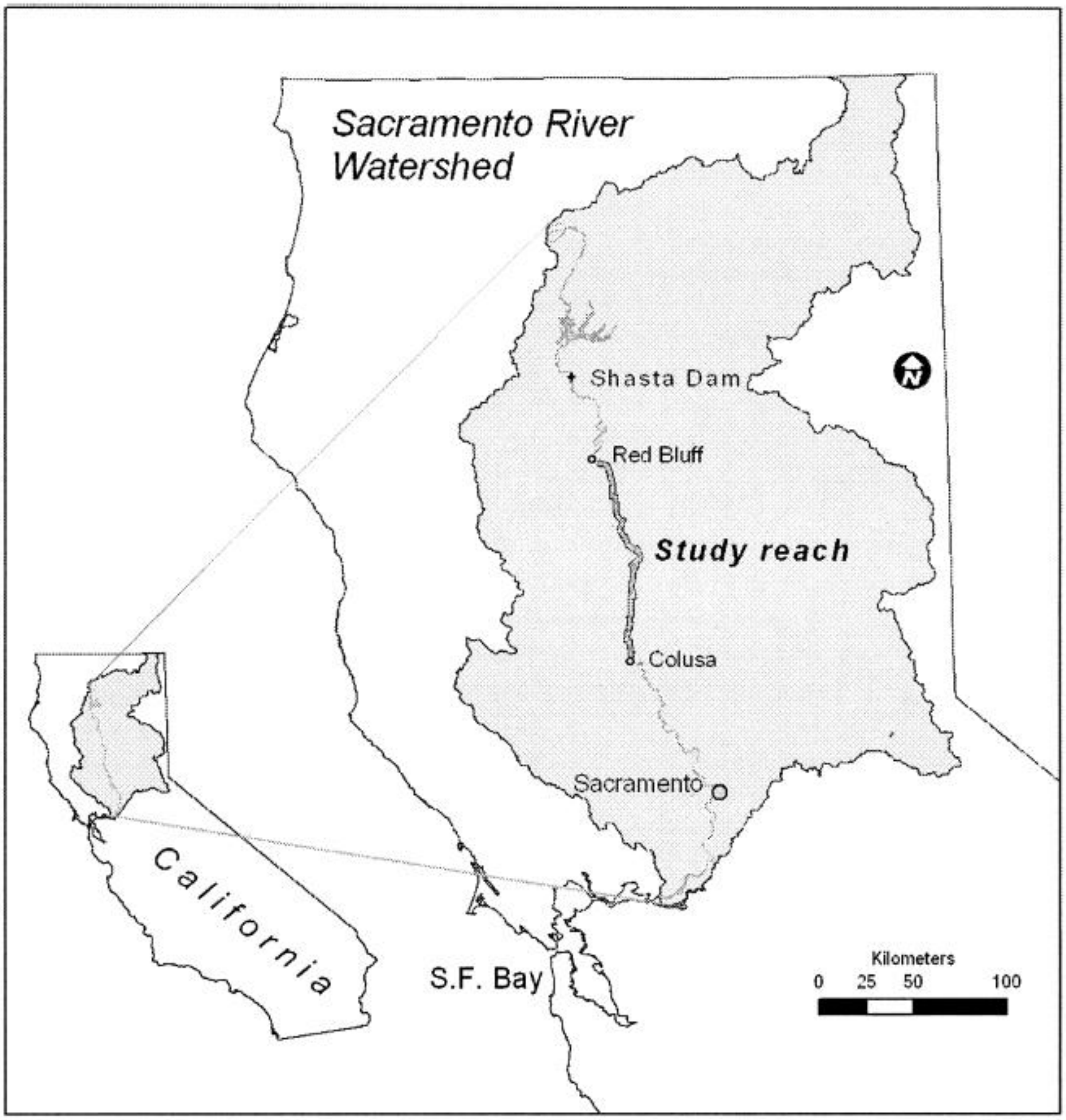

Figure 1 Sacramento River study area

The fall-run Chinook salmon redd-dewatering relationship that was used by SacEFT and which we 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 1996), 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 1996). 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. We used these curves in our analyses.

Flows

On the Sacramento River, extensive gauged flow data are available for the upper Sacramento River below Keswick Dam (River Mile (RM) 301.4), near Bend Bridge (RM 260.3), at Woodson Bridge (RM 218.3), at Hamilton City (RM 199.3), at Ord Ferry (RM 184) and at Butte City (RM 168.6) from which observed flows from Water Year (WY) 1946 to WY 1994 were used. Two additional flows series were developed that cover the same time period, but represent two different hypothetical reservoir operations: NODOS (the proposed North of Delta Offstream Storage facility, or Sites Reservoir) and Shasta (the proposed 18.5 ft height increase for Shasta Dam) (The Nature Conservancy 2008) (Figure 2 and Figure 3). Because environmental-flow-type analyses tend to key on pre- and post-dam issues and because a dam was installed in 1945, we chose a time segment that excluded the pre-dam flows. In addition, there were no modeled flows for the NODOS and Shasta scenarios past WY 1994, and only data up to that point were used.

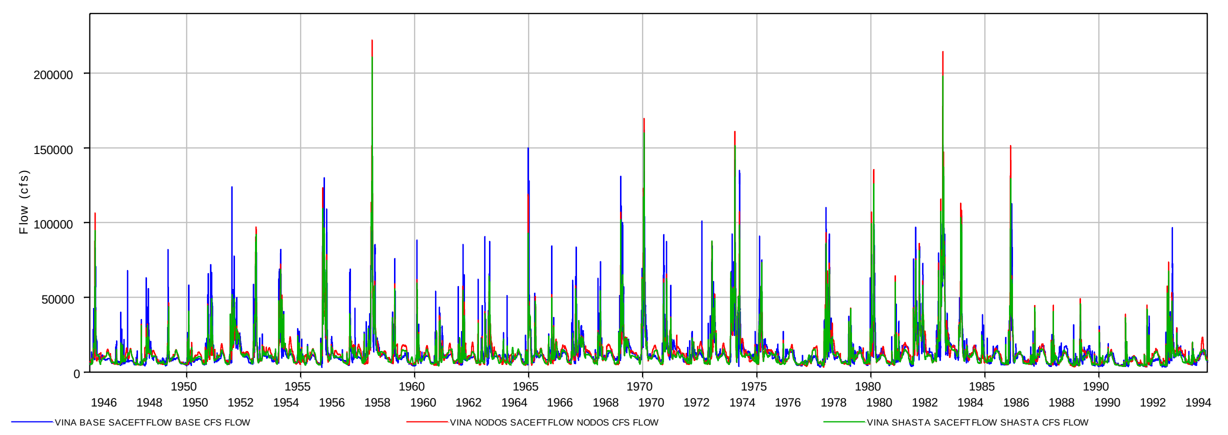

Figure 2 Base, NODOS, and Shasta flows 1946 to 1994

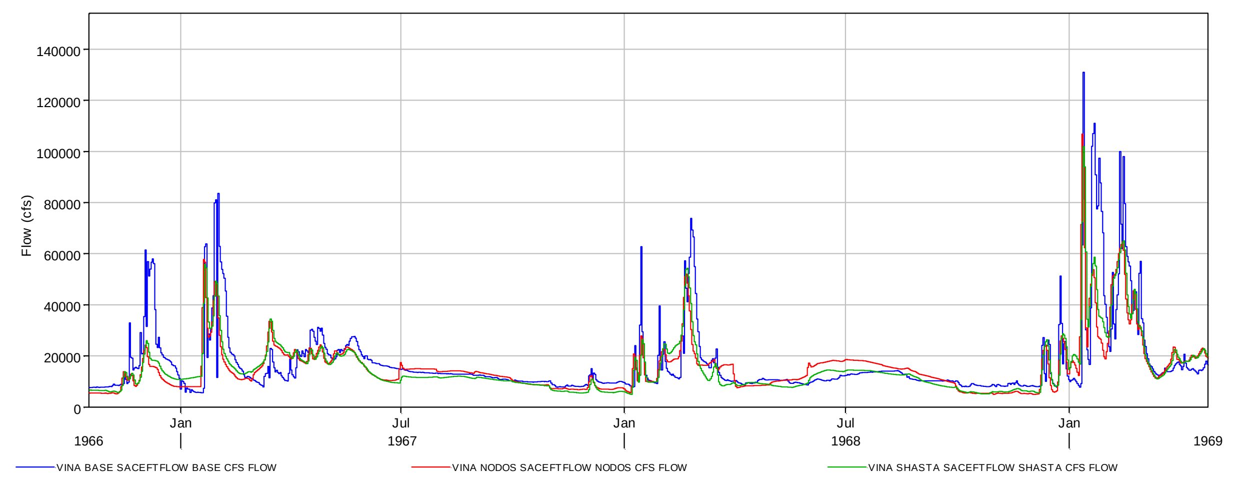

Figure 3 Base, NODOS, and Shasta flows; a sample of data from 1966 to 1968

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 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 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. The results for total number of nodes were used for the final comparison with other software packages (figure ref). 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.

In order to have a different discrimination than the poor-fair-good allowed, a sum of total number of appropriate nodes from 1946 to 1994 was used as the metric for assessing the relative potential for cottonwood establishment. This is not a metric that is reported in the standard summaries, but was derived from the available annual report. Figure 4 shows the total number of potential recruitment nodes for each of the flow scenarios.

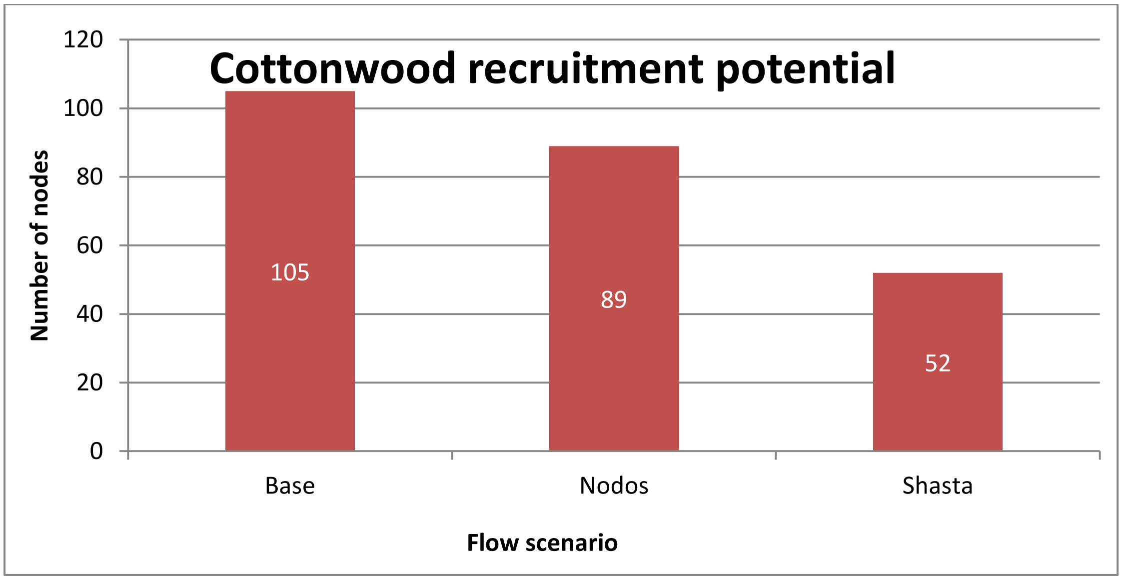

Figure 4 Number of potential cottonwood recruitment nodes in SacEFT run

In seeking an overall evaluation, the total number of nodes of suitable habitat over the entire time period reports the results in a different way from the multi-year roll-up.

Figure 4 suggests that the relative potential habitat of the NODOS case (flow scenario 3a) is 85% that of the Base case (1a), and that the Shasta (4a) is 50% of the Base case. Because the flows in the three scenarios only slightly differ in magnitude, it is questionable whether the habitat would differ to such a great degree (Fremier NODOS paper ref). An alternate interpretation is that the overall habitat potential is qualitatively ranked in the order shown in Figure 4. As we will find with all the software packages, these modeling efforts produce a general view of the habitat quality, without precise detail. As with all the software packages, because the *quantitative* evaluation is in reality a quantity based on set of rules that approximate habitat dynamics, the numbers that result are more precise than accurate. A final *qualitative* evaluation seems most appropriate.

The results may be a consequence of one of the defined habitat rules in preference to the others. It is unclear what role the chosen stage (based on discharge 8500cfs elevation + 3ft *(ref))* has in determining the final outcome. It is not clear why this single discharge would be the only one evaluated for cottonwood seed recruitment and initiation.

"Riparian initiation calculations are by their nature highly site-specific, tied to the index cross sections and the specific stage-rating curve. Thus, a key assumption for more general flow prescriptions is that the index sites chosen are representative of the focal habitat one would like to see initiation and establishment occur in throughout the larger management area. Some of the other details of the model (tap root growth rate, 45cm "safe" taproot length, capillary fringe depth, etc.) are other user configurable assumptions. The code used was originally developed for use by cottonwood experts for flow prescription development in the Trinity River Restoration Program (John Bair, McBain & Trush)"[2].

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[2] Pers com Clint Alexander, ESSA Technologies 10/13/2009

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 14. 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.

Chinook salmon EFT dewatering

	% Poor	% Fair	% Good
Base flow	33	29	38
Nodos flow	12	51	37
Shasta flow	27	34	39

Table 3 EFT “rollup” results for fall-run Chinook Salmon

In order to compare these results with the output from the other models, we developed a non-dimensional rating system similar to the one we 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 5, 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 5) to compare with the results from the other software packages (Error! Reference source not found.).

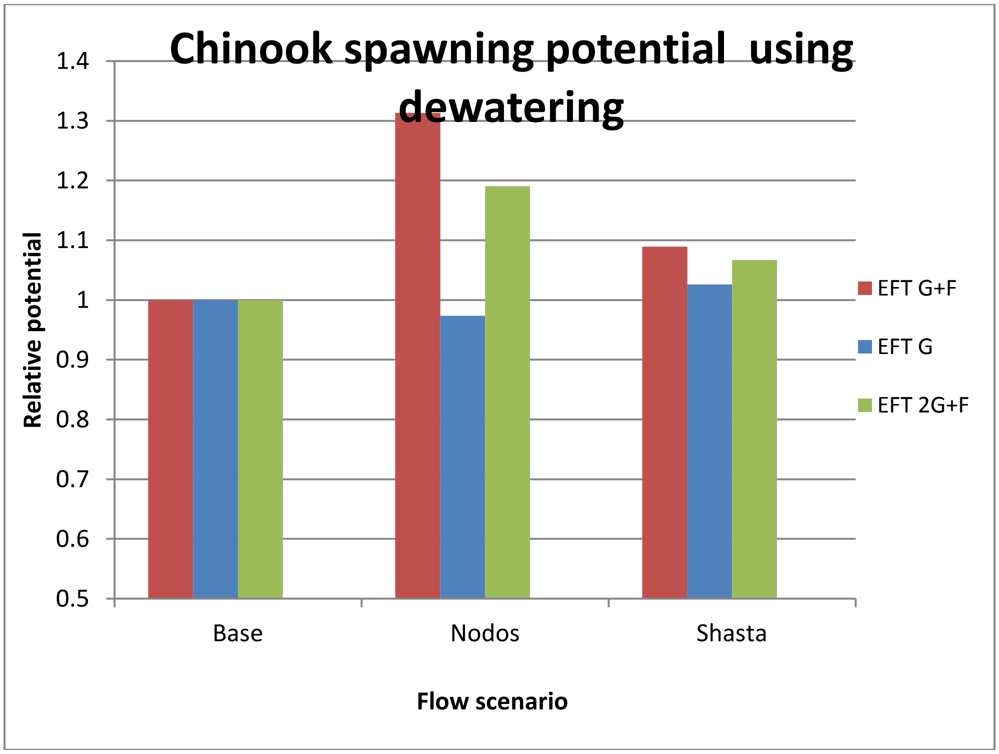


Figure 5 Chinook spawning potential non-dimensional comparison for EFT results

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 then results in two numbers that can be inserted into the dewatering lookup table (USFWS 2006). Each combination of flows returns a percent dewatered. The conceptual model is 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. There are a number of statistics that can be used to establish the resulting discharges. We used three: the 20% exceedance, 50% exceedance (5-yr and 2-yr recurrence intervals), and the mean.

	20% exceedance (5-yr flow)			**50% exceedance (2-yr flow)**			**Mean**		
	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%

Table 4 HEC EFM Chinook fall run dewatering output analysis results

The inverse of the percent dewatered was non-dimensionalized, plotted, and the different methods were compared to each other (Figure 6), and used in the final comparison (**Error! Reference source not found.**). The inverse was used because the more dewatered, the less the good habitat, and the final metric was chosen to represent the good habitat.

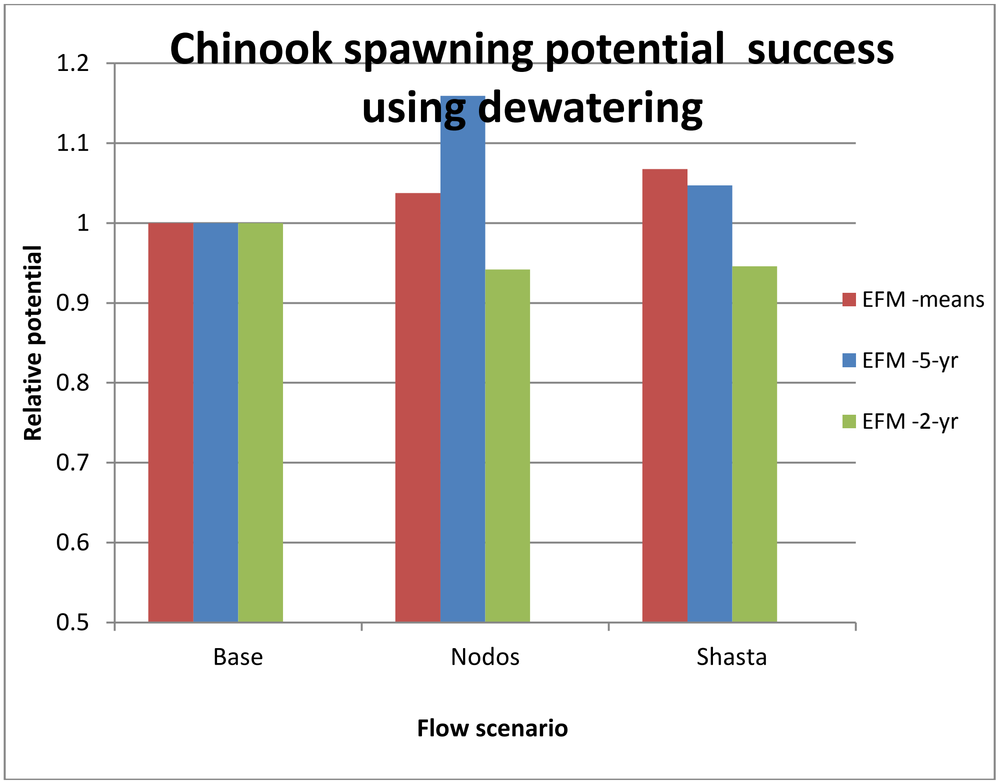


Figure 6 HEC EFM Chinook fall run dewatering output using different flow frequencies

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 ten 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 (10-year recurrence interval flow, or stage) is better than a lower 10-yr 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 ten years (Table 5). In the case of the cottonwood relationship, these default output are difficult to interpret. For example, it is not clear whether a higher 10-yr flow (stage) indicates better or worse habitat conditions.

	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

Table 5 HEC-EFM sample summary output table

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 6.

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

Table 6 HEC-EFM results for cottonwood seedling recruitment

These results were plotted in comparison to the results of the other software packages (**Error! eference source not found.**), where non-dimensionalizing the results allows a comparison where the Base case is represented by 100% in all the models.

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. We selected a set of IHA indices and applied them to various weighted combinations to evaluate cottonwood seedling recruitment habitat. Three different hypotheses were considered: 1) the faster the flow recedes, then 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 fallrate*” 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 fallrate*” is 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, we have counted the number of “killing” fall rates (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, we subtracted the number of killing rates in a specific scenario 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.

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

Equation 1 Composite index for cottonwood seedling initiation for use in IHA

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 that 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 per 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.

		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 7 IHA statistics for evaluating Cottonwood recruitment potential

	Weighting factors			**Composite Index value**		
Graph name	**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

Table 8 IHA Composite index of Cottonwood recruitment potential

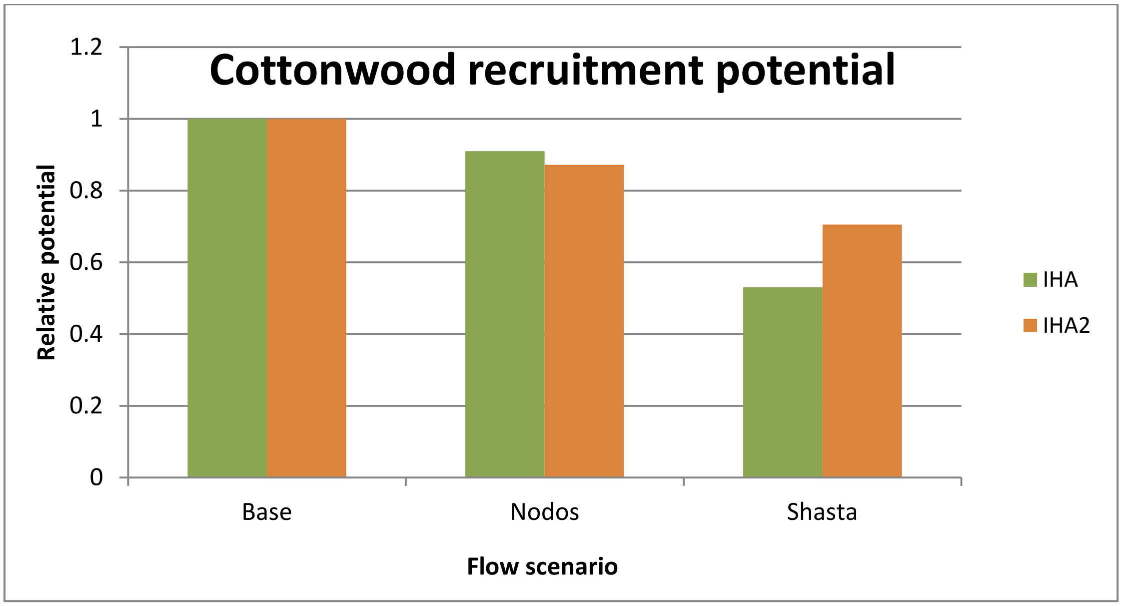


Figure 7 Cottonwood recruitment potential

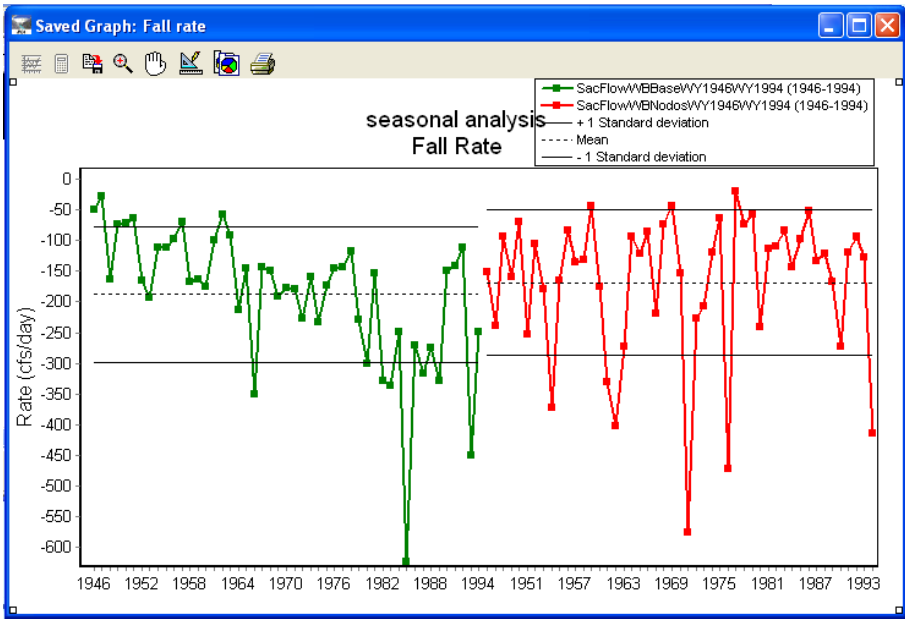


Figure 8 IHA Seasonal analysis of mean fall rate
This is for Base and Nodos (Note: the data used for cottonwood recruitment assessment was taken from the dotted lines, which is the mean fall rate in the recruitment season.)

Figure 7 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).

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. We used IHA 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. We used the tabular data, processed with some additional mathematical steps, to develop the dewatering table. For the third method we used standard IHA indices and sought a parameter that could measure flow decrease, because redd dewatering increases monotonically with higher flow decreases.

We used the same life-history conceptual relationship as we did in the previous cases. The first part of the IHA analysis was to examine the average flow in the season for the egg laying (October 1 to December 31). Next we examined flow decreases following the egg-laying. 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 (**Error! Reference source not found.**) as 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, we chose to use a statistical measure (the mean and the median of the entire 49 year record) of the flow in the egg-laying season to characterize the egg-laying flow. This is the same statistical value calculated in EFM. Following this step, we used the data in IHA 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 the minimum that occurred sometime in the 60 days after the specific date of egg-laying.

We used both the mean value of each of the egg-laying Q and the incubation period minimum, and then the median. Based on the values of the Q’s, we entered the look-up table and calculated the percent of redds dewatered.

	Mean			Median		
	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%

Table 9 IHA redd dewatering

We looked for IHA indicators that represent flow decreases. 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.

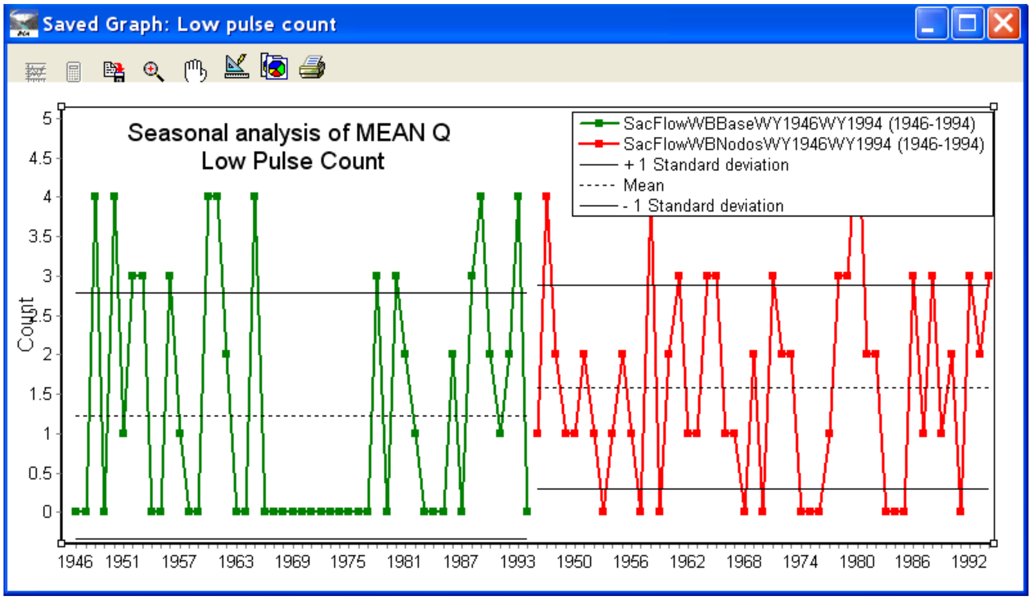


Figure 9 IHA low pulse count

Base	60
Nodos	78
Shasta	64

Table 10 IHA seasonal low-flow pulses over 49 years

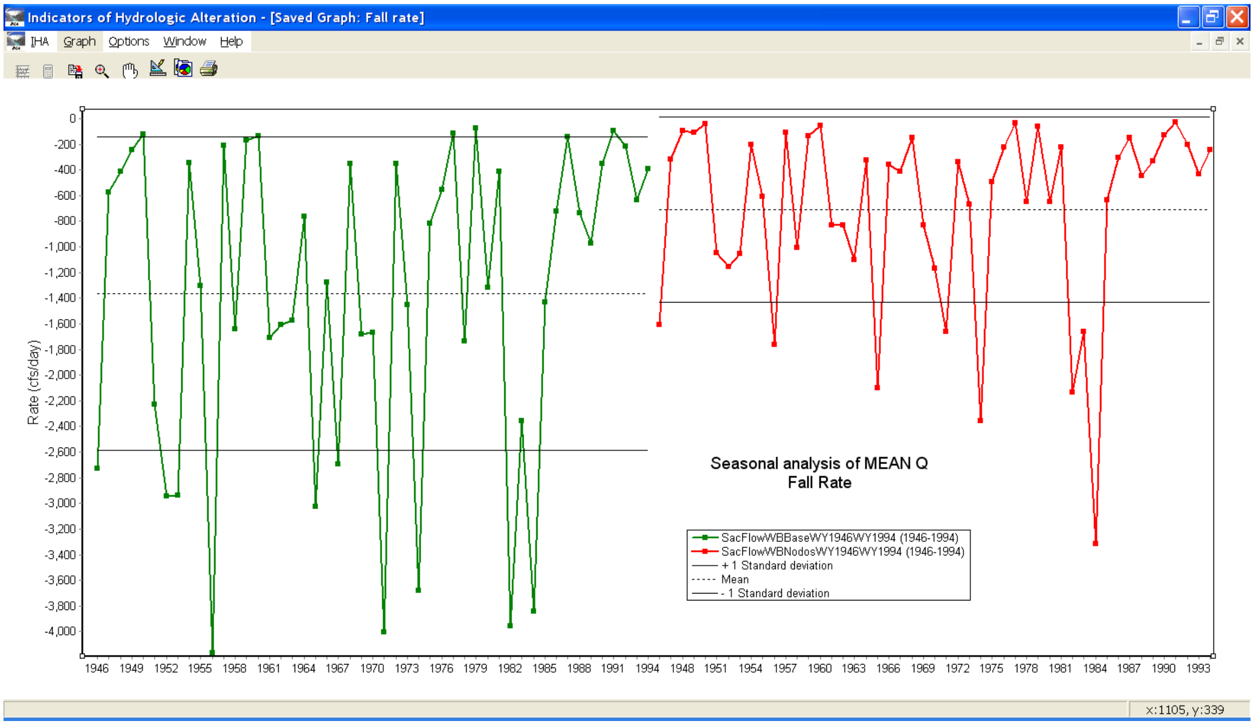


Figure 10 IHA seasonal fall rate

Base	-13144
Nodos	-6458
Shasta	-6646

Table 11 IHA sum of fall rate over years of record

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.

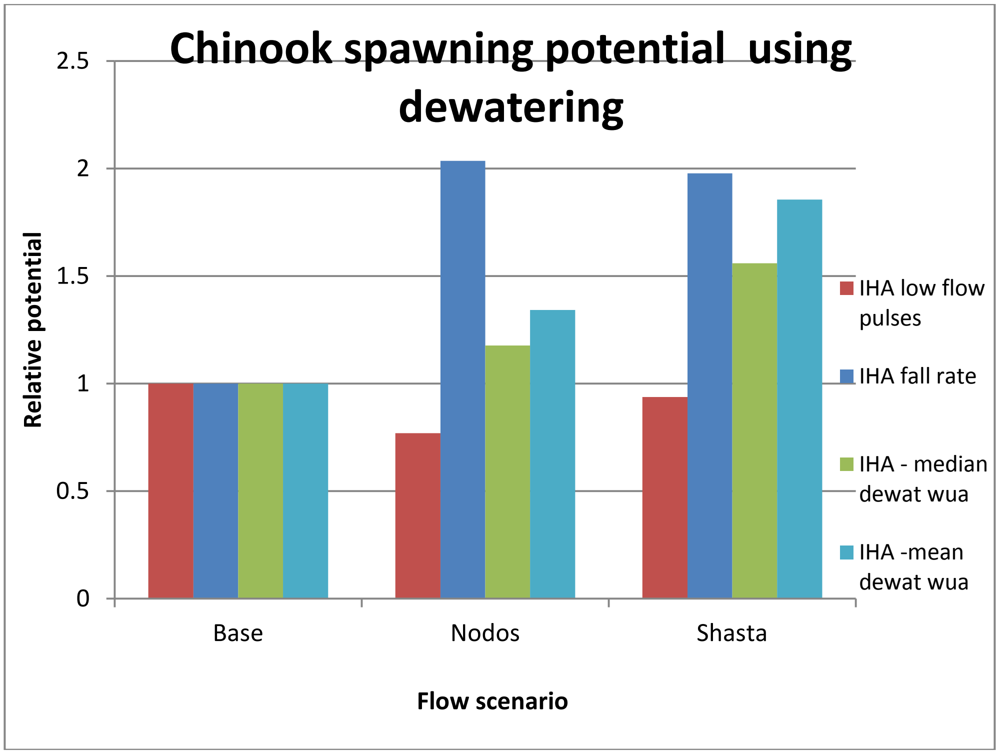
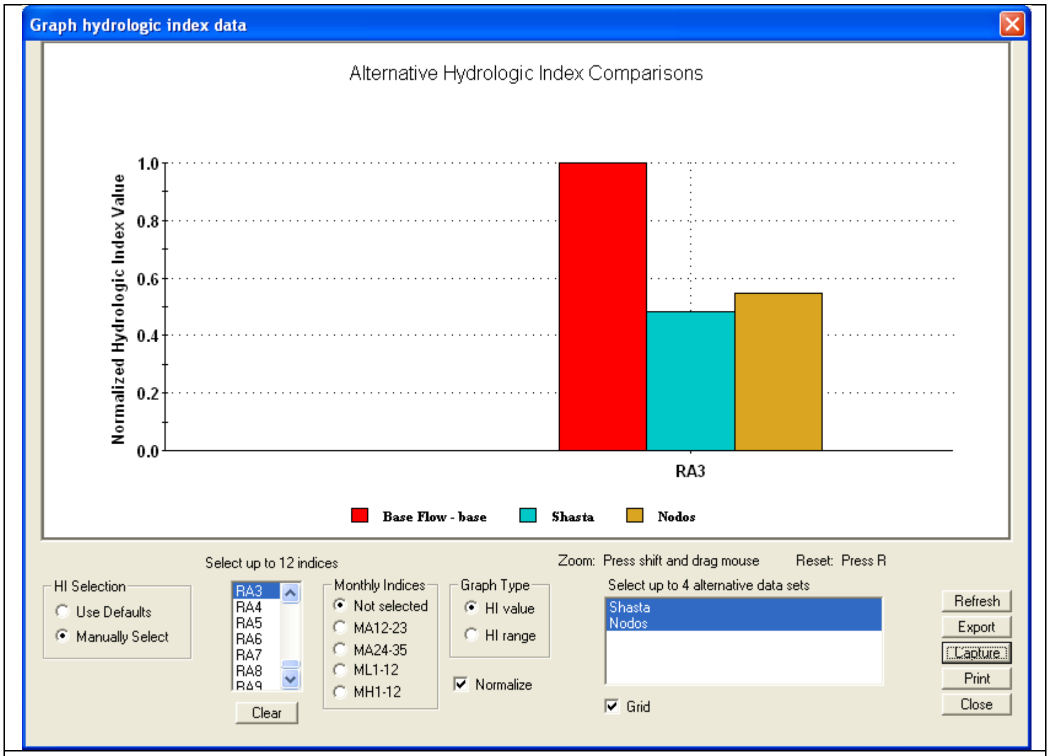


Figure 11 IHA dewatering analysis

HIP/HAT

In applying the HAT to the cottonwood recruitment example scenario, it was necessary to study the definitions of the pre-defined indices and to choose one or a combination of indices that seemed applicable to the problem. After assessing different combinations, a single index (RA3) seemed the most appropriate, which was the mean rate of flow fall for those days when the flow reduces (Figure 12). This is almost the identical approach to the one taken with IHA, but it is less versatile and less precise than IHA, because it does not have a way to use an average limited to the recruitment season. It differs also in that it is the average only on the days when the flow reduces.



	Base	Shasta	Nodos
Value of indices	1	0.483	0.548

Figure 12 HAT output
This output shows the hydrologic index for mean rate of flow fall for those days when the flow reduces

The information used was less precise than that for IHA, because a seasonal average was not available. We are limited to using single or groups of indices that must be defined for our target species. In the case of cottonwood, this was not very precise in the case of HAT. The qualitative relationship between the potential habitat under different flow rates is the same as for IHA: Base is best, NODOS is second, and Shasta is third.

Summary results for Freemont cottonwood

The recession rate is the common factor in these relationships. If one even takes the average for the whole year, not limited to the recruitment season, the qualitative results seem to be quite similar as they are for a more complex relationship that includes things included by EFT and EFM. EFT and IHA are almost identical. All of the packages show that the Base flow case is the best; the NODOS and Shasta follow in that order.

This figure shows the non-dimensional results of modeling the potential for seedling recruitment habitat for the four software packages.

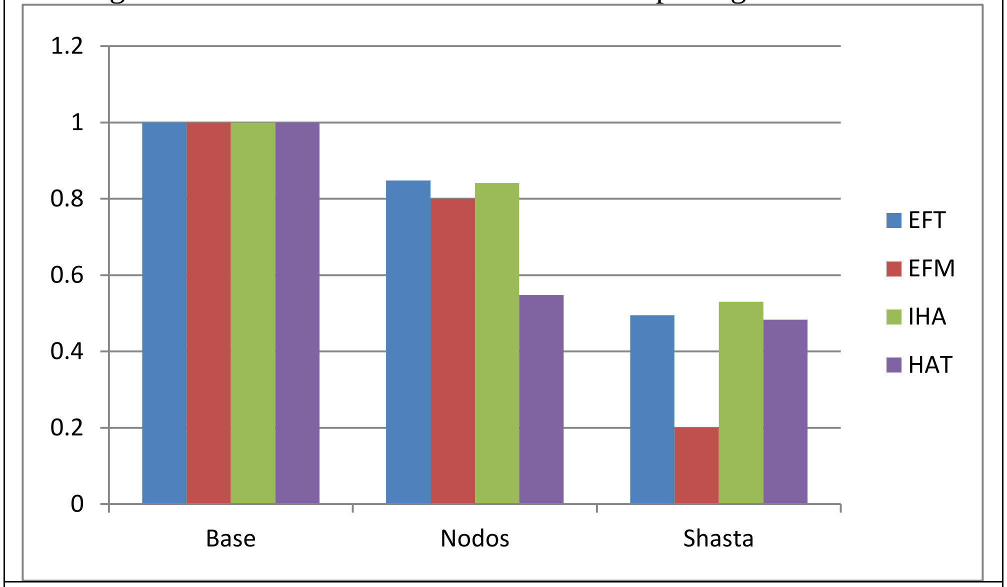


Figure 13 Cottonwood seeding establishment
Results of evaluating potential Cottonwood seedling establishment with four software packages

Chinook salmon redd dewatering methods and results

Chinook salmon (Onchohynchus tshawytscha) have different populations called “runs” to characterize when their typical spawning occurs. In California, there are five “evolutionarily significant units,” or ESU’s. The Central Valley fall-run was once was the most abundant run in California, spawning in streams tributary to the Sacramento and San Joaquin Rivers in Northern California (Moyle 2002). Now populations are severely limited, and understanding habitat preferences is an important issue.

The life history of fall-run Chinook has adapted for spawning in lowland reaches of big rivers and their tributaries. Fall-run are named for the timing of the spawning runs of adults. The mature adults move in from the ocean beginning in June and travel up the Sacramento River. The time for spawning is October 1 to December 31. The spawning fish stay on the redds a few days or weeks. The eggs remain in the spawning gravels to mature and young fish emerge as juveniles. The period for this averages 60 days and emergence can occur from Dec 1 to March

31. Juveniles then rear for some period of time and subsequently move downstream and out to the sea (Moyle 2002).

The basic strategy for spawning seems to be that the fish time their spawning in the Sacramento River and its tributaries so spawning just precedes the high flow time period. This strategy makes it possible to avoid being washed away by high flows. At the same time, the fall weather may provide cooler than summer temperatures for the spawning fish. In choosing to focus on only one salmon parameter, we considered redd dewatering rather than spawning habitat or other possible limiting factors for two reasons: 1) at existing population levels, spawning habitat is not having a population-level effect because spawning habitat is not currently a limiting factor, while redd dewatering will have an impact on any population size, since it is based on the percentage of dewatered redds; and 2) under current Sacramento River operations, flow fluctuations, with their effect on redd dewatering, probably have a much bigger effect than the actual flow levels, since spawning habitat is maximized at relatively low flows.

A conceptual model of the link between redd dewatering and population impacts follows. Eggs may be laid at any flow during the spawning period. Correlating 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 reduces flows, the eggs die.[3]

The dewatering relationship that was used by SacEFT and which we 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 (ref). The U.S. Fish and Wildlife Service developed habitat suitability criteria for redd dewatering based on depth, velocity and bed exposed as described below.

USFWS assumed that there would be reduced survival of eggs or pre-emergent fry, and thus spawning habitat would be lost, if the tailspill was exposed or if velocities dropped to the point where there was insufficient intragravel flow through the redd….Ssince the USFWS needed to pick a single value of the difference between the tailspill and redd depths for the redd dewatering analysis, they selected the average difference for fall-run chinook salmon (0.5 foot) … redds with redd depths less than 2 feet. If the tailspill is 0.5 foot higher than the depth at the head of the pit (the depth used to compute spawning habitat), chinook salmon spawning habitat would be lost if the spawning depth fell below 0.5 foot. … The USFWS assumed that there would be insufficient intragravel flow through the redd if the spawning velocity was less than the lowest velocity at which they found a fall-run, late-fall-run or winter-run chinook salmon redd in the Sacramento River.[4]

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[3] *U.S. Fish and Wildlife Service. 2006. Relationships between flow fluctuations and redd dewatering and juvenile stranding for Chinook salmon and Steelhead in the Sacramento River between Keswick Dam and Battle Creek. Report prepared by the Energy Planning and Instream Flow Branch, U.S. Fish and Wildlife Service, Sacramento, CA. 94p.*[3]

[4] From dewatering report 2006

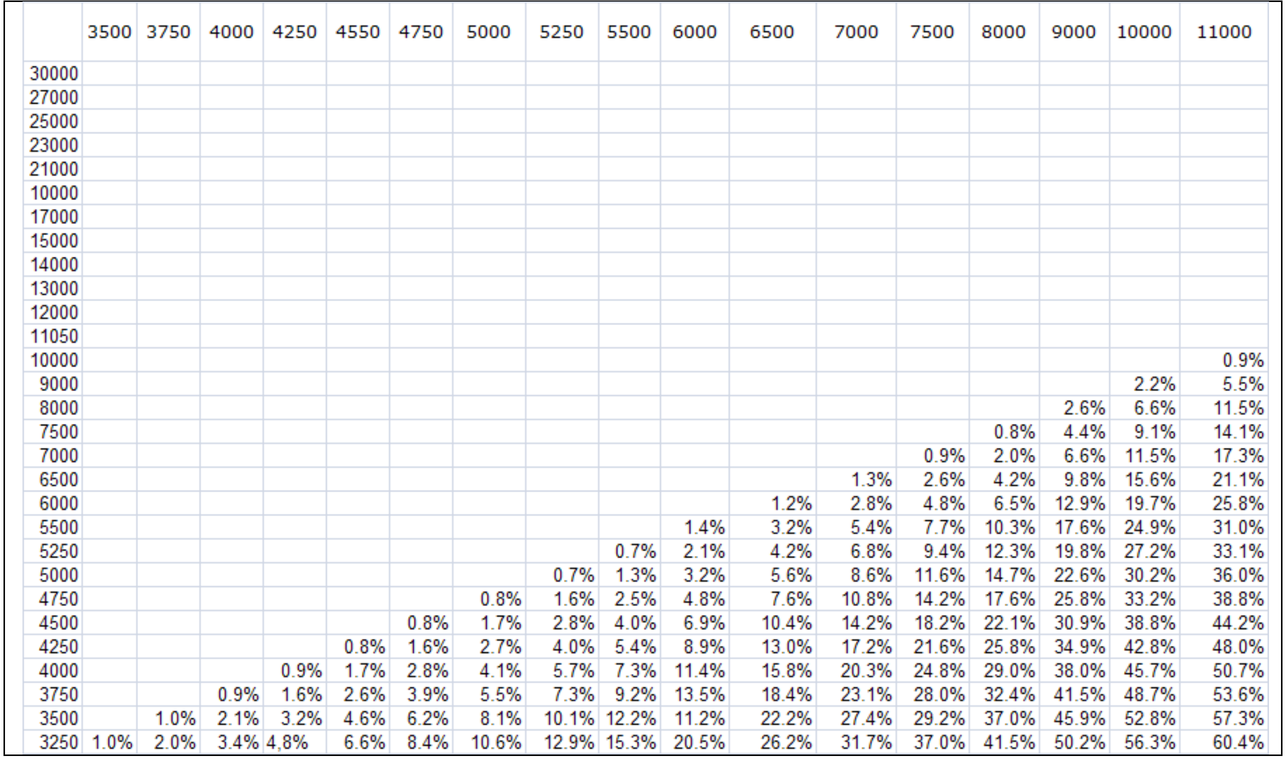
The table below summarizes the habitat suitability criteria described above.

Water Velocity (Ws)	SI Value	Water Depth (ft)	SI Value	Channel Index Value	SI Value
0.00	0.00	0.00	0.00	0.00	0.00
0.31	0.00	0.50	0.00	1.00	1.00
0.32	1.00	0.52	1.00	100.0	1.00
100.0	1.00	100.0	1.00		

Table 12 Redd Dewatering HSC Fall-run Chinook Salmon
(Table 9 USFWS 2006)

The redd dewatering relationship used in the current study was taken from the relationship that the U.S. Fish and Wildlife Service developed for a location between Mill and Deer Creeks, (their section 2) near river mile 223. The flow data that are used in the current study are from a gaging station at Vina/Woodson Bridge, which is located at RM 218.3, as described above. Therefore, the sites where the dewatering relationship and the flow data were collected are relatively close to each other, and making analyses using these two data sets seems reasonable.

Based on the habitat suitability criteria (HSC) in Table 12, the USFWS developed a lookup table that can be used for determining the percent area dewatered given the egg-laying flow, and the minimum flow in the incubation period following egg-laying (Table 13).



	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%

Table 13 Fall-run Chinook redd-dewatering relationship (U.S. Fish and Wildlife Service 2006)

Sac EFT

As discussed, EFT has a predefined set of relationships and output at this time, and because the relationships are fixed we used the EFT relationship details as the "default" for the other models, in order to reasonably compare the use and output of the various models. *Redd dewatering in EFT is measured on a location-and species- specific basis by estimating the proportion of spawning habitat lost when discharge declines to some lower flow after the spawning day and before the emergence of juveniles. Because redd locations are fixed, it is possible to calculate the proportion of redds dewatered during the spawning and development period.*[5]

Sac EFT assigns red/yellow/green to a habitat characteristic such as redd dewatering for a single year, or for the cumulative period in the "roll-up" view. The boundaries for these categories were established based on ….. (Don Robinson, Clint – what were they based on?).

The final "roll-up" results for the SacEFT analyses are shown in Table 14. These data show that the Base flow scenario has the most "poor" potential habitat; the "good" habitat is almost identical between all three scenarios. The Nodos flow scenario has the most "fair" habitat.

Chinook salmon EFT dewatering

	% Poor	**% Fair**	**% Good**
Base flow	33	29	38
Nodos flow	12	51	37
Shasta flow	27	34	39

Table 14 EFT "rollup" results for fall-run Chinook Salmon

In order to compare these results with the output from the other models, we developed a non-dimensional rating system similar to the one we used for the cottonwood, where the values for all three flow scenarios are non-dimensionalized by the base value. For example, in Table 14 the 1.0 for the (G+F) Base flow scenario is $(38+29)/(38+29) = (G+F)_{Base}/(G+F)_{Base}$; in that case, the Nodos value is $(37+51)_{Nodos}/(38+29)_{Base} = (G+F)_{Nodos}/(G+F)_{Base}$.

We tried different weighted combinations of the good and fair percentages to consider what the best would be to compare model results with other models. The columns labeled "EFT G+F" represent the percent good+ percent fair; with this comparison we see that the scenarios are ranked (best to worst): Nodos, Shasta, Base. "EFT G" shows the percent good only; the results show relatively equal habitat quantity. The columns labeled EFT 2G+F represent a weighted average of the good and the fair, with the good given twice the weight of the fair; the pattern is the same as the Good+Fair, but has less extreme differences.

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[5] From eft web description

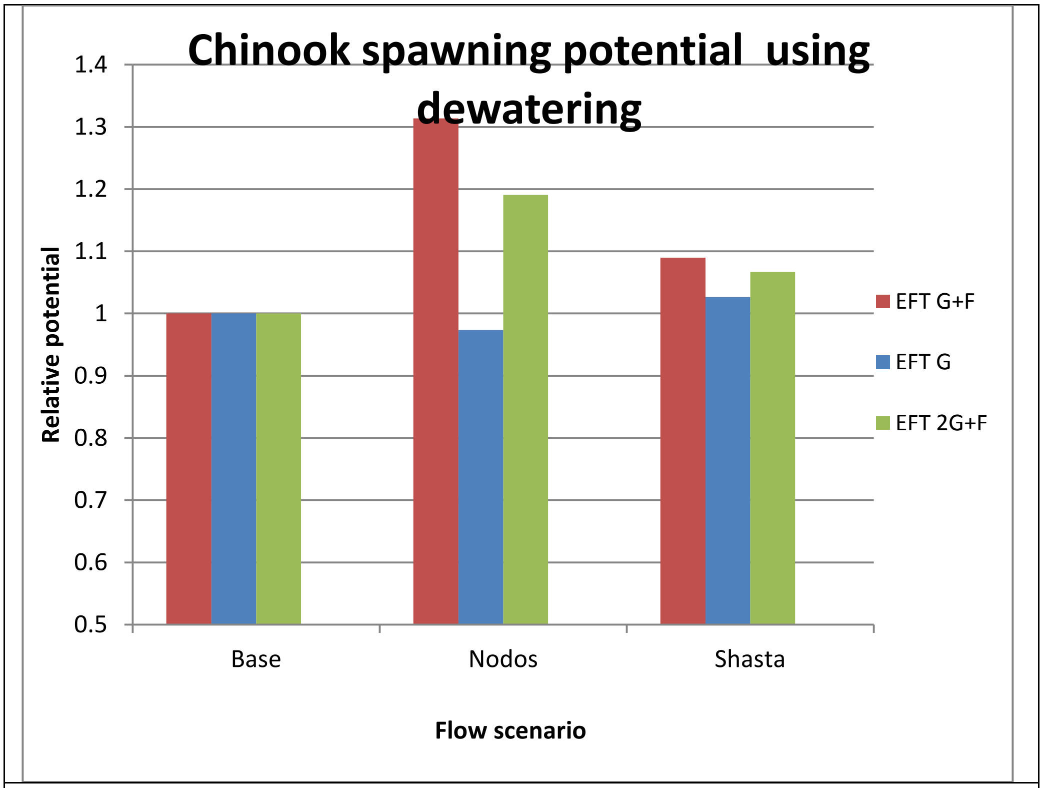


Figure 14 Chinook spawning potential non-dimensional comparison for EFT results

HEC-EFM

HEC-EFM can accommodate a wide range of user-defined relationships. One of its strengths is that a user can build a functional relationship model based on technical knowledge of the life history and other factors of a species. The flow and stage input data are combined with the four basic statistical criteria to define a functional relationship.

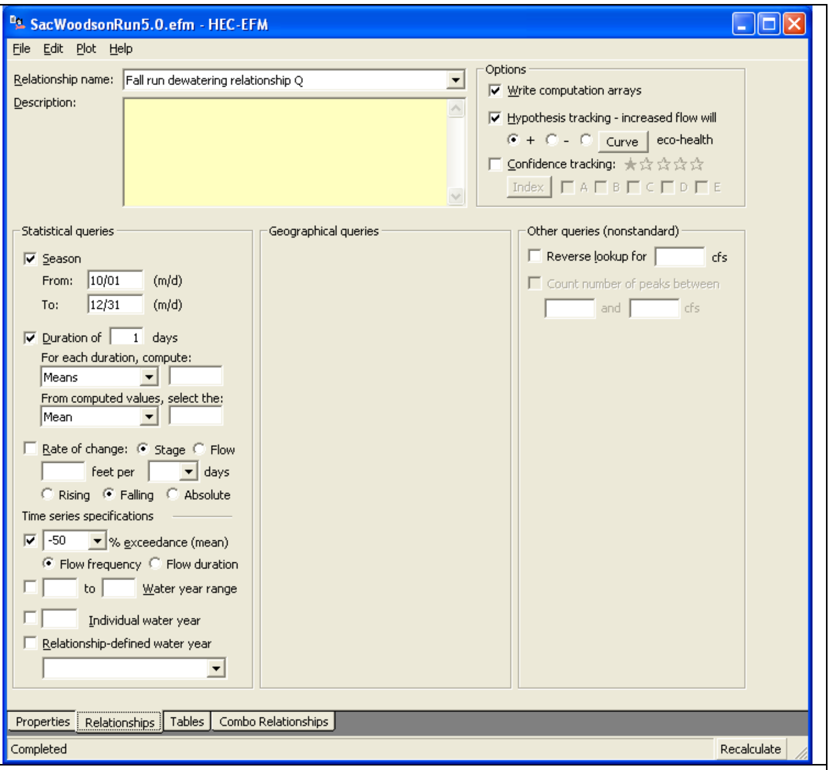
In EFM, the dewatering relationship was defined in the following way. We first look at the flow in each single day of the egg-laying season, which was defined as October 1 to December 31. Then, from each day, we look at the minimum flow that occurs anytime in the interval 60 days after the eggs are laid. This then gives us two numbers that can be inserted into the dewatering lookup table (USFWS 2006). Each combination of flows returns a percent dewatered. The idea is that eggs can be laid in gravels that become exposed or so dewatered that the reduced flows cannot support the egg survival.

In EFM model use (see EFM entry screen shot (Figure 15), determining the dewatering relationship is a two stage process. The first stage is to determine a single number that represents the discharge in the egg-laying season. In the EFM methodology, you first choose a season, which is October 1 to December 31 for the egg-laying season. For each of the days in the season (in the model you input “duration” = 1), you take the discharge on that day (“*For each duration, compute*:” **means**. Note that if you say mean, median or minimum in this box, you will get the same answer, because there is only one discharge on that day.) The next step is to “*From the computed values, select the*:” We take the mean value here. This means that EFM will take the mean value of the discharges in the egg-laying season, for each of the 49 years of record. This is the seasonal result. In the last entry we select the mean of all those values (*Time series specifications*: "-50" returns the mean.)

Method of selecting the representative Q at which eggs are laid:

- Look at a single day, and take its value (duration 1, mean)
- Then take the mean of the entire season.
- Take the mean of the 49 years of record.

[mark said: I think a better way to look at the results from this would be to graph cumulative habitat exceedance, the same way you would do a flow-exceedance curve but with habitat instead of flow]



Relationship name: Fall run dewatering relationship Q
Description:

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

Statistical queries
☑ Season
From: 10/01 (m/d)
To: 12/31 (m/d)
☑ Duration of 1 days
For each duration, compute: Means
From computed values, select the: Mean
☐ Rate of change: ● Stage ○ Flow
feet per days
○ Rising ● Falling ○ Absolute
Time series specifications
☑ -50 % exceedance (mean)
● Flow frequency ○ Flow duration
☐ to Water year range
☐ Individual water year
☐ Relationship-defined water year

Geographical queries

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

Completed

Figure 15 HEC EFM dewatering relationship input software format

The second step is to calculate a metric that will represent the minimum flow 60 days from the time an egg is laid.

Method of selecting the minimum Q in the 60 days following egg-laying:

- Look at each day in the egg-laying season and look 60 days out (duration)
- In that window, take the minimum flow that occurs.
- Take the mean of the minimums over the season.
- Take the mean of 49 years of record.

The results for the analysis for both of these flows are shown in Table 15. We are not using the data for stage, the confidence level, nor the hypothesis testing (shown in “chg.” which means “change”.)

		Base2		Shasta2			Nodos3		
Relationship			**Flow, cfs**			**Flow, cfs**		**Stage, ft**	**Flow, cfs**
Fall run dewatering relationship Q			10,708			9,816		167.1	9,696
Fall run dewatering relationship min Q 60 days out			6,432			6,484		166.2	6,075

Table 15 HEC EFM Chinook fall run dewatering output in software format

Based on the discharges that were determined and show in Entering the values into the table for dewatering results in the data in Table 16, the discharges were entered into the dewatering lookup table (ref) and the percent of redds dewatered was determined.

	20% exceedance (5-yr flow)			**50% exceedance (2-yr flow)**			**Mean**		
	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%

There are a number of other statistics that can be used to establish the discharges. We used two other ones to get results, the 20% and 50% exceedance (5-yr and 2-yr recurrence interval.)

	20% exceedance (5-yr flow)			**50% exceedance (2-yr flow)**			**Mean**		
	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%

Table 16 HEC EFM Chinook fall run dewatering output analysis results

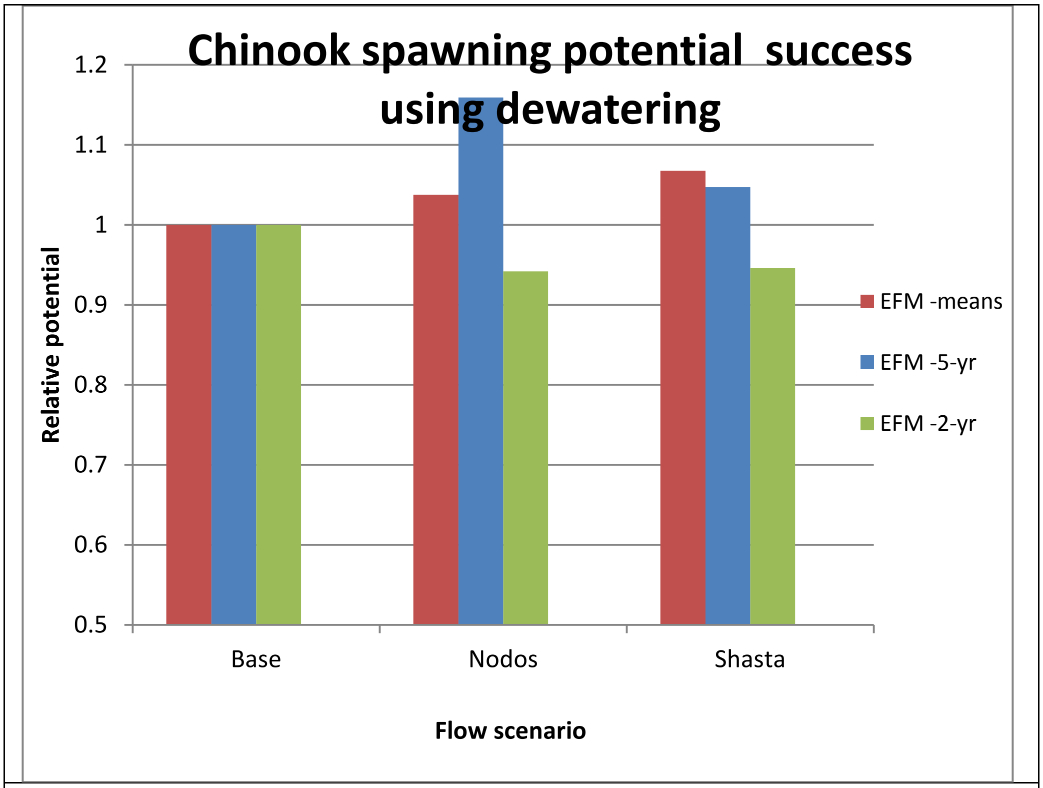


Figure 16 HEC EFM Chinook fall run dewatering output using different flow frequencies

The decision that is faced here is a common one, and there is not an easy guideline for which metric to choose. In some ways, the process of examining the different possibilities gives us information. If one metric only is chosen, it is ultimately a subjective judgment. In the current case, we decided to carry two different metrics forward, the mean and the 5-yr.

When the results in this table are plotted non-dimensionally with the EFT data, the pattern for the 5-yr flow is similar to the EFT pattern; the pattern for the means differs.

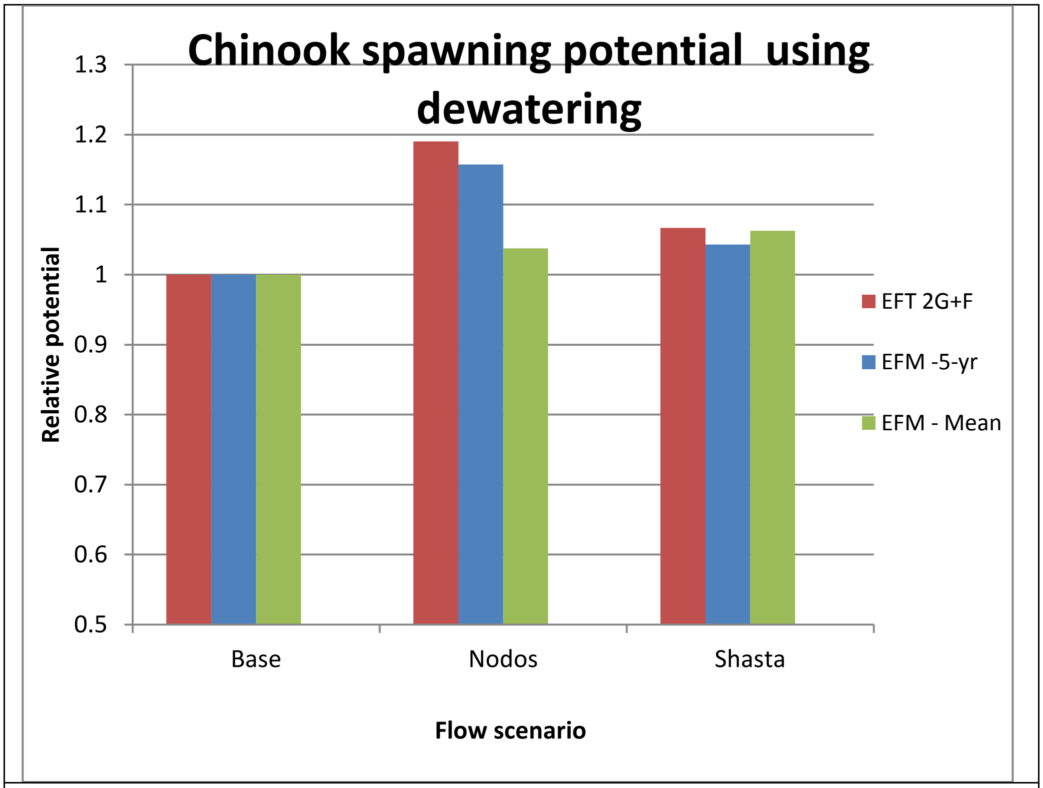


Figure 17 HEC EFM Chinook fall run dewatering output compared with SacEFT output

Kill function

There are two layers here to the ecological story, as HEC EFM looks at it: a “kill” function and a “spawning/emergence” function. In EFM, both of those layers can be looked at in a number of different ways.

Chinook salmon redds consist of gravels and small cobbles, within which the eggs are laid, and where the eggs incubate and hatch. If the flow reaches a stage that scours the gravels, the eggs will be destroyed. Based on this simple concept, we developed the “kill” rule for eggs on the Upper Sacramento River. One estimate of the flow that will scour redds is 50,000 cfs for the lower limit of the influence, and 60,000 for a level that is fatal (ref Bartholow[6]). In the parlance of EFM functional relationships, recall that there are four primary considerations 1) season, 2) duration, 3) rate of change, and 4) percent exceedance.

The logic behind the season is that they start to spawn on October 1, and that is the first day that the eggs can get laid, and therefore it is the first day on which they are available to be washed away. The end of the spawning season is December 31. Because the incubation can last for 60 days, we have chosen the end date for this relationship 60 days after the end of the spawning season, or February 28.

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[6] Bartholow, J.M., and V. Heasley. 2006. Evaluation of Shasta Dam scenarios using a Salmon production model. Draft Report to U.S.G.S. 110 p.

For duration, we are interested in what occurs on a single day. If the flow is high enough on a single day, then that is enough to scour the eggs. Because our data are daily values, and because we have chosen one day, the next entry could be maximum, minimum or mean. Using “mean” reflects the fact that we are really looking at daily means. Because we are considering flows that have the potential to kill, we are looking at the peak flows, so the next entry is the maximum. There is no rate of change consideration.

The statistical query is entirely user-defined. EFM has the capability of getting a range of statistics. In some cases, the life history suggests a suitable recurrence interval. For example, in the case of Freemont cottonwood, knowing that seedling establishment is important about once every 10 years provides a rationale for using a 10-year recurrence interval for the statistic. In the case of redd destruction or egg kill, we chose the 2-year recurrence interval flow.

One of the features of EFM is that it can be used to test hypotheses. Setting an hypothesis and then having a simple positive/negative answer to the hypothesis test is an effective method to use modeling for a manager or other non-technical user. In this case the hypothesis is that increased flow will be negative for ecosystem health. The results for this run of EFM (figure nnn) show that the 2-yr recurrence interval (mean of high flows) flow is higher for base, and about the same for Shasta and Nodos flows.

Fall-run Chinook spawning emergence kill rule EFM style				
Base	Hypothesis test	Shasta	Hypothesis test	Nodos
flow				
54,000	Pos	33,730	Pos	34,694
46.7	Pos	32.7	Pos	33.8

Table 17 HEC EFM Chinook fall run kill rule software output

The results show that both Shasta and Nodos flows are positive for the ecosystem function related to egg kill. The flows are lower, and therefore, have less of a tendency to cause sediment movement and for the eggs to be scoured.

Another benefit of EFM is that it can look at relationships in different ways. “Reverse lookup” for which the user specifies the flow and EFM computes the percent of years that the flow is equaled or exceeded. The reverse flow look-up may be more directly related to the high flows, because it actually specifies the 60,000 cfs, which is the lethal flow. This information does not give us information on the timing of the killing flows. For example, a 60,000 or redd-destroying two flows that occurred every 59 days would effectively destroy all the eggs laid. On the contrary, a half dozen 60,000 cfs flows on successive days in the first week of October might affect only a few of the eggs.

EFM has another tool, EFM plotter, to effectively explore such questions.

IHA

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. We used IHA 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. We used the tabular data, processed with some additional mathematical steps, to develop the dewatering table. For the third method we used standard IHA indices and sought a parameter that could measure flow decrease, because redd dewatering increases monotonically with higher flow decreases.

Redd-scouring flows

Redd dewatering analysis

We used the same life-history conceptual relationship as we did in the previous cases. The first part of the IHA analysis was to examine the average flow in the season for the egg laying (October 1 to December 31). Next we examined flow decreases following the egg-laying. 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 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 the60-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, we chose to use a statistical measure (over the entire 49 year record) of the flow in the egg-laying season to characterize the egg-laying flow. This is the same statistical value calculated in EFM. Following this step, we used the data in IHA 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 diffed from the one derived in EFM, which was more particularly derived the minimum that occurred sometime in the 60 days after the specific date of egg-laying.

We used both the mean value of each of those, and then the median. Based on the values of the Q’s, we entered the look-up table and calculated the percent of redds dewatered.

We tried

	Mean			**Median**		
	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%

Table 18 IHA redd dewatering

As with EFM, we also used the IHA methodology to analyze specific aspects, or attempted to use IHA more as it was designed to be used, not as an adapted WUA-statistics-analyzer.

We looked for IHA indicators that represent flow decreases. One of those might be "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.

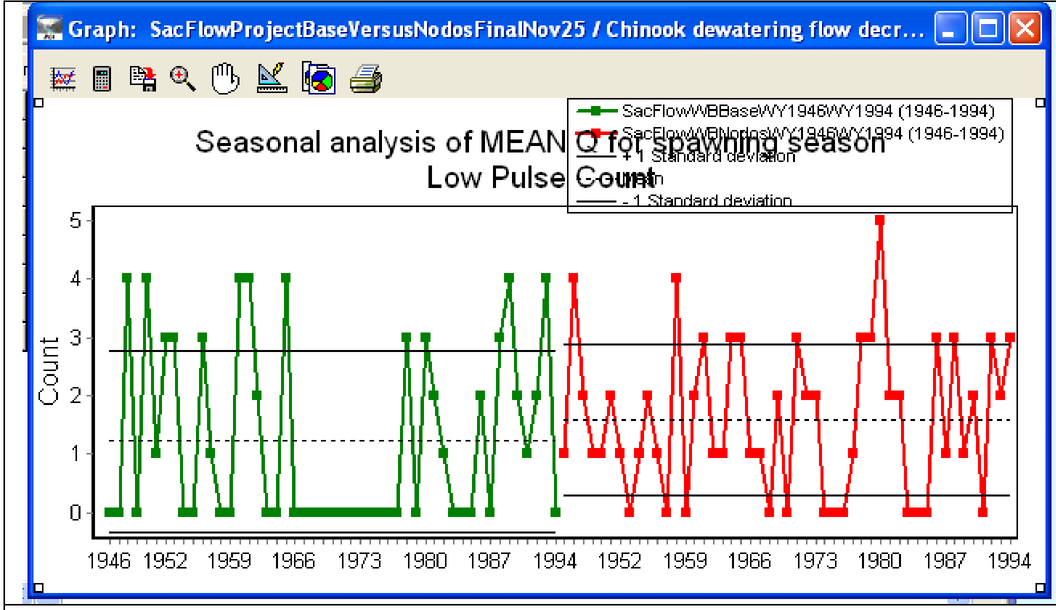


Figure 18 IHA low pulse count

Seasonal low flow pulses over the 49 years		
	Base	60
	Nodos	78
	Shasta	64

Table 19 IHA seasonal flow pulses

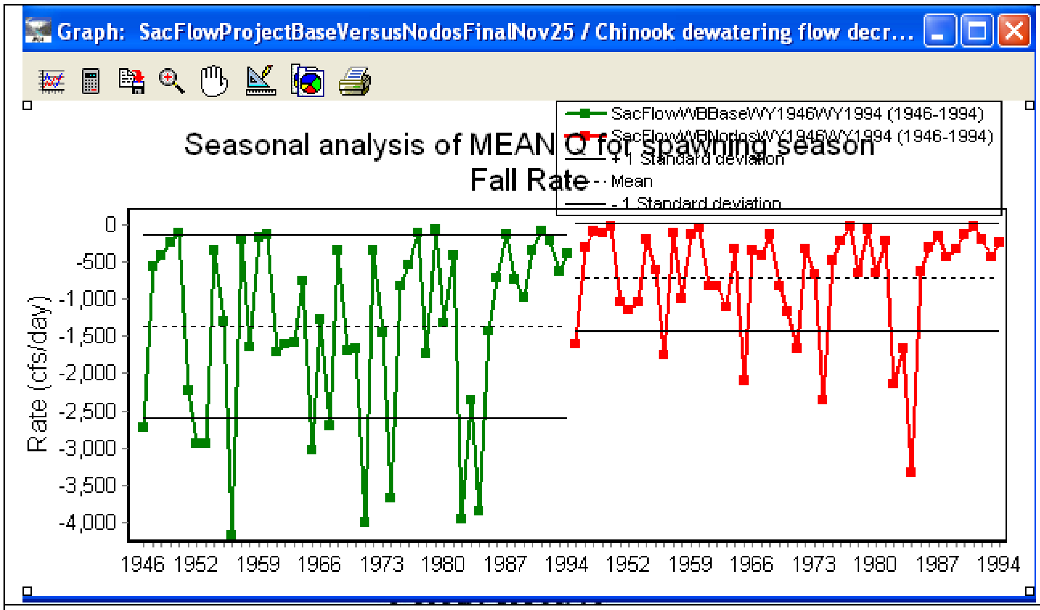


Figure 19 IHA seasonal fall rate

sum fall rate in season over the years of record		
	Base	-13144.5
	Nodos	-6458.037
	Shasta	-6646.05

Table 20 IHA fall rate

Looking at all the results for the IHA parameters considered, we see very similar results for the two analyses that use the 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.

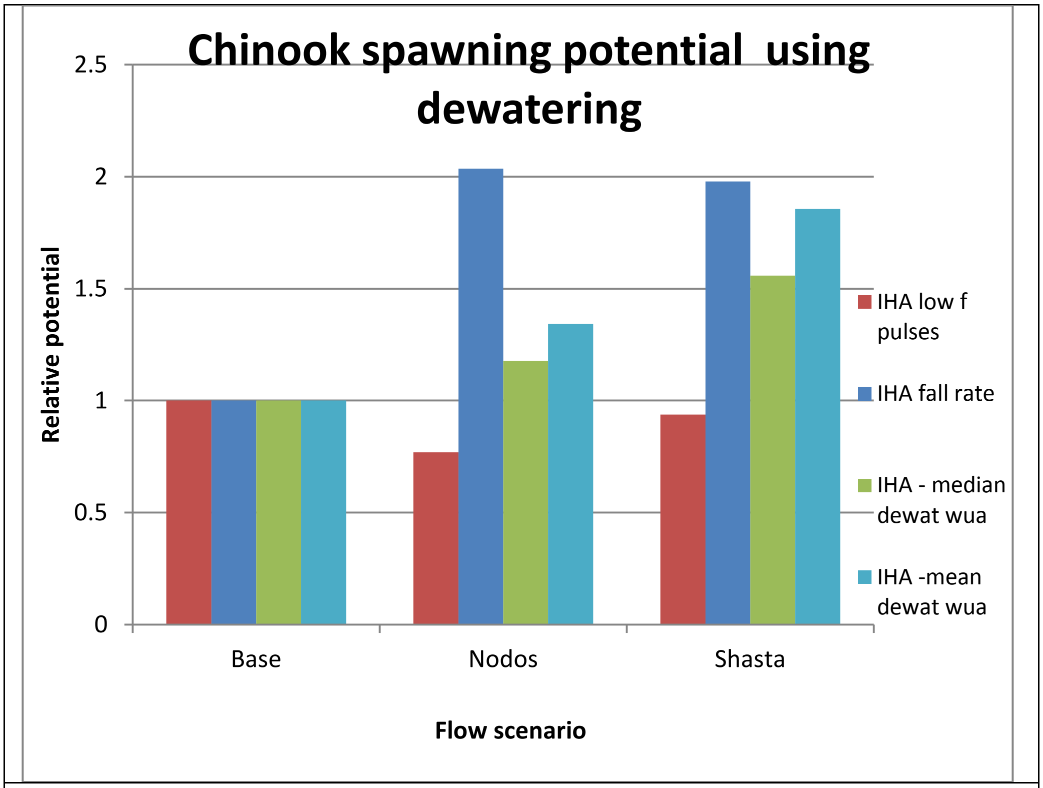
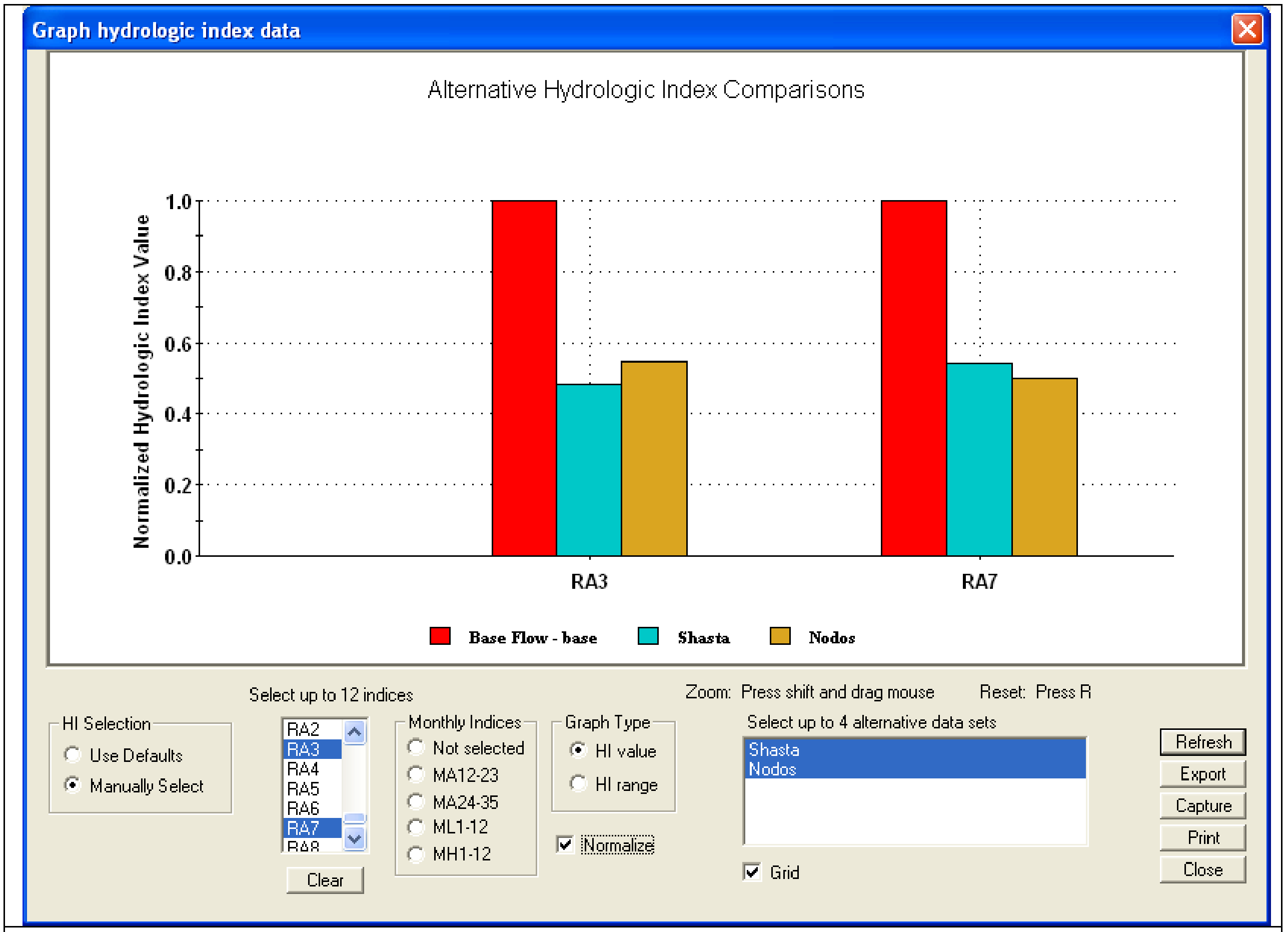


Figure 20 IHA dewatering analysis

HIP/HAT

The pre-defined indices that best represent the dewatering phenomenon both relate to the fall rate of the flows. As with, IHA, there is not a method to limit the calculatioins to the season in question, so the indices represent the entire flow year.

RA3 **(**fall rate**) “c**ompute**[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 per 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 per second/day).



HI Selection: ○ Use Defaults ● Manually Select

Monthly Indices: ○ Not selected ○ MA12-23 ○ MA24-35 ○ ML1-12 ○ MH1-12

Graph Type: ● HI value ○ HI range

☑ Normalize

Selected data sets: Shasta, Nodos

☑ Grid

Figure 21 HIP/HAT indices

	Base	Nodos	Shasta
RA3	1	0.548	0.483
RA7	1	0.5	0.542

Table 21 HIP/HAT indices

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.

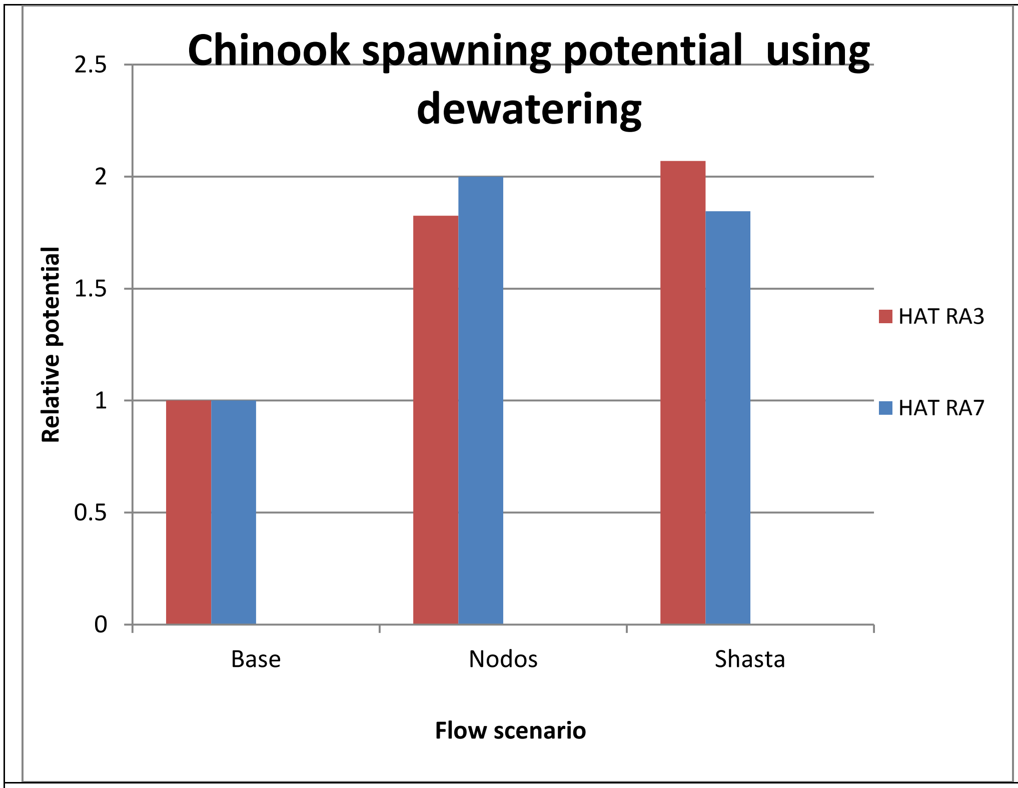


Figure 22 HAT dewatering results

Summary for Chinook dewatering

In order to get a comprehensive picture of all of the indices that were calculated, including the cases where numerous indices were calculated, all were plotted together (ref). On the average, the Nodos and Shasta scenarios show potentially better habitat for the salmon, based on the redd-dewatering relationship.

	Base	Nodos	Shasta		Base	Nodos	Shasta
EFT G+ F	1	1.31	1.09		1	3	2
EFT G	1	0.97	1.03		2	1	3
EFT 2G+F	1	1.19	1.07		1	3	2
EFM mean	1	1.04	1.07		1	2	3
EFM 5-yr	1	1.16	1.05		1	3	2
EFM 2-yr	1	0.94	0.95		3	2	2
IHA low pulses	1	0.77	0.94		3	1	2
IHA fall rate	1	2.04	1.98		1	2	2
IHA - median dewat wua	1	1.18	1.56		1	2	3
IHA -mean dewat wua	1	1.34	1.86		1	2	3
HAT RA3	1	1.82	2.07		1	2	3
HAT RA7	1	2.00	1.85		1	3	2
AVERAGE	1.00	1.31	1.37		1.42	2.17	2.42

Table 22 Chinook redd-dewatering potential with different flow scenarios as modeled by four software packages

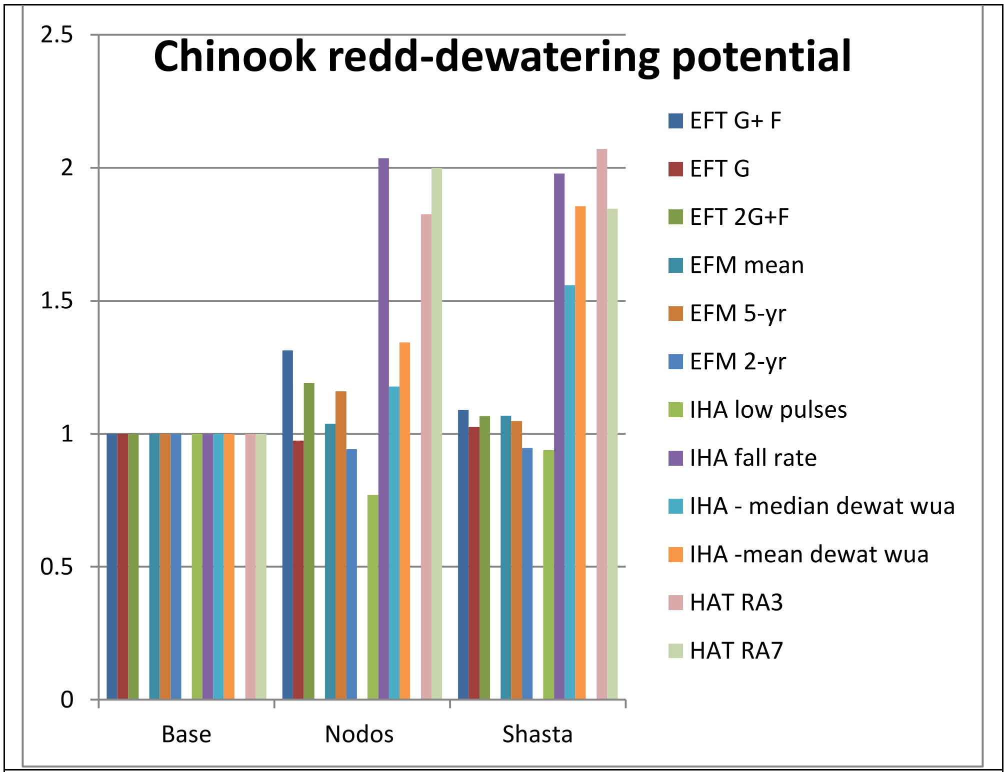


Figure 23 Chinook redd-dewatering potential
This was evaluated with different flow scenarios as modeled by four software packages

Another view of the relative ranking of the flows is shown in Figure 24, which is a plot

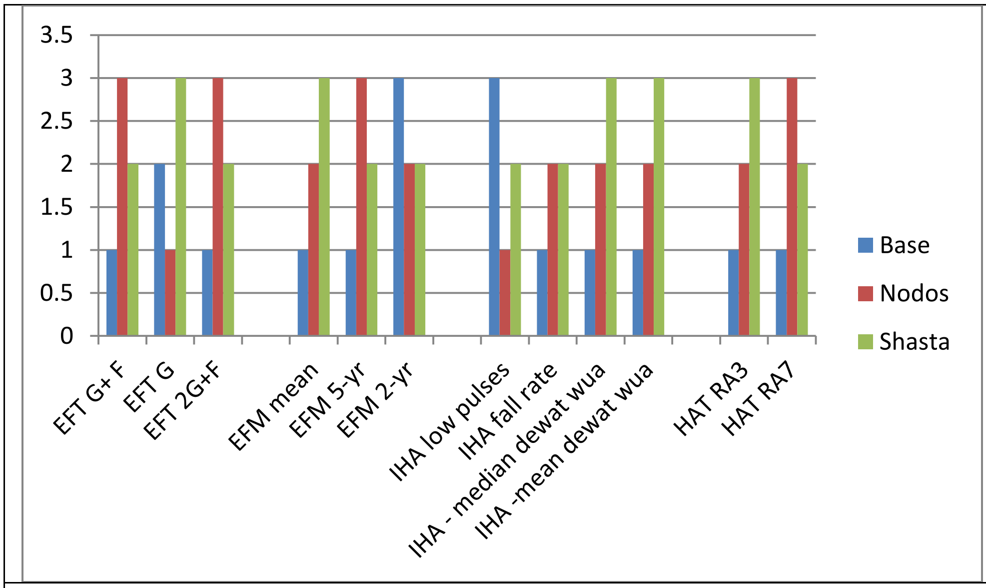


Figure 24 Chinook redd-dewatering potential
This was done with different flow scenarios as modeled by four software packages

of these data.

If you go by the overall average of the indices from all the different methods, the picture is that the Base flow scenario clearly does not provide as much good habitat as the other two scenarios in terms of redd-dewatering. The data suggest that the Shasta case might be slightly better than the Nodos case, but this difference is not probably statistically significant.

Results and discussion

The scale of the quantitative metrics differed in each software program; therefore, the results for the different programs were non-dimensionalized, with each value presented as a percentage of the Base flow scenario case. The results are similar for IHA, HAT, and RAP probably because a very similar metric was chosen to represent the recruitment model.

Figure 25 suggests that the relative potential habitat of the NODOS case (flow scenario 3a) is 85% that of the Base case (1a), and that the Shasta (4a) is 50% of the Base case. Because the flows in the three scenarios only slightly differ in magnitude, it is not clear whether the habitat would differ to such a great degree. An alternate interpretation is that the overall habitat potential is qualitatively ranked in the order shown. With all the software packages, the modeling efforts produce a general view of the habitat quality, without precise detail. As with all the software packages, because the *quantitative* evaluation is in reality a quantity based on set of rules that approximate habitat dynamics, the numbers that result are more precise than accurate. A final *qualitative* evaluation seems most appropriate.

"Riparian initiation calculations are by their nature highly site-specific, tied to the index cross sections and the specific stage-rating curve. Thus, a key assumption for more general flow prescriptions is that the index sites chosen are representative of the focal habitat one would like to see initiation and establishment occur in throughout the larger management area."[7]

The recession rate is the common factor in these relationships. If one even takes the average for the whole year, not limited to the recruitment season, the qualitative results seem to be quite similar as they are for a more complex relationship based on variables included by EFT and EFM. EFT and IHA are almost identical.

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[7] Pers com Clint Alexander, ESSA Technologies 10/13/2009

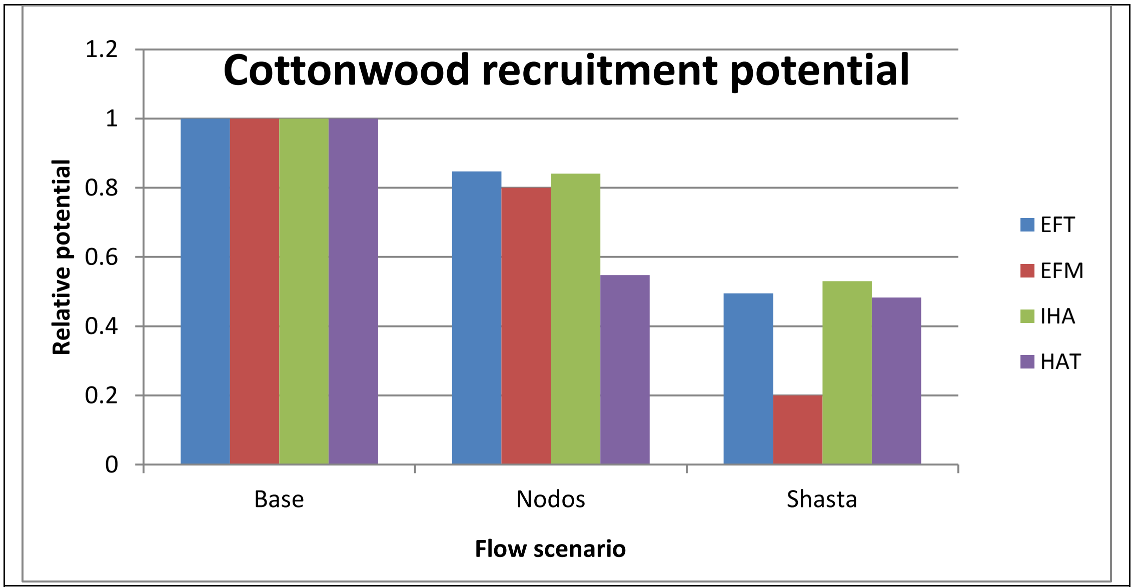

Figure 25 Cottonwood recruitment potential results

Models tend to be designed with target applications and target users in mind. Knowing the main goal of a modeling application and being aware of different models will make a decision on which models to use easier. In the applications examined here, the two types of models were complementary. The environmental flow models were most useful as general screening tools, and the ecosystem function models simulated species-specific scenarios.

Both types of models seem to have a similar process of application. The process of applying software tools for ecosystem flow models and other analysis tools like environmental flow models begins with examining individual life stages of a species in question (step 1 in the chart below). 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). The habitat preferences for each life stage and how a specific habitat preference is linked to flow is then reconsidered (step 3). Based on that, the process differs slightly for the two types of models that we have 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).

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 is valuable. Based on these analyses, interpretation of output results and hypotheses testing (step 6) can result from technical advisory meetings based on the presentation of the visual output. Decisions may be made to refine some of the preceding steps (step 7), until a working set of results is agreed upon.

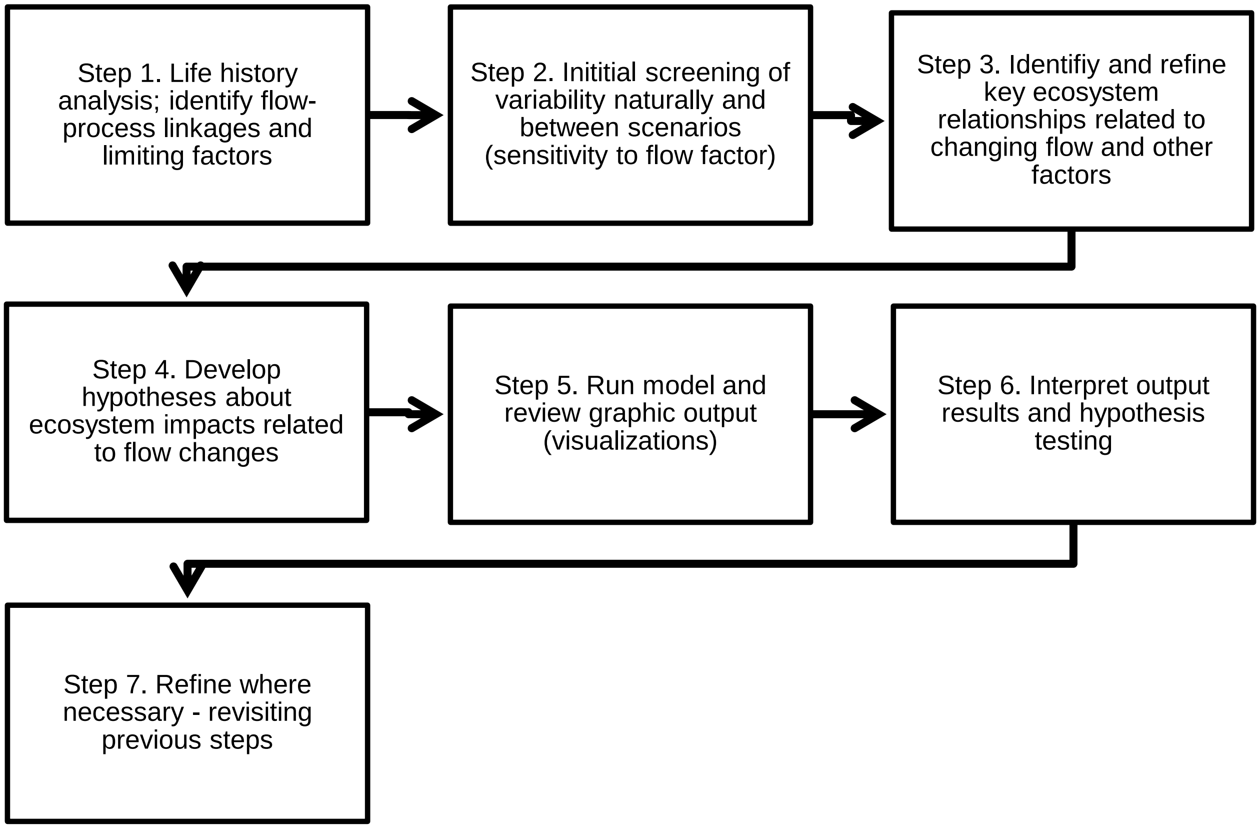

Figure 26 Conceptual stages in using ecosystem modeling to inform management decisions

The process of utilizing an ecosystem functions and environmental flow modeling approach is similar to the Range-of-Variability approach (Richter 1997; Richter and Richter 2000), which is effective for setting quantitative flow-management goals. The RVA approach used in IHA can be a subset of step 2 in the flow chart.

One important consideration for many of the models is how specific representative situations, such as representative cross sections in EFT and a representative gaging location in EFM, are chosen and how well they represent the reach in question. In essence, the cottonwood initiation dynamics at these specific cross sections represents the ecological processes for the entire river reach. This is a common assumption in most ecosystem process models.

The results for the EFM cottonwood modeling are approximations based on a significant assumption at the end of the modeling procedure. We assumed that the habitat suitability would be proportional to the quantity of area that exists between the high water where the seedling establishment initiates and the lower water when the season for recruitment ends. Whether this is a correct assumption or not is not clear. Correlations with observed data would be useful to clarify this point. Because the resultant modeling metric for the Nodos case is four times as large as for the Shasta case, and we note that the flows do not differ by such a large amount, it may be that the difference between the Shasta and the other two flow regimes is exaggerated by this methodology. We assume that the magnitude of difference may not be accurate, but that the relative ranking of the three cases is correct.

Hersh and Maidment (2006) compared IHA and HAT for use in characterizing stream flow hydrographs for specific use in a Texas Instream Flow Program. The comparison concluded that for analyzing hydrographs in general, both programs do a similar job. For a range of variability (RVA) analyses and comparisons of two alternative flows, IHA is more appropriate. For stream specific characterization, the HAT has defined a stream classification process that can define regional-specific factors that influence the dynamics of flow and the resulting hydrographs. The study concluded that HAT fit the needs of the Program because of its flexibility in determining thresholds and regionalizing analyses.

The HIP/HAT process assesses flow records, and is thus very similar to IHA. In fact, many of the 171 flow indices that are determined by HIP/HAT are identical to the ones that are produced in IHA. Questions that might be asked are “how do these 171 indices relate to species diversity or to biomass?” Those types of questions are not yet addressed in the HIP/HAT process. It is not clear which of these and other questions are the most important to ask. The current form of the NATHAT, which is the heart of the HIP/HAT outside of New Jersey, is a statistical exercise, where the flow records are analyzed for indices.

Although the HIP/HAT process is powerful and useful in manipulating downloaded USGS records, the next steps as applied to ecological evaluation are less objective. Developing relationships that describe aquatic health is not easy. All of the relationships that have been developed to describe biological relationships are not strong predictive relationships. There are other processes involved that are not yet understood or described. Many of these relationships characterize an interval of response and the HIP/HAT process only includes a portion of the process. Flows are indeed important factors, but they do not determine everything. More needs to be done in order to define what is possible with these relationships. The definition and what is being done essentially results in “feel-good” statements.

Clearly flow issues are important and relate to processes, but we do not clearly know how important they are. The five indices of flow issues in HIP/HAT are important, but in a sense were a “backlash” to the “instream minimum flow” concept. This is an area where it is not easy to make concrete statements. There are many research opportunities available here.

HIP/HAT software allows you to compare flow indices under different flow scenarios. You reconstruct a flow scenario to compare with other flow scenarios. This is similar to the IHA process. The rules which include ideas like 25% -75% intervals coincide with the ideas that are used in IHA. The problem is that there are no ecological processes defined for this, just hydrologic analyses of flow records. In the work done by the USGS in New Jersey and other places a lot of time was spent with statistical processes to define stream types utilizing gage data.

One of the logical problems encountered when trying to use the flow indices, either EFC's or HIT, 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 PA streams.   When using rules like 25th to 75th percentiles in HIP/HAT or mean plus or minus 1 SD as Richter proposed, you rapidly run into the issue of how to obtain such intervals simultaneously across multiple flow indices. There will always be tradeoffs in some 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 is 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. No one software package is the answer to all questions.

The implicit message here is that the software packages can be complementary. Using the same data, you can first use IHA (or USGS HIP/HAT process) to help define/refine relationships; and then apply both EFT and EFM to a defined ecosystem question, which IHA helped you to formulate and refine. The degree to which the answers agree or diverge informs you more fully than a single software package can.

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Appendices

Appendix 1 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. Angela 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	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.
4	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

Appendix 2 User bases for the software packages

	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	IHA	Widely used. http://www.nature.org/initiatives/freshwater/files/iha_apps.pdf

		provides a 20 page list of known applications.
4	HIP/HAT	