THE ECOSYSTEM FUNCTIONS MODEL

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Abstract: The Hydrologic Engineering Center (CEIWR-HEC), in conjunction with the Sacramento and San Joaquin River Basins Comprehensive Study, is developing the Ecosystem Functions Model (EFM). The EFM is a planning tool that analyzes ecosystem response to changes in flow regime. It is applicable to a wide range of ecotypes and Corps' projects. The model uses hydrologic and hydraulic data, statistical analyses, and GIS spatial coverages to help predict biological responses to proposed study alternatives. Environmental planners, biologists, and engineers would use the EFM to help determine whether the proposed study alternatives (e.g., reservoir operations, channel modifications or levee alignments) would maintain, enhance, or diminish ecosystem health. Three pilot applications of the EFM have been performed in the Sacramento and San Joaquin River Basins. HEC is exploring other opportunities to use the EFM outside of California. This paper discusses the development of the EFM, presents its capabilities, addresses case studies done to date, and emphasizes the advantages of the EFM process. A beta release of the EFM is expected by the end of May 2002.

INTRODUCTION

Origin: Due to several large and damaging flood events in the State of California during the 1980's and 1990's, most notably the January 1997 event, a Flood Emergency Action Team (FEAT) was assembled. The team was to provide an assessment of flooding problems and recommendations for system improvements. Through FEAT recommendations, the U.S. Congress funded the Sacramento and San Joaquin River Basins Comprehensive Study and directed the U. S. Army Corps of Engineers to develop system-wide, comprehensive plans for flood control and ecosystem restoration. In order to understand how proposed flood damage reductions measures would impact the ecosystem and to identify opportunities for ecosystem restoration along the lower Sacramento and San Joaquin Rivers, the Hydrologic Engineering Center and the Sacramento and San Joaquin Comprehensive Team developed an Ecosystem Functions Model (EFM).

Purpose: The EFM is intended to predict how aquatic and terrestrial ecosystems along a river reach, wetland, or estuary may be impacted by the implementation of floodway management measures or changes to flow regime. With- and without-project conditions can be evaluated by the EFM. Using input variables such as flow, existing vegetation, and topography, the model evaluates how changes in flow regime and riverine morphology would impact key attributes of the river-floodplain ecosystem. Examples of the attributes are: changes in the extent of suitable riparian seedling establishment areas, extent of seasonally inundated aquatic habitats, and key river channel flow conditions.

Process: Central to EFM analyses are "functional relationships." Developed by biologists, hydraulic engineers, and environmental managers, these relationships link characteristics of hydrologic and hydraulic time series (flow and stage) to elements of the ecosystem. There is no limit to the number or genre of relationships that may be developed and a graphical user interface has been constructed to facilitate entry and inventory of criteria

After relationships are developed, a statistic computations package (also managed by the interface) analyzes flow and stage time series for the specified criteria and produces a single flow value for each relationship. This process is repeated to assess a modified flow regime and resulting values for without and with project conditions are compared to indicate the direction of change of ecosystem health.

A strength of the EFM is its ability to assess results spatially. In addition to the statistical computations, EFM analyses typically involve hydraulic modeling, which translates statistical results to water surface profiles and spatial coverages of water depth, velocity, and inundated area, and GIS capabilities to display these generated coverages as well as other relevant spatial data (i.e., soils, vegetation, and land-use maps).

Hydraulic modeling and GIS improve EFM applications by 1) helping project teams to visualize existing ecologic conditions or highlight promising restoration sites (see Figure 1), 2) computing depth and velocity data that can be used as criteria to further define relationships, and 3) making it possible to assess multiple alternatives incrementally - through GIS, inundated areas for individual relationships can be compared and ranked as a measure of the relative enhancement (or decline) of that ecosystem element for any number of alternatives.

Spatial functions of the EFM are being programmed as extensions for ArcGIS software. The goal of this effort is to package a few commonly used functions in an easy to use interface for model users who are not GIS specialists.

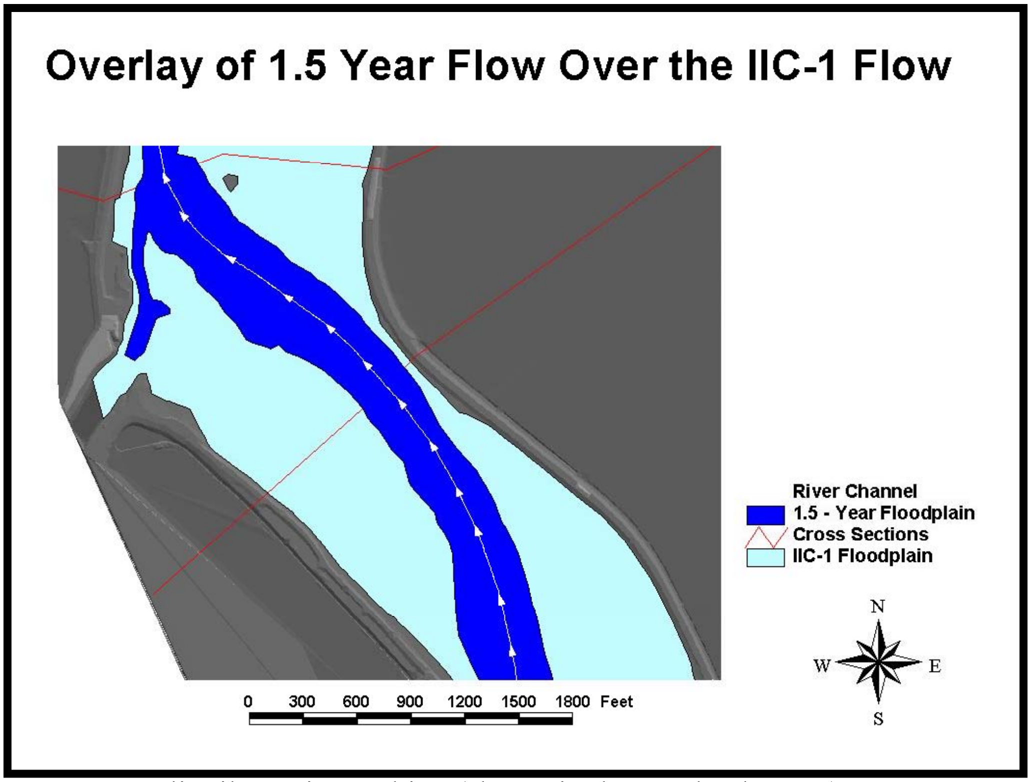


Figure 1 Splittail Rearing Habitat (shown in the overbank areas)

FUNCTIONAL RELATIONSHIPS

Development of functional relationships initiates the EFM process. These relationships use hydraulic and hydrologic parameters such as depth, velocity, shear stress, season, flow frequency, duration, and rate of stage recession to indicate how biological (terrestrial and aquatic) factors are likely to change. For example, if a change to the flow regime causes the shear force in the channel to increase over the existing conditions, then the biological response may be that there is an increased rate of recruitment of woody debris into the channel. The increase in woody debris is likely to improve fish habitat and, therefore, suggests a positive biological response. Currently, EFM results are more qualitative than quantitative, but some indicators translate to increases in terrestrial or aquatic area and highlight locations of restoration potential. It is important to note that the relationships developed for one area of the country most likely will not be applicable to another. Therefore, functional relationships unique to that area must be identified.

In preparation for pilot applications of the EFM, functional relationships were developed for the low gradient rivers of California's Central Valley. A team of agencies including the USACE, CA Department of Water Resources (DWR) and Jones, Stokes, and Associates (JSA) developed the relationships documented in, Final Functional Relationships for the Ecosystem Functions Model, (JSA 2000). The pilot applications used fifteen relationships to investigate a range of ecosystem elements including fish spawning, fish rearing, fish stranding, recruitment of large woody debris, channel migration, riparian forest regeneration, and many others. The fifteen relationships used for the Comprehensive Study are provided in Table 1 below.

Table 1 Functional Relationships for Comprehensive Study

Sub-Element ID	Sub-Element Name	Statistical Requirement	Ecological Response
Terrestrial 1A-1	Substrate Characteristics	None	Optimal soil suitability for various plant communities. Use soils maps to identify soils
Terrestrial 1A-2	Depth of Groundwater Surface	1. Average August Flow (Stage)	Average water table depth in later growing season.
Terrestrial 1A-3	Flood Events Suitable for Plant Establishment	1. Time period=April 1 July 15 2. Must have a stage decline rate<=0.88 feet/week 3. Must have a return period<=10 years	Overbank flows in seed release period that recede slower than a threshold rate. Creates regeneration area.
Terrestrial 1A-4	Scour Regime of Riparian and Channel Zones	1. Need 10-year flow on an annual basis 2. Need 5-year flow on an annual basis	Relative extent of wetland and riparian zones compared to depth for 5-year and 10-year events. Use vegetation mapping and overlay depths at zonal boundaries for the w/o project condition. Keeping boundary depths constant, note changes in boundary location for w/project conditions.
Terrestrial 1A-5	Inundation of Channel Margin Habitat	1. Time period=July 15-August 15 2. Need highest stage sustained for 21 days for events that meet Criteria 1A-3	Inundation of plant establishment area during later season that causes seedling drowning. Dependency on 1A-3.
Composite		None	Overlaying of 1A-5 on top of 1A-3. The remaining area created from 1A-3 is the regeneration area.
Terrestrial 1B-1	Rates of Channel Migration	1. Need 5-year flow on an annual basis 2. Need 1.5-year flow on an annual basis	Rate of habitat renewal. Changes in shear force represent changes in rate of channel migration (+,-,0)
Terrestrial 1B-2	Frequency of Flood Scour	1. Need 10-year flow on an annual basis 2. Need 5-year flow on an annual basis 3. Time period=July 15-August 15 4. Need highest stage sustained for 21 days for events that meet Criteria 1A-3	Distribution of flow depth for a given flow recurrence. See 1A-4.

Table 1 Functional Relationships for Comprehensive Study (continued)

Sub-Element ID	Sub-Element Name	Statistical Requirement	Ecological Response
Terrestrial 1B-4	Rates of Germination Flows	1. Time period=April 1-July 15 2. Must have a stage decline of <=0.88 feet/week 3. Must have a return period <=10 years	Recurrence of overbank flow in seed release periods that recedes slower than a threshold rate. See 1A-5.
Aquatic 2B-1	Spawning Habitat Abundance (overlay with vegetation mapping)	1. Time Period= February 1-May 31 2. Need highest stage sustained for 21 days 3. Return period of x<=4 years	Suitable floodplain fish-spawning habitat.
Aquatic 2C-1	Rearing Habitat Abundance (overlay with vegetation mapping)	1. Time Period= December 1 - May 31 2. Need highest stage sustained for 7 days 3. Need return period<=4 years	Suitable floodplain fish-rearing habitat.
Aquatic 2C-3	Floodplain-channel Connectivity	1. Find mean April and May flows and choose the larger 2. Find 3-year flow on an annual basis	Isolated floodplain habitat that develops possible fish stranding pools. The area between the 3-year inundation layer and the inundation layer caused by the mean April or May, whichever is greater, will be evaluated for stranding pools.
Aquatic 2E-1(A)	In-channel Rearing Habitat	None	Quality of channel gravels available for juvenile fish rearing. Determine if 2-15 cm gravels are present. Determine if mobilization of gravels change with project.
Aquatic 2E-1(B)	In-channel Rearing Habitat	1. Need 1.5-year flow on an annual basis 2. Need 5-year flow on an annual basis	Changes in shear stress to represent changes in rate of woody material recruitment (+,-,0)
Aquatic 2E-1(C)	In-channel Rearing Habitat	1. Need average August flow 2. Need highest stage sustained for 21 days for events that meet Criteria 1A-3	Bankfull flow in relation to average low flow. Presence of overhead cover along stream banks

A Graphical User Interface (GUI) written for the EFM facilitates entry of these relationships into the model and there is no limit to the number or genre of relationships that may be developed. An example of the GUI interface is provided in Figure 2.

STATISTICAL PACKAGE

The Comprehensive Study used fifteen relationships twelve of which required statistical analysis to provide the stage or flow values necessary to evaluate biological response. A new statistical program, coded in Fortran, was written to provide duration, rate of stage recession, frequency, and sequential event analysis. Also accessible through the EFM GUI, the statistical package analyzes flow and stage time series (historical, existing, and/or post project conditions) for the

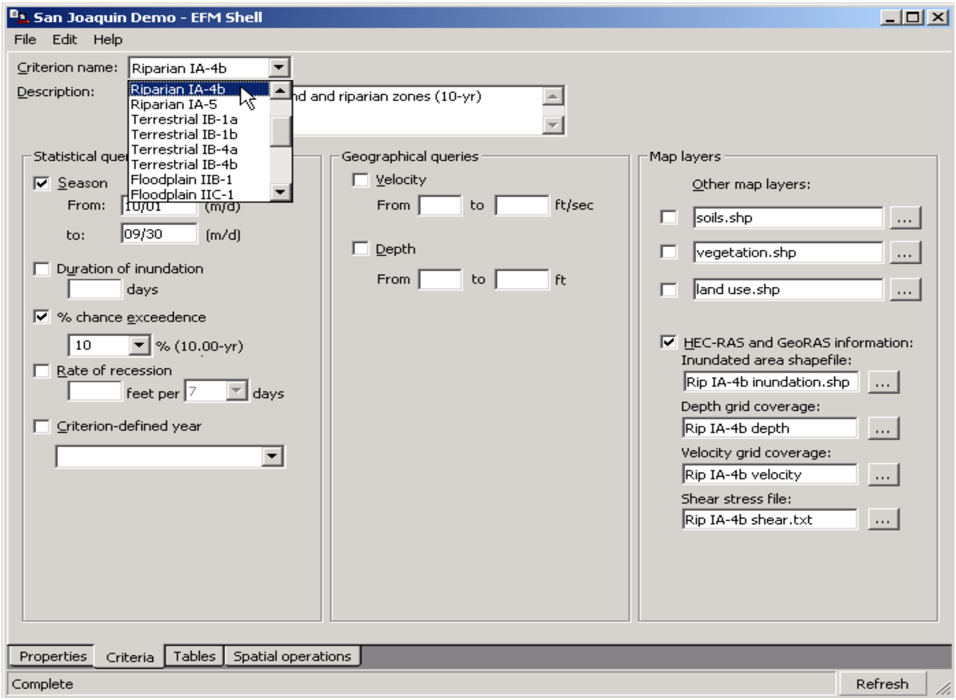


Figure 2 EFM Criteria Tab

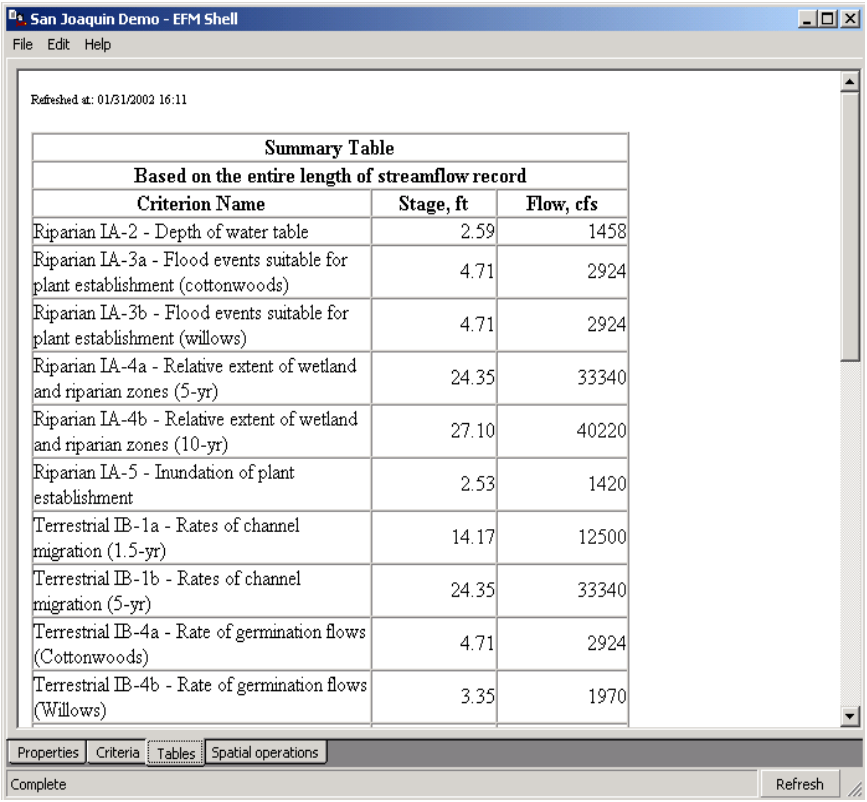
specified criteria and produces a single flow value for each relationship. The EFM does not calculate the stage or flow time series rather, they are provided to the EFM as paired data.

As an example of the statistical analysis needed by a functional relationship, one of the functional relationships from the Comprehensive Study is now given. In order to identify cottonwood regeneration zones, the mid-April to late-May time period for each year must be separated from the times series. Next, the events in that time frame must be analyzed to determine if they have a stage decline of less than 0.88 feet/week. For the events that meet this stage recession requirement, the stage associated with the 10-year recurrence interval must be identified. The flow value associated with this computed stage will then be entered into the hydraulic software so a flood inundation boundary map can be made. This map will identify the outer boundary of the possible cottonwood regeneration zone and used to compare alternatives.

As noted above, the results of the statistical analysis can become the input into the hydraulic and later the GIS analysis. This process is repeated to assess any modified flow regimes and the resulting values for without and with project conditions are then compared to indicate the direction of ecosystem change. An example of the statistical output is provided in Figure 3.

STREAM SELECTION

The EFM process continues by selecting an area of interest along a stream, river, estuary, etc. If the area has good habitat, then the goal of the biologist is to determine if the change in the flow regime (possibly caused by a flood damage reduction measure) will enhance, maintain, or diminish the existing habitat. If the area had good habitat but has suffered a decline for some reason, then the biologist wants to see if the flow regime modification will improve the habitat. Originally, the goal of the EFM was to represent riverine systems (rivers and their associated



Summary Table		
Based on the entire length of streamflow record		
Criterion Name	Stage, ft	Flow, cfs
Riparian IA-2 - Depth of water table	2.59	1458
Riparian IA-3a - Flood events suitable for plant establishment (cottonwoods)	4.71	2924
Riparian IA-3b - Flood events suitable for plant establishment (willows)	4.71	2924
Riparian IA-4a - Relative extent of wetland and riparian zones (5-yr)	24.35	33340
Riparian IA-4b - Relative extent of wetland and riparian zones (10-yr)	27.10	40220
Riparian IA-5 - Inundation of plant establishment	2.53	1420
Terrestrial IB-1a - Rates of channel migration (1.5-yr)	14.17	12500
Terrestrial IB-1b - Rates of channel migration (5-yr)	24.35	33340
Terrestrial IB-4a - Rate of germination flows (Cottonwoods)	4.71	2924
Terrestrial IB-4b - Rate of germination flows (Willows)	3.35	1970

Figure 3 Statistical Results from EFM

floodplains), however, the EFM can be used to evaluate estuaries, wetlands etc. as well.

As the EFM typically relies on the statistical analysis of flows and stages, a stream gage with sufficient record length is identified within the study area. Many times, however, the stream gage is not located in the reach to be studied or the cross-sectional shape at the gage does not physically represent those found in the stream reach. Therefore, the gaged time series records must be transferred to a representative cross-section in the reach. This representative cross-section is called the index location. The index cross-section represents the entire reach and, therefore, must be chosen carefully. It should approximate the physical shape of cross-sections through the reach. A hydraulic engineer performs the transfer of the gaged records outside of the EFM. The transfer of the gaged data must take place prior to the statistical analysis because part of the statistical analysis can be performed on the records that meet certain stage requirements. Since the stages at the gaged location and the index location will most likely be different, the transfer of data must be performed. The rate of stage recession was a factor in some of the functional relationships for the Comprehensive Study, and so it was necessary, for those relationships, to find this cross-section and perform the statistical analysis at that index cross-section.

For the Comprehensive Study, the HEC-RAS (Hydrologic Engineering Center's River Analysis System) computer program was used to perform this transfer. Using the discharge versus frequency relationship from the stream gage and an existing HEC-RAS model that extended through the reach, a stage-discharge relationship was developed at the index location. This rating curve was then used to convert the time series at the gage to a time series at the index location. Flow and stage time series at the index location were then input in statistical program.

HYDRAULIC ANALYSIS

After the statistical program processes the statistical requirements stated in the functional relationships, the resulting flows are then entered into a calibrated, geo-referenced hydraulics model. For the Comprehensive Study, the HEC-RAS model was used. In addition, to create flood inundation boundary maps, HEC-GeoRAS, a pre- and post-processor for HEC-RAS, was used. Flood inundation boundary maps are the primary output from the EFM and are used to compare and contrast with other GIS spatial maps. For example, a flood inundation boundary map could overlay a soils map. The intersection of the proper soils with the proper depth could give an indication as to the suitability of the intersected area for some sort of ecological response. Using tools within the EFM, the depths and velocities at any grid cell can be identified. Comparing depths and/or velocities over different scenarios also helps to determine what environmental impacts (good or bad) are likely to be associated with various actions.

For the Comprehensive Study, the HEC-RAS and GeoRAS models produced the flood inundation boundary maps, and velocity and depth grids necessary to evaluate each of the functional relationships. As an example, flood inundation boundary maps of the splittail floodplain spawning relationship for existing conditions and, for illustrative purposes, an alternative focused on the use of reservoir releases to mimic a more natural flow regime are shown in Figure 4. In this case, the expanded area in the floodplain suggests that increased reservoir releases in a given season will increase splittail-spawning opportunities. These maps could be generated and compared for various flood damage reduction measures to see if the

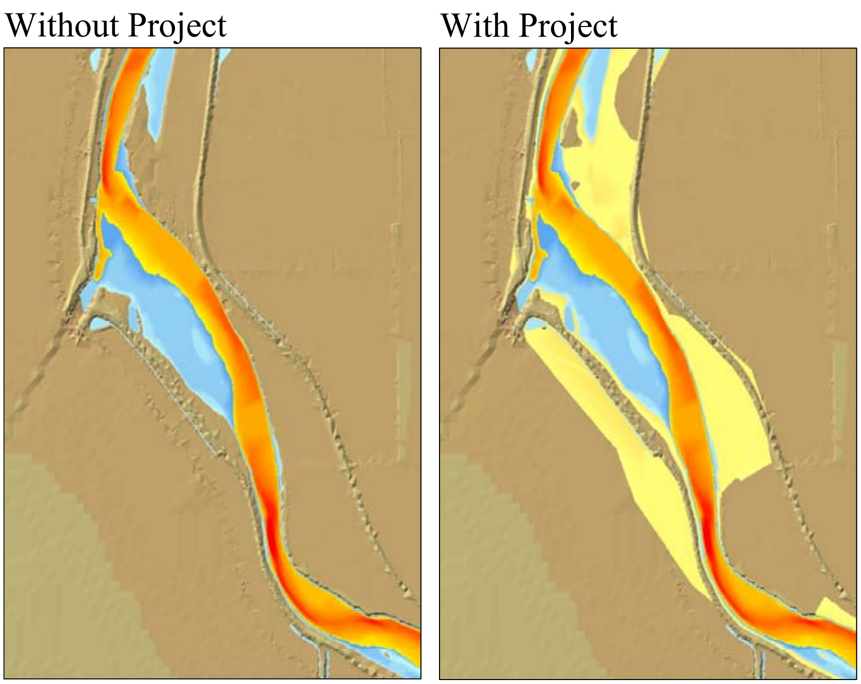


Figure 4 Visual Comparison of Floodplain Spawning Habitat for Splittail under Without and With Project Conditions

spawning area decreased or increased. Depths and velocities at any grid cell, for these given stages, could also be computed if they were necessary to evaluate the functional relationship. Along with the visual representation afforded by the inundation maps, the attribute tables associated with the inundation maps allow the user to quantify the amount of increased or decreased area created by the change to the flow regime.

SPATIAL ANALYSIS

A strength of the EFM process is its ability to develop, display, and compare spatial maps of the biological responses. These maps convey information that would otherwise be difficult to understand or visualize. They are useful for internal or public meetings and biologists, planners, project managers can review the layers to determine the impact of the changed flow regimes.

As noted above, the EFM process generates numerous inundation maps. Nearly every functional relationship developed for the Comprehensive Study required one or more inundation maps to visualize its biological response. The maps were either produced by the EFM process (flood inundation boundary maps, depth and velocity grids) or imported (soils, land use, vegetation, groundwater etc.) into the EFM.

To expedite this process, the EFM's Spatial Processor allows users to directly import GIS layers (such as the soils and land use maps), created outside of the EFM process and the inundation maps generated during the hydraulic analysis. Users can overlay layers and perform GIS computations using commonly applied GIS tools to intersect existing layers and develop and compare layers. One of the goals of the EFM's spatial processor is to provide some commonly applied GIS tools within the spatial processor so that users can perform certain functions without being GIS specialists. These GIS techniques will allow the biologists to make all sorts of maps that might look for velocity or depth bands or inundation areas. The EFM's spatial evaluation screen is shown in Figure 5.

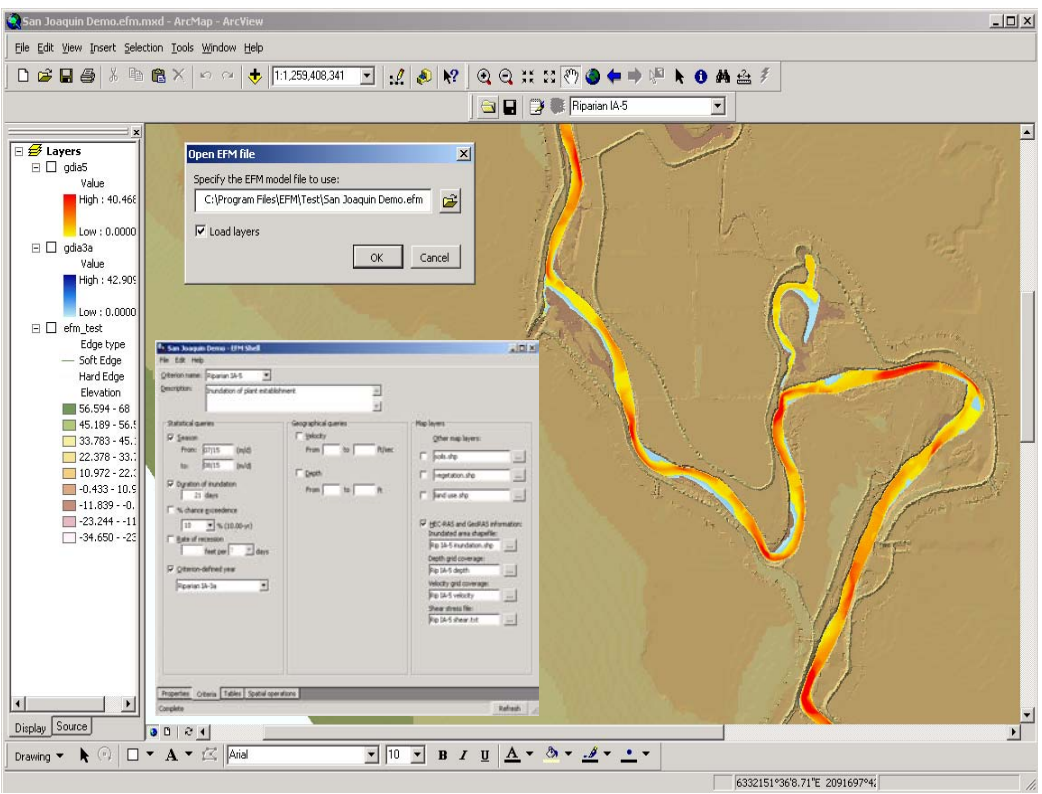


Figure 5 EFM Spatial Evaluator

ECOLOGICAL INTERPRETATION/MODEL VERIFICATION

Tables and maps produced by the EFM do not produce final results by themselves, but rather they provide information to users to help them make decisions about the possible success or failure of ecosystem suitability or sustainability. Other relevant data such as endangered species occurrences and ecological landscape parameters will be used along with the results of the EFM to determine the suitability or priority of a given area for restoration.

Because the EFM relies on a statistical approach, thus providing an averaged concept of how an ecosystem may react over time, it is important to verify the functional relationships. If the user believes that output resulting from meeting the functional relationships are logical indicators of biological response then the EFM could suggest, that over time, one alternative is better or worse than another alternative because it has more or less of a given suitable habitat. However, other questions still exist. For example, does one functional relationship override the results of another functional relationship or does one have a greater priority than another. With continued work on the EFM, these types of questions may be answered, but for now, the EFM is used to provide an indication of biological suitability.

For the first pilot area evaluated for the Comprehensive Study, engineers and biologists visited the lower San Joaquin River to locate areas with riparian seedlings. The goal was to determine whether results from the EFM predicted the location of the riparian seedlings. The engineers and the biologists were able to determine the age of the seedlings. Team members found over fifteen sites with riparian seedlings, all of which were within EFM predicted establishment areas. While this evaluation only considered one functional relationship, it is an indicator that the EFM may be able to predict the location of suitable habitat for ecosystem restoration projects. More verification will occur in the future.

CONCLUSIONS

The Ecosystem Functions Model (EFM) is intended to help environmental planners, biologists, and engineers predict how aquatic and terrestrial ecosystems along a river reach, wetland, or estuary may be impacted by changes to the flow regime. Typically, the changes to the flow regime are caused by the introduction of flood damage reduction measures but could also be caused by ecosystem restoration projects. The EFM uses hydrologic and hydraulic data, statistical analyses, and GIS spatial coverages to help predict biological responses and is applicable to a wide range of ecotypes and Corps' projects.

While further field verification and case study applications needs to be performed, the techniques and results from the EFM are promising. In the future, the Hydrologic Engineering Center expects to add enhanced features to the EFM so that period-of-record evaluations can be performed and uncertainties evaluated. A beta version of the software should be available by May 2002.

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