EFT
Ecological Flows Tool

Application of the Ecological Flows Tool to Complement Water Planning Efforts in the Delta & Sacramento River

Multi-Species Effects Analysis & Ecological Flow Criteria

Ecosystem Restoration Program
Agreement E0720044

Final Report
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The Sacramento River Program of The Nature Conservancy

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Organization of Report

To facilitate your ability to identify background and findings that are of most interest, this report is organized as follows:

Chapter 1. Overview – This Chapter describes the vision, history and goals of the project; its tasks and deliverable products to date. It describes categories of ecological flow needs assessment and how these needs are tackled by the Ecological Flows Tool.

Chapter 2. Ecological Flow Needs Considered and Methods – This Chapter summarizes the kinds of management actions that can be evaluated using EFT. It also describes the species and ecological needs which are considered by EFT, and includes high level narrative descriptions of the 25 indicators that form Sacramento River and Delta EFT. The Chapter also provides high level descriptions of each indicator along with *where* and *when* the indicator effects take place. This Chapter also provides a concise explanation of how each indicator's results are combined (rolled up) in different ways, to provide outputs that range from the detailed to high level summaries. In addition to describing various categories of outputs available from EFT, we provide an explanation of the different approaches to synthesizing outcomes and comparing results using a weight-of-evidence approach to develop higher level net effect conclusions. Descriptions of the external models that EFT leverages (e.g., CALSIM) which provide input to EFT are also provided in this Chapter (including how these models can be substituted for others as they become available). The Chapter also describes the methodology involved with using EFT to develop rule-sets and eco-friendly flow regimes for incorporation into other physical planning models.

Chapter 3. Recent EFT Applications – This Chapter provides a description of recent applications of EFT to water operation planning, with particular emphasis on multi-level results. This includes the first *full* application of EFT (SacEFT and DeltaEFT) to selected Bay Delta Conservation Plan alternatives. We include net effect summaries, summaries of physical change as well as detailed species and indicator results for several water operation and future climate scenarios. These effects analyses are structured according to defined comparisons intended to isolate water operation and conveyance effects, as well as anticipated effects associated with future climate change and human demand. A second major focus of this Chapter is to unveil results for a pilot study showing how EFT can be used to develop rule-sets and recommended flow regimes for incorporation into physical planning models (e.g., in this example, CALSIM). As an initial test of the approach, we illustrate results of the method as applied to winter Chinook and Delta smelt. A summary of a previous application of SacEFT to a North-of-the-Delta Offstream Storage investigation is also provided.

Chapter 4. **Where to From Here? –** Isolates the biggest lessons learned over more than 10 years of work, and plots a course for the next phase of coupled, multi-species, ecological flow decision support for the Sacramento River and Delta.

Appendix A – Provides the original backgrounder report that was provided prior to the first Sacramento River Ecological Flows Tool design workshop. While it is superseded by the SacEFT Record of Design in Appendix B, this companion document illustrates the structured workshop and peer review approach taken in the development of SacEFT.

Appendix B – Provides the Record of Design for the Sacramento River Ecological Flows Tool. A standalone report, this document provides additional detail about the development and technical implementation of each SacEFT indicator too voluminous for inclusion in the main body of this report.

Appendix C – Provides the original backgrounder report that was provided prior to the first Delta Ecological Flows Tool design workshop. While it is superseded by the DeltaEFT Record of Design in Appendix D, this companion document illustrates the structured workshop and peer review approach taken in the development of DeltaEFT.

Appendix D – Provides the Record of Design for the Delta Ecological Flows Tool. A standalone report, this document provides additional detail about the development and technical implementation of each DeltaEFT indicator too voluminous for inclusion in the main body of this report.

Appendix E – Provides the software user guide for the Ecological Flows Tool Reader software.

Appendix F – Isolates and provides the systematic indicator screening & selection criteria used to guide decisions about what species and habitat indicators to include in EFT.

Appendix G – This Appendix provides details on the *default* relative suitability thresholds used to establish EFT's roll-up ratings of good, fair and poor annual performance by indicator. These suitability thresholds help characterize outputs, are fully configurable, but are only *one type* of information provided by EFT.

Appendix H – A comprehensive listing of all EFT input and output locations mapped to each species and performance indicator.

Appendix I – This Appendix provides a complete list of EFT derived rule-sets and recommended flow/water temperature regimes for all species and indicators.

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List of Abbreviations, Measurement Units and Fundamental Terms

Abbreviations

BA	Biological Assessment
BASW	Bank Swallow
BDCP	Bay Delta Conservation Plan
BO	Biological Opinion
CALSIM	California's monthly hydrosystem planning tool
CDEC	California Data Exchange Center
CEQA	California Environmental Quality Act
CRSS	Colorado River Simulation System
CS	Chinook salmon
CVP	Central Valley Project (California)
Delta	San Joaquin-Sacramento Delta
DeltaEFT	Delta Ecological Flows Tool
DEM	Digital Elevation Model
DFG	California Department of Fish and Game
DRERIP	Delta Regional Ecosystem Restoration Implementation Plan
DRR	Delivery Reliability Report
DS	Delta smelt
DSM2	(San Francisco) Delta Simulation Model version 2 (California)
DWR	California Department of Water Resources
EBC	Existing Biological Condition
EC	Electroconductivity
EFT	Ecological Flows Tool (includes SacEFT for the Sacramento River, and DeltaEFT for the Delta)
EHW	Extreme High Water
EIS/R	Environmental Impact Study/Report
ELT	Early Long Term (2025)
ERP	Ecosystem Restoration Program
ESO	Expected Starting Operations
FC	Fremont Cottonwood
GCID	Glenn-Colusa Irrigation District
GIS	Geographic Information System
GS	Green sturgeon
HEC-5Q	Flood control and conservation systems simulation model
HEC-RAS	Hydrologic Engineering Center River Analysis System
HOS	High Output Scenario
ICIF	ICF International
ID	Invasive deterrence
IFIM	Instream Flow Incremental Methodology
IHA	Index of Hydrologic Alteration

IMF	Instream Minimum Flow
LLT	Late Long Term (2060)
LOS	Low Output Scenario
LS	Longfin smelt
LWD	Large Woody Debris
MTL	Mean Tide Level
NAA	No Action Alternative
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NMFS BO	National Marine Fisheries Service Biological Opinion
NOAA	National Oceanic and Atmospheric Administration
NODOS	North-of-the-Delta Offstream Storage
OCAP	Operations Criteria and Plan
PHABSIM	Physical Habitat Simulation
PI	Performance Indicator
PPIC	Public Policy Institute of California
PTM	Particle Tracking Model
RKI	River Kilometer Index
RM	River mile
ROA	Restoration Opportunity Area
RPA	Reasonable and Prudent Alternative
SacEFT	Sacramento River Ecological Flows Tool
SAIC	Science Applications International Corporation
SLWRI	Shasta Lake Water Resources Investigation
SRWQM	Sacramento River Water Quality Model
SS	Splittail
SWP	State Water Project (California)
SWRCB	State Water Resources Control Board
TNC	The Nature Conservancy
TUGS	The Unified Gravel-Sand sediment transport model
TW	Tidal wetlands
TXFR	Transfer
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USFWS BO	United States Fish and Wildlife Service Biological Opinion
USGS	United States Geological Survey
USRDOM	United States Bureau of Reclamation Daily Operations Model (Sacramento River, California)
VEC	Valued Ecosystem Component
WRESL	Water Resources Simulation Language (used in CALSIM)
WUA	Weighted Usable Area
WY	Water Year
WYT	Water Year Type
X2	Distance (km) from the Golden Gate Bridge to the location of the low salinity zone, defined as 2‰ bottom salinity

Measurement Units

%	Percent (a fraction of one hundred)
‰	Permille (a fraction of one thousand)
cfs	cubic feet per second
cm	centimeter
ft	feet (ft^2 = square feet)
ha	hectare
kcfs	thousand cubic feet per second
km	kilometer
m	meter
MAF	million acre-feet
mm	millimeter

Fundamental Terms and Concepts

Indicator Performance indicator Metric Valued Ecosystem Component (VEC) Performance measure	Throughout this report, the word "indicator" is used in a general sense as it commonly is in applied science, without specific reference to how different authors occasionally decide to customize meanings of this (plastic) word. In this report, an "indicator" is analogous to a "performance indicator", or "metric", or "valued ecosystem component" (VEC). For our purposes, these words refer synonymously to any element of the environment that has ecological, economic, social or cultural significance. Subtleties and nuances as to whether an indicator "suggests, gets close to, approximates" but does not provide an objective "measure" are easily resolved by reviewing the actual definition for the indicator (or performance indicator, *etc.*). All of these terms are used to answer the question, 'how do I know' whether an action, or some fundamental natural driving conditions in the environment are causing things (that have value) to get better, worse or stay the same. The lack of a distinction between an *indicator*, or a *metric* is actually useful as it opens up more options as to what is an acceptable way to assess 'how do I know'. Decision makers, stakeholders, and members of the general public can make judgments and decisions with "indicators" just as well as "metrics" so long as the terms are clearly defined and logically linked to something of value.
EFT baseline simulation	An EFT baseline simulation was used for some indicators to inform decisions about relative suitability thresholds (see Section 2.7.2 for details). EFT baseline simulations are selected to maximize the range of water year types and year to year variation in flow conditions based on available data. Because of the requirement for long-term, high-resolution datasets (both temporal and spatially), this typically necessitated selection of the available long-term historical record. Historical data includes modified, regulated, artificial flows following construction of major dams, diversions and pumping plants. For some indicators (when the historic record was short), the EFT baseline combined the available historic data with simulated no action or reference case data. See Section 2.7.2.

Historical flows	The measured empirical flows that occurred during the selected period of record (for our purposes, typically some continuous sequence of years within 1939-2002). These flows often include a shifting mixture of modified, regulated, artificial (potentially "degraded") flows following construction and operation of dams, diversions, conveyance structures and pumping plants. Shifting climate change effects on precipitation and other hydrologic processes are also embedded. When the time series is long enough, they will also include a range of water year types and related flow variations that even though regulated, still manage to "show through" in the historic dataset. Historical flows ≠ natural / pristine / unregulated / unmodified / unimpaired flows.
Natural flows	Natural flows represent the pristine, unmodified, unregulated, unaltered flows that would occur in the absence of any human presence, infrastructure, modifications, hydrosystem operations, water withdrawals and related land-use changes (e.g., forestry, agriculture). In this report, this is merely a theoretical concept. We do not use natural flows in our simulations (because they are not available).
Unimpaired flows	Reverse engineered flows found by attempting to remove the effects of reservoirs and diversions on *existing hydrology time-series*. These flows are thought of as a proxy for natural flows. Challenges with these estimates are manifold, and include absence of the effects of levees, channelization 'improvements', wetland storage and related evaporation processes, forest practices, groundwater interactions, *etc*. Unimpaired flow estimates are typically not performed for a wide range of locations, are often monthly in temporal resolution, and typically rely on volume correlations, precipitation correlations, subbasin to subbasin extrapolations and other techniques that produce unquantifiable errors.
Reference case scenario	Represents a chosen point of comparison, or baseline, that embeds any number of assumptions about the level of human development, climate change, and baseline system operations.
Study scenario	Represents an action scenario that contains alternative assumptions about any one or more of the level of human development, climate, and system operations. Depending on the chosen reference case scenario, the chosen study scenario can be used to isolate a specific effect, such as a system operation and conveyance change or a change in expected future climate (or both).

Executive Summary

The Need

Beginning with the launch of the current phase of this project in October 2008 and extending through to its conclusion in 2014, the Ecological Flows Tool (EFT) project has had the goal of improving water planning in the Sacramento River and the San Joaquin-Sacramento Delta. The waters which flow through these two ecoregions are among the most highly regulated anywhere in the world, serving over 20 million people, supporting a $40 billion agriculture industry, and sustaining diverse, although highly altered, ecosystems. Because of a chronic inability to find "balance" in the trade-offs among competing objectives and resource demands, the Delta is universally regarded to be in crisis. A central challenge in managing the Sacramento River and Delta is evaluating how alternative river management scenarios are likely to impact different components of the ecosystem. Our project directly addresses this challenge. Aided by over 70 scientists and managers since the project's 2004 inception, we have developed an integrated bio-physical tool that characterizes how a suite of focal species are expected to respond to alternative flow, river bank, and gravel management scenarios. EFT interfaces with existing water management tools, and is intended to be used to support the recovery of the Delta and Sacramento River ecosystems that are currently managed primarily to meet human water delivery needs.

An important challenge that has faced water managers has been the gap in scientifically credible, representative, flow-based ecological models which can be linked to appropriate physical hydrological models at a daily (or finer) resolution and at biologically relevant locations. EFT has helped to fill this gap through the development of submodel algorithms which simulate the physical needs of 13 representative focal species (and habitats) across the Sacramento River and Delta ecoregions. The peer-reviewed species submodels are made up of 25 key life-history indicators, each of which is driven by relevant measures of flow, water temperature, channel migration, salinity and/or stage at a daily timescale. In addition to coupling multiple ecological indicators to the physical inputs simulated by a standard suite of hydrological tools for evaluating operations and conveyance alternatives (CALSIM, SRWQM, DSM2 and their numerous components), EFT is linked to models of channel migration, soil erosion and sediment transport. This enables evaluations of the potential benefits not only of flow modifcation, but also of riprap removal and gravel augmentation.

By design, the development of each EFT indicator is based on a logical progression of steps that begins with the development of cause-effect conceptual models which link the physical regime to representative life-history stages of the focal species. Based on the implementation of these models, it is possible in a second step to identify flow management regimes that best meet critical needs of specific life-history stages. Prior to the creation of the EFT model and software, much of the knowledge related to focal species and their needs was isolated in reports, papers and disconnected models and tools that were difficult to access. EFT provides an integrated framework that can synthesize a very wide range of ecological information to allow far more comprehensive consideration of environmental needs than was previously possible. This level of synthesis and integration makes it possible to identify and address trade-offs among multiple focal species.

The outputs created by EFT are varied to meet the needs of different users. For research biologists familiar with the physical needs and temporal patterns of each focal species' life-history, daily and location specific graphs can be produced for any flow scenario and year, showing how each indicator and its driving physical processes vary by location and date. This allows users with specialized knowledge to evaluate model behavior and predictions at the finest scale. Other animated data visualizations are included for Delta species and performance indicators. For system managers and operators, a synthesis of detailed results is provided through a simple suitability rating system (Good/Fair/Poor "traffic light" assessments). These can be visualized by year or can be combined ("rolled up") even further by pooling years, for a very broad comparison of relative performance of alternative scenarios.

EFT Applications

The demand for and value of the Ecological Flows Tool is reflected in its use in several major investigations in the last few years. These investigations began with the use of the Sacramento River (SacEFT) branch of the decision analysis tool in 2011, to evaluate relative ecological effects of several alternative North-of-the-Delta Offstream Storage (NODOS) scenarios. The results of that analysis were considered in the interim joint environmental impact study/report (EIS/R) and revealed mixed impacts, depending on species and indicators. Most recently, we applied the *full* EFT model to selected Bay Delta Conservation Plan (BDCP) alternatives (a focus of Chapter 3). The analysis of BDCP scenarios included scenarios for expected starting operations (ESO), low output (LOS), and high output (HOS), as well as for climate change. Prior to the full EFT analysis of BDCP alternatives, a subset of focal species models (Sacramento River salmonids and green sturgeon) were used as part of the set of tools brought to bear on the BDCP EIS/R effects anlaysis. In addition to these three analyses, a prototype version of SacEFT (previous project phase) was used to study some of the early alternatives being considered as part of the Shasta Lake Resource Investigation. In all, EFT has demonstrated its ability to incorporate physical inputs simulated by a widely-used suite of planning tools and to provide defensible ecological outputs which have been used as part of the decision-making process for each investigation.

EFT analyses of the BDCP alternatives show that overall, the LOS BDCP alternative is preferable for species completing life-history stages in the Sacramento River (especially fall-run Chinook, late fall-run Chinook and spring-run Chinook) while the HOS BDCP alternative is preferable for San Joaquin-Delta species (especially longfin smelt and, to a lesser degree, Delta smelt). Fall-run Chinook, late fall-run Chinook and splittail do better under all BDCP alternatives considered ("winners"), while green sturgeon, deterence of invasives, and brackish wetland habitats are expected to experience deteriorating conditions. Spring-run Chinook are expected to do the most poorly under ESO and HOS alternatives in terms of spawning habitat, egg-to-fry survival, and redd dewatering. In general, juvenile stranding losses increase, particularly for winter-run Chinook. Delta temperature stress on winter-run Chinook also increases over all Early Long Term (ELT) alternatives. Likewise, Delta temperature stress is also elevated over all ELT alternatives for steelhead. While LOS ecosystem benefits are superior for species in the Sacramento River, results from HOS are generally very similar. *The various trade-offs noted*, the HOS alternative is likely the most preferable in terms of delivering ecological benefits. EFT results suggest the HOS is more likely to benefit Delta smelt and the LOS is predicted to be detrimental to longin smelt.

With a few exceptions, the climate change signal and effects in the BDCP study generally dwarfed the operational alternatives considered, especially in the Late Long Term period (LLT) (2065). Even though compensation was *not* the general outcome, the BDCP alternatives do have the potential to provide some offsetting benefits to help cope with climate change effects. In particular, spawning habitat is improved by the conveyance and operations in BDCP alternatives for fall-run Chinook and spring-run Chinook (LOS alternative only). Delta rearing conditions are improved by notching of the Fremont Weir associated with the ESO, LOS and HOS BDCP alternatives, offsetting losses that are otherwise expected for late fall-run, winter-run and, to a lesser degree, spring-run Chinook. Spring-run Chinook also receive compensatory offsets of otherwise detrimental climate change effects from the LOS scenario, in terms of reductions to redd dewatering losses and improved Sacramento River rearing conditions. A caveat with these improvements lies in the relative benefit of the flow mediated improvements versus the detrimental effects of warming spawning, rearing and Delta water temperatures.

Analyses of the EFT BDCP scenarios – all of which include changes in future climate and sea level – highlight the need for greater focus on efforts to mitigate for climate change itself. The magnitude of climate effects in the BDCP analyses shows the inadequacy of simply comparing whether certain operations are better or worse relative to a progressively deteriorating baseline, meanwhile ignoring the downward trend of the baseline itself. Studies which ignore such changes to the baseline divert attention from the cumulative total change in ecological conditions and can mask what can often be striking differences between historic operations and those proposed. Use of a historical reference case was recommended by the Delta Science Panel in its review of BDCP, even though the approach is unwelcome by some who feel that use of a historical record is a flawed reference with numerous shifts in operational standards and climate. The counterpoint to this critque is that the use of a historical reference case enables the study of the level of cumulative change, regardless of whether it is produced by climate change, changes in operations and conveyance, or increasing human water demand.

During the initial development of EFT's conceptual models and algorithms, communication between the physical driving models and EFT was completely unidirectional. The hydrologic models (CALSIM, DSM2 and related tools) provided input to EFT, which in turn was run to create multi-species ecological effects output. As we gained familiarity with the hydrologic models, it became apparent that the ability of EFT to simulate positive ecological outcomes could be harnessed to improve the rule-sets used in the physical models themselves. To test this ability, we conducted an initial pilot study using only a few of the 25 EFT indicators (for winter-run Chinook and Delta smelt) where analysis of EFT flow traces and conceptual models were used to create new rules for CALSIM that attempted to improve outcomes for these two focal species.

The initial pilot investigation demonstrated that the operation of the California water system can be changed to make timing of releases from Shasta Dam more beneficial to selected species without adverse consequences on storage and water exports. However, it also highlighted the inherent trade-offs between species and life-stages and how applying the same rule-set for a given water year type every year actually constrains options and contributes to the inability to adequately balance trade-offs.

Where To From Here?

There is a pressing need to develop greater awareness of the value of flexibility to manage ecosystem trade-offs over time within and among objectives. The detailed applications of EFT in Chapter 3 crystalize the fact that it is impossible to achieve all ecosystem objectives – let alone the co-equal goals of meeting human, agricultural and environmental needs – each and every year. There are plain, irreconcilable and ceaseless trade-offs that must be tracked and confronted, with winners and losers in different years depending on hydrologic conditions and priorities. These trade-offs do not occur because of a failure to create clever enough models that magically find the optimal solution; rather, an optimal solution does not exist. In Chapter 4 we describe a paradigm shift involving seeing balance as a condition which does not involve the same species or objectives losing (or winning) unnecessarily often. A key element is state-dependent priorities instead of one-size-fits-all water year rules. Under state-dependent priorities, flows are optimized for different species according to the recurrence interval necessary to support healthy population conditions along with ongoing tracking of the recent history of conditions and related ecosystem outcomes.

The further improvement of interaction between EFT and the hydrologic models is the current “leading edge” of inquiry for the EFT model. Implementing the new paradigm will require extending the modeling system by adding the capability to perform dynamic, state-dependent, multi-objective optimization with highly parallel simulations. This will enable the exploration of a much broader solution-space for multiple ecological criteria. An important aspect of this ongoing research is the application of ecosystem and water management rules which vary ("on", "off") according to the recent history of hydrologic conditions and the “most needy” ecological indicators.

Human communities, agricultural users and the ecosystems of the Sacramento River and San Joaquin-Delta are all facing very pressing challenges. EFT represents a large investment in the synthesis and integration of a vast body of knowledge and tools to respond to these challenges. It is a successful and rare example of a coupled, interacting model of operations, hydrodynamics, and multi-species ecosystem and geomorphic responses between the linked Sacramento River and Delta ecoregions; the kind of approach envisioned by the CALFED Science Advisory Panel in 2008, and subsequently by the Delta Science Council and a variety of other cross-disciplinary researchers (e.g., PPIC, UC Davis).

More than ever, there is great value and potential in the development and application of integrative modeling tools. EFT provides a robust framework for the joint collaborative work of experts and resource managers to come together to explore, develop, test and improve solutions to California's water management problems. Scientific uncertainties, coupled with the time required for iterative learning, will mean that the development of ecological flow recommendations will take many years and undergo periods of surprise and change. With its emphasis on specific cause-effect linkages based on functional flow, EFT provides a solid framework that remains open to testing, enhancement and adaptation over time.

Final Report

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Environmental & Cumulative Effects Assessment

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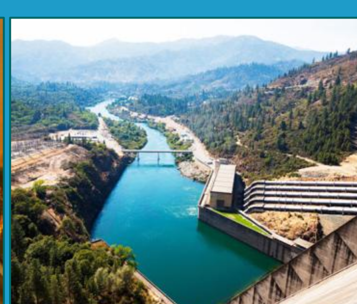

Aquatic Species at Risk & Water Resource Management

Terrestrial Ecology & Forest Resource Management