COMPOREHENSIVE STUDY INFORMATION PAPER:

TECHNICAL EVALUATION PROCESS

The purpose of this document is to describe how the various technical models or tools developed by the Comprehensive Study are used together to evaluate alternative scenarios and conditions. These tools include hydrologic, hydraulic, geotechnical, risk and economics. The tools can be used independently or in conjunction to perform various analyses. This document outlines the process by which information is passed between the tools to perform successive analyses and compare baseline and with-project results, the level of detail suitable to this type of analysis, and the assumptions inherent in the evaluation process.

COMPREHENSIVE STUDY TECHNICAL DATA AND TOOLS

There are four components to the technical evaluation process adopted by the Comprehensive Study:

- Synthetic hydrology
- Reservoir operation models (HEC-5)
- Geotechnical evaluation
- Hydraulic models (UNET, FLO-2D)
- Project Performance and Economics (FDA)

Information is passed between the various technical tools for any given condition or plan. The individual tools also provide information that may be used for numerous related but independent evaluations, such as reservoir reoperation or optimization, reach-specific hydraulics (such as channel capacity, scour potential, sediment transport, etc), and many others. The individual technical tools are described below, followed by a discussion of their role in the technical evaluation process.

Hydrology

Synthetic hydrology was developed for seven storm events (events with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year) for various storm centerings in the Sacramento and San Joaquin River basins. The five mainstem and 18 tributary storm centerings are based on patterns observed in gage data from historic events. The 30-day synthetic storm hydrographs are routed through the reservoir operations models to develop regulated flood hydrographs.

Reservoir Operations

HEC-5 reservoir operation models are used to simulate both headwaters reservoirs (upstream from the primary flood control reservoirs) and major flood control reservoirs in the Sacramento River and San Joaquin River basins. Unregulated, 30-day synthetic hydrographs are input to the reservoir operation models, which then simulate existing or proposed storage allocations, release schedules, objective flows, and other operational criteria. Two pairs of HEC-5 models are used, with one each in the Sacramento and San Joaquin River basins: headwaters HEC-5, and lower basin HEC-5. These models produce regulated hydrology (downstream from the major flood control reservoirs) that is used as input to the hydraulic models.

Geotechnical

A geotechnical analysis was performed to determine the stability and reliability of levees within the flood management system. A levee failure methodology was derived to determine at what elevation simulated flows could cause levees to fail. Levee reliability was simulated by developing a likely failure point (LFP) profile along both riverbanks on a reach-by-reach basis. The LFP represents the stage on the levee where there is a 50% probability of levee failure and is the basis for: identifying initial failure points in the levee, delineating floodplains, and determining in-channel stage-frequency relationships. The LFP is determined using the various levee failure curves that were developed to represent different levee conditions based on geotechnical data (soil type and geometry) and engineering judgment. The LFP elevation is used in the hydraulic models to trigger levee failures.

Hydraulics

The UNET hydraulic models cover the main channels and major tributaries of the Sacramento River and San Joaquin River. UNET is an unsteady, one-dimensional hydraulic model that uses detailed channel geometry and is capable of simulating weirs, bifurcations, storage, levees, and levee breaks. The upstream boundaries of the UNET models are where data are handed off from the hydrologic to the hydraulic analyses. Two-dimensional FLO-2D models were also developed for routing flood flows through large overbank and floodplain areas and are used to determine flood depth and extent (development of inundation areas for various flood frequencies). FLO-2D floodplain depths were also used to develop initial depth-damage relationships for economic evaluation, but FLO-2D is not used in the technical evaluation process for alternative plans. Hydraulic output from UNET is passed to the project performance and economic component in the form of stage- and discharge-frequency curves.

Project Performance and Economics

The Corps' primary model for performing flood damage reduction analysis is the Hydrologic Engineering Center's Flood Damage Reduction Analysis model (HEC-FDA, V 1.2), which integrates hydrologic, hydraulic, and geotechnical engineering and economic data. HEC-FDA incorporates uncertainty for risk-based analysis using a Monte-Carlo simulation procedure. Although HEC-FDA was designed to estimate urban flood damage, it was adapted for agricultural analyses. Each basin is divided into numerous economic impact areas that cover the valley floodplains and other flood-prone areas along the major tributaries.

The primary outputs of HEC-FDA that are used in project formulation and evaluation are project performance statistics and expected annual damages. Project performance statistics include the expected annual probability of flooding from all events in a given year, the long-term risk of flooding over specific time periods, and the conditional non-exceedence probability for specific events (probability of passing a specific flood event). Expected annual damage is calculated as the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge-exceedence probability, stage-discharge, and stage-damage relationships and their associated uncertainties.

TECHNICAL EVALUATION PROCESS

An iterative process is used to evaluate plans using the Comprehensive Study's technical tools. Through an iterative process, the Comprehensive Study's technical tools are used to evaluate alternative plans. It is important that these tools in the same manner to evaluate alternative plans to ensure that the comparison of results both with existing conditions and other alternatives is valid. The existing condition results provide a baseline for comparison with other alternative plans or scenarios and the determination of their hydraulic and economic impacts. The flow of information involves initial evaluation by the hydrologic models, which pass flow data to the hydraulic models, which in turn pass flow frequency information to HEC-FDA. This process is outlined below in **Figure 1**, and described in detail in the following sections.

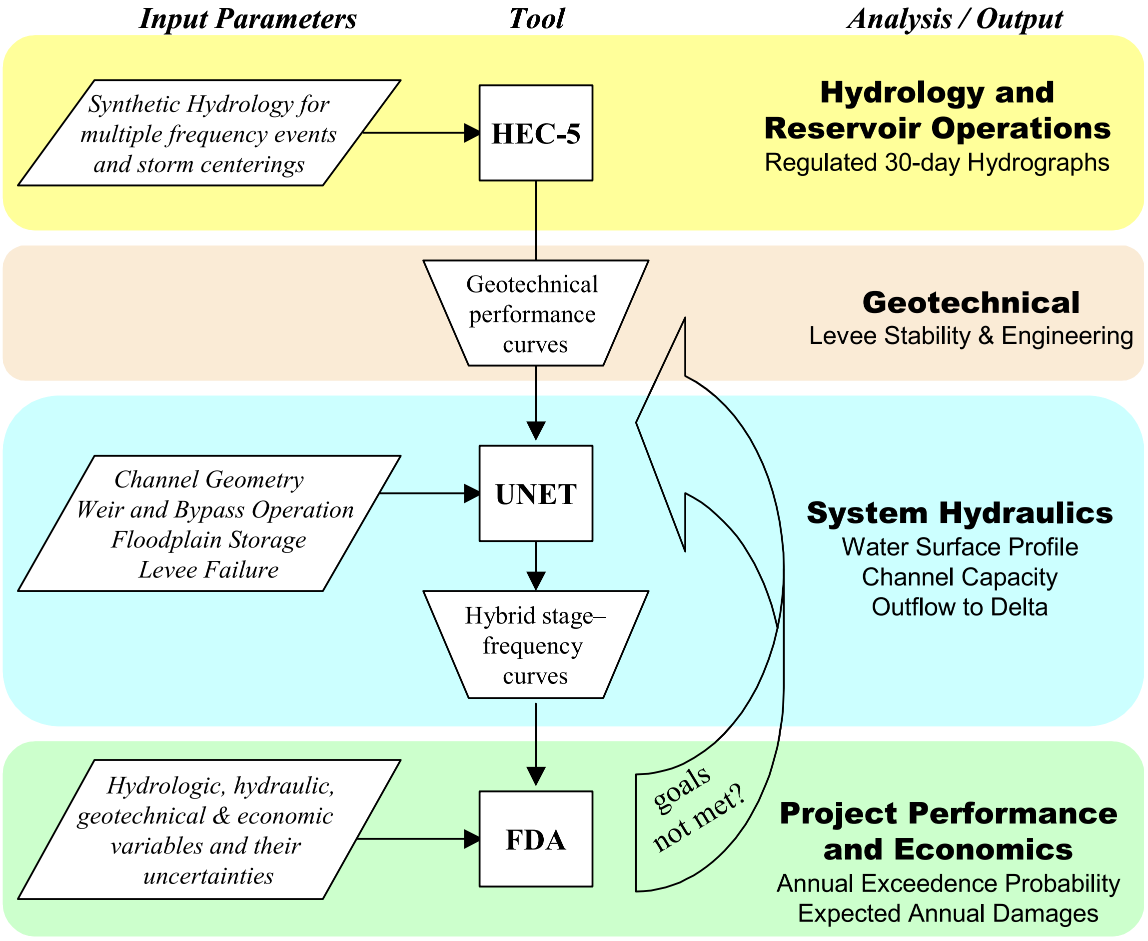


Figure 1 – Flow of Information Between Technical Tools

Hydrology and Reservoir Operations

Hydrology, in the form of 30-day unregulated hydrographs, is the starting point for any evaluation. Hydrographs are fed into the reservoir operations models to determine the impacts of existing storage facilities, expanding or reoperating existing facilities, or adding new storage facilities. The baseline hydrology is used if a plan or alternative does not include any changes to existing reservoir operations or storage. For each alternative, regulated hydrographs are developed for each of the seven storm events and each of the dominant storm centerings.

Geotechnical Performance

The chance of levee failure is represented through a geotechnical performance curve. This curve is the relationship between river stage and probability of geotechnical failure and is applied to each damage reach. The curves assume that damages can accrue in one of two ways: either the river stage becomes high enough to overtop the levee, or the stage rises significantly enough to cause geotechnical failure. The geotechnical performance of a levee depends on local soil conditions and construction and considers multiple modes of failure including under-seepage, through seepage, and strength instability.

The levee performance curves reflect a qualitative evaluation of the major geotechnical aspects of levee integrity. To define weak points within any particular reach, the likely failure points (LFP), probable non-failure points (PNP) and probable failure points (PFP) were defined along the reach’s levee. The PNP is the water surface elevation at which levee failure becomes *highly unlikely*, and the PFP is the water surface elevation at which levee failure becomes *highly likely*. For this study, the PNP is the point at which the chance of failure is 15 percent and the PFP is the point at which the chance of failure is 85 percent. As described previously, the LFP represents the point at which the chance of failure is 50% and is used by UNET to trigger levee failure. The PNP, PFP and LFP values are based on the results of field investigations, past levee stability calculations, levee performance in the 1997 and 1998 flood events, and engineering judgment.

For geotechnical and structural analysis, the factors affecting uncertainty are rare flood stresses and loads, geologic properties of foundations, seepage through and below levees, construction materials (sand vs. clay), and maintenance practices. Uncertainty in structural performance occurs due to a levee's physical characteristics and construction quality. The geotechnical performance curves are used with the stage-frequency curves (see Hydraulics, below) to calculate performance and economics in HEC-FDA.

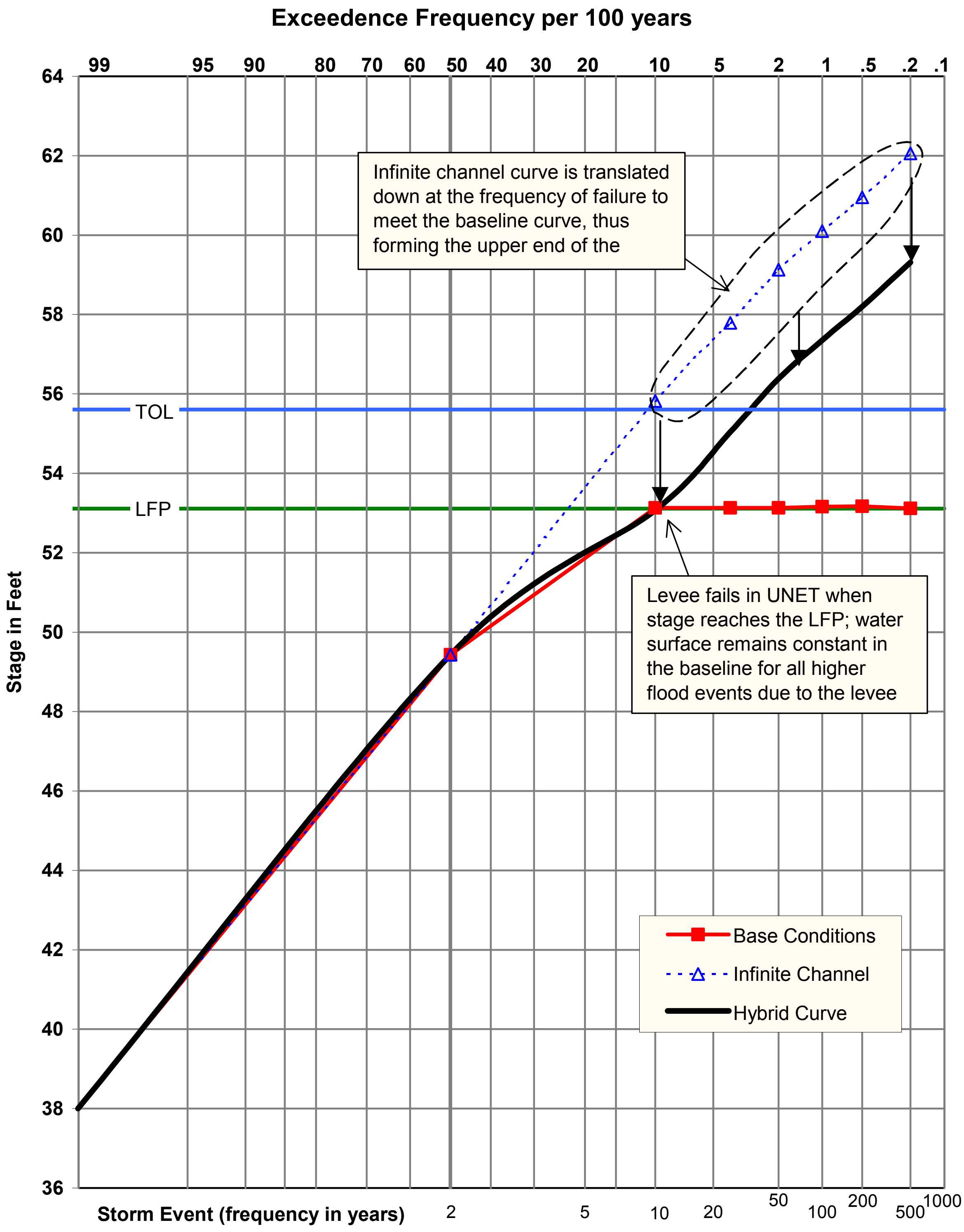
Hydraulics

The UNET hydraulic models route the regulated flood hydrographs through the system of tributary and mainstem channels in each basin for the various storm events and centerings. UNET is capable of reporting data at any of the thousands of cross sections in the models, but key index points have been chosen in each basin in order to make output analysis and handoff more manageable. Index points also provide the link between hydraulics and HEC-FDA (performance and economics).

The index point locations were chosen based on the first or initial breakout point within a river reach. In a given reach, this is the location where the first levee failure occurs in the baseline condition simulation, taking into account all storm centerings and frequencies. An index point is assigned to each economic impact area, providing a handoff point from UNET to HEC-FDA. For the baseline condition, the index point corresponds to the location where simulated flood damages would first begin to occur, representing the worst-case levee or bank condition within the reach. There are 62 index points in the Sacramento River Basin and 42 in the San Joaquin River Basin.

UNET modeling results are reported at each index point as a plot of event frequency versus water surface elevation. For example, the peak simulated water surface elevation produced by the various storm centerings for a 50-year flood event forms one point on the curve. Peak water surface elevations from UNET for the various centerings are plotted for each of the seven event frequencies and connected to form a stage-frequency curve.

For reaches with levees, the stage-frequency curve flattens or becomes horizontal at the point where the levee fails (at the LFP elevation). After failure, the water surface elevation remains relatively constant for all higher flow frequencies because flows are escaping into the floodplain through the levee break. The HEC-FDA model needs a complete stage-frequency curve to the top of the levee, so the upper end of the curve is extrapolated above the frequency of levee failure using the infinite-channel UNET run. The infinite channel run assumes that no levee breakouts occur (infinitely high LFP elevation) and that all water is contained within the main channels. The portion of the infinite channel frequency curve above the frequency of levee failure is translated down to meet the baseline (with-failure) curve where it intersects the LFP and flattens. The resulting hybrid curve, a combination of the with- and without levee failure scenarios, is then entered into HEC-FDA. Because no events less than a 2-year event are modeled, the slope of the curve between the 2-year and 10-year plot points is used to extend the curve downward to intersect the y-axis. The development of the hybrid stage-frequency curve is shown in **Figure 2**.



Infinite channel curve is translated down at the frequency of failure to meet the baseline curve, thus forming the upper end of the

Levee fails in UNET when stage reaches the LFP; water surface remains constant in the baseline for all higher flood events due to the levee

Figure 2 – Construction of the Hybrid Stage-Frequency Curve

Project Performance and Economics

FDA integrates input from the hydrologic, geotechnical and hydraulic technical tools in a risk-based analysis. Input data includes information relating to the uncertainty of the hydrologic data (such as period of record), levee performance curves, stage-frequency curves from UNET, and economic data (such as land use and property value). ***The primary outputs of HEC-FDA that are used in project formulation and evaluation are project performance and economic performance.***

A basic understanding of statistics and the Corps' risk and uncertainty practices is desirable in order to properly interpret the results from HEC-FDA. This section will provide a brief overview, but further reading materials are listed at the end of this document under Technical Resources. Exceedence probability reflects the probability that an event will occur or be exceeded in any given year.

Project Performance

The three primary project performance or flood risk results reported by HEC-FDA are annual exceedence probability, long-term risk, and conditional non-exceedence probability.

> **Annual Exceedence Probability (AEP):** AEP is a measure of the likelihood that an area will be flooded in any given year, considering the full range of floods that can occur and all sources of uncertainty (NRC 2000). For example, the 0.01 exceedence probability event has one chance in a hundred or a one percent chance of occurring in a given year. The 0.01 exceedence event is often misleadingly termed the 100-year event (by taking the inverse of 0.01), but it does **not** statistically represent an event that will occur once in 100 years. For instance, someone living in a 0.01 or 100-year frequency floodplain has a one in four chance of experiencing flooding during a 30-year period. Because the terms can be misinterpreted, several results from HEC-FDA are used to properly communicate flood risk.
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> **Long Term Risk (LTR):** Long-term risk is the probability of damages occurring during a specified period of time. LTR is reported for 10-year, 25-year, and 50-year time periods. For example, a value of 0.850 for the 25-year reporting period reflects an 85% chance of flood damages during a 25-year period.
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> **Conditional Non-Exceedence Probability by Events (CNE):** Conditional non-exceedence is the probability of safely containing an event with a known frequency, should that event occur. CNE is reported for the 10%, 4%, 2%, 1%, 0.4%, and 0.2% probability events. For example, a value of 0.04 for the 2% event corresponds to a four percent chance of passing the 2% or 50-year frequency flood.

Although these measures of risk seem similar, there are distinct differences between them. AEP accumulates all the uncertainties into a single value, whereas CNE is conditional on the severity of the flood event. Further, while AEP describes the likelihood that flooding *will occur*, CNE describes the likelihood that flooding *will not occur* during a given year (NRC 2000). Other agencies also use these measures of risk and uncertainty. For example, FEMA uses conditional non-exceedence in its certification criteria for levees, requiring a 90% probability of containing the 1% event.

Economic Performance

Economic performance is expressed in terms of expected annual damages (EAD). In a risk-based analysis, EAD is defined as the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge-exceedence probability, stage-discharge, and stage-damage relationships and their associated uncertainties. It is calculated as the integral of the damage-probability function. EAD is used to calculate the Corps' National Economic Development (NED) objective (as described in USWRC 1983). NED is communicated as a ratio of project benefits to project costs and is commonly referred to as the B-C ratio.

ITERATION PROCESS

Iterations are performed within each analysis tool and between the tools until the planning goals or objectives are met. For example, successive iterations might be performed within UNET until a target water surface is achieved only to find that the risk target for that area was not met in HEC-FDA. In this case, additional iterations between UNET and HEC-FDA may be required until the risk target is also achieved. Adjustments may also be made directly to the stage-frequency curves, rather than going back to UNET, to fine-tune HEC-FDA results.

The number of iterations performed both within the models and between the models is largely dependent upon the type and number of planning objectives set for a particular plan and the level of detail desired. Initial simulations may be performed that examine only a few key index points to quickly narrow in on the targets; a final simulation examining all index points would be performed to refine the plan. Similarly, an expedited analysis process was developed to decrease the amount of time required to arrive at a plan that meets specified objectives. This expedited process is described below.

Expedited Analysis

Generating hybrid stage-frequency curves from the hydraulic models and passing this data to HEC-FDA is one of the most time-consuming steps in the technical evaluation process. During early iterations it may not be necessary or time-efficient to examine all index points and damage areas. As an alternative to generating stage-frequency curves and HEC-FDA output at all of the index points and corresponding damage areas in each basin, the index points and damage areas were grouped into larger, "bubble" areas for quick analysis. There are nine bubble areas in the Sacramento River Basin and seven in the San Joaquin River Basin, shown in **Figures 3 and 4**. One index point is chosen to represent all damage areas within a bubble area. The index point is chosen based on several factors including stage conditions, topography, initial breakout, and significance of damages caused. The hydrology and reservoir operation stages of the process do not change, and hydrographs from all frequency events are still run through UNET. Iteration is stopped when the HEC-FDA risk results are within an acceptable margin of either the baseline conditions or specific risk targets.