Memorandum

Date:	~~Friday, April 24, 2020~~ ~~Revised Friday, May 22, 2020~~ Revised Thursday, July 02, 2020
Project:	Lake Mendocino Forecast-Informed Reservoir Operations (FIRO) Full Viability Assessment (FVA) Water Control Plan (WCP) Alternative Analysis
To:	Jay Jasperse, PE and Chris Delaney, PE
From:	Michael Konieczki, PE (CA Lic. # 74357), D.WRE; Joanna Leu, PE; Ric McCallan, PE; and Huck Rees
Subject:	Proposed Procedure for Consequence Analysis

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Background

In 2014, Sonoma Water (SW) undertook a study to confirm the agency could manage Lake Mendocino storage more efficiently for authorized project purposes by integrating reservoir inflow forecasts explicitly in release schedule decision making. That study—which was referred to as the Preliminary Viability Assessment (PVA)—confirmed SW could increase water supply benefit without adversely affecting the flood risk reduction capability if forecast-informed reservoir operation (FIRO) procedures were used. The U.S. Army Corps of Engineers (USACE), which is responsible for flood operation of Lake Mendocino, agreed with the finding and subsequently approved SW's request for a major deviation from the Lake Mendocino Water Control Plan (WCP). This temporary deviation permitted SW greater flexibility in managing Lake Mendocino storage, pending additional investigation that would support incorporation of FIRO procedures in a formal revision of the WCP.

The PVA evaluated candidate FIRO strategies in a reconnaissance-level technical study, confirming viability of FIRO in concept. However, the PVA did not recommend a single specific strategy for integrating FIRO into a future WCP. That task is to be completed in a subsequent planning study—the Full Viability Assessment (FVA). The objective of the FVA is to identify, through appropriate detailed technical analyses and other considerations, the best FIRO strategy for Lake Mendocino, along with the manner in which it can be implemented in real-time operation by SW and USACE and the WCP changes necessary to permit that change permanently.

The FVA is managed by the Lake Mendocino FIRO Steering Committee (SC), who identified technical studies consistent with USACE guidance needed for FIRO strategy analysis. The SC prepared a hydrologic engineering management plan (HEMP) that is "a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem" (FIRO SC 2019). The objective of the HEMP is to identify and evaluate Lake Mendocino FIRO alternatives in a systematic, defendable, and repeatable manner, providing information to the SC so it may recommend a FIRO strategy.

According to the HEMP, the alternatives must be evaluated in terms of how they change flood risk, based on the following metrics:

- M8 – Expected annual inundation damage (EAD) at critical Russian River locations.

- M9 – Expected annual potential (statistical) loss of life (EALL) due to floodplain inundation at critical Russian River locations.

The alternatives will also be evaluated based on other metrics, such as annual maximum frequency functions at Lake Mendocino, Lake Sonoma, Hopland, Cloverdale, Healdsburg, and Guerneville; ability to meet minimum instream flow requirements during rearing and spawning seasons; and impacts to recreation, operations, and power supply.

Task

We have developed a proposed procedure to compute EAD and EALL for the FVA. It prescribes application of a consistent computational method to yield EAD and EALL results that are comparable between the baseline condition and alternatives. This memorandum documents the proposed procedure identifying the tools, methods, organizational responsibilities, and workflow required.

Procedure

In this section we provide an overview of the study area, discuss analysis considerations, and detail the methodology for computing EAD and EALL.

Study Area

Lake Mendocino, formed by the impoundment of the East Fork of the Russian River by the Coyote Valley Dam, is located 3 miles east of the City of Ukiah. Figure 1 shows its location. The 1,485-square mile Russian River watershed is a narrow valley between 2 adjacent northern coastal mountain ranges. The watershed is about 100 miles long and varies from 12 to 32 miles in width. Inflows to Lake Mendocino include diversions from an upstream hydroelectric facility and runoff from an approximately 105-square-mile drainage area. Water from Lake Mendocino flows generally south down the East Fork Russian River until its confluence with the Russian River mainstem. Flow continues south near the towns of Hopland, Cloverdale, and Healdsburg. Just south of Healdsburg, Dry Creek flows into the Russian River from the west. The Russian River continues west past Guerneville to the Pacific Ocean.

The damage reaches and associated index points are in the process of being identified. The final damage areas and index points will be approved by the study team.

Analysis Considerations

Hydrologic Considerations

The primary factor driving the consequence analysis workflow is the limited availability of historical ensemble forecast information (hindcasts) in the hydrologic dataset. The California Nevada River Forecast Center (CNRFC) of the National Weather Service (NWS) has created a limited series of hindcasts and scaled ensembles. All alternatives analyzed will use the same hydrologic dataset. This dataset includes:

- Historical reservoir inflow and downstream local flows; the local flows are computed by the CNRFC.

- Hindcasts for the period of record (POR) of 1/1/1985 through 9/30/2017. This period includes the largest annual events for water year (WY) 1985 to WY 2017.
- Design events that represent events rarer than those seen in the hindcast period. Specifically, CNRFC created 8 design events based on 2 scalings of 4 historic event patterns. This data set includes reservoir inflows, coincident downstream local flows, and associated ensembles representing forecast information for the design event. The 8 design events are listed in Table 1.

Further descriptions of the hindcast and ensemble development can be found in the *Development of Forecast Information Requirements and Assessment of Current Forecast Skill Supporting the Preliminary Viability Assessment of FIRO on Lake Mendocino* report from CNRFC (CWE3E 2017).

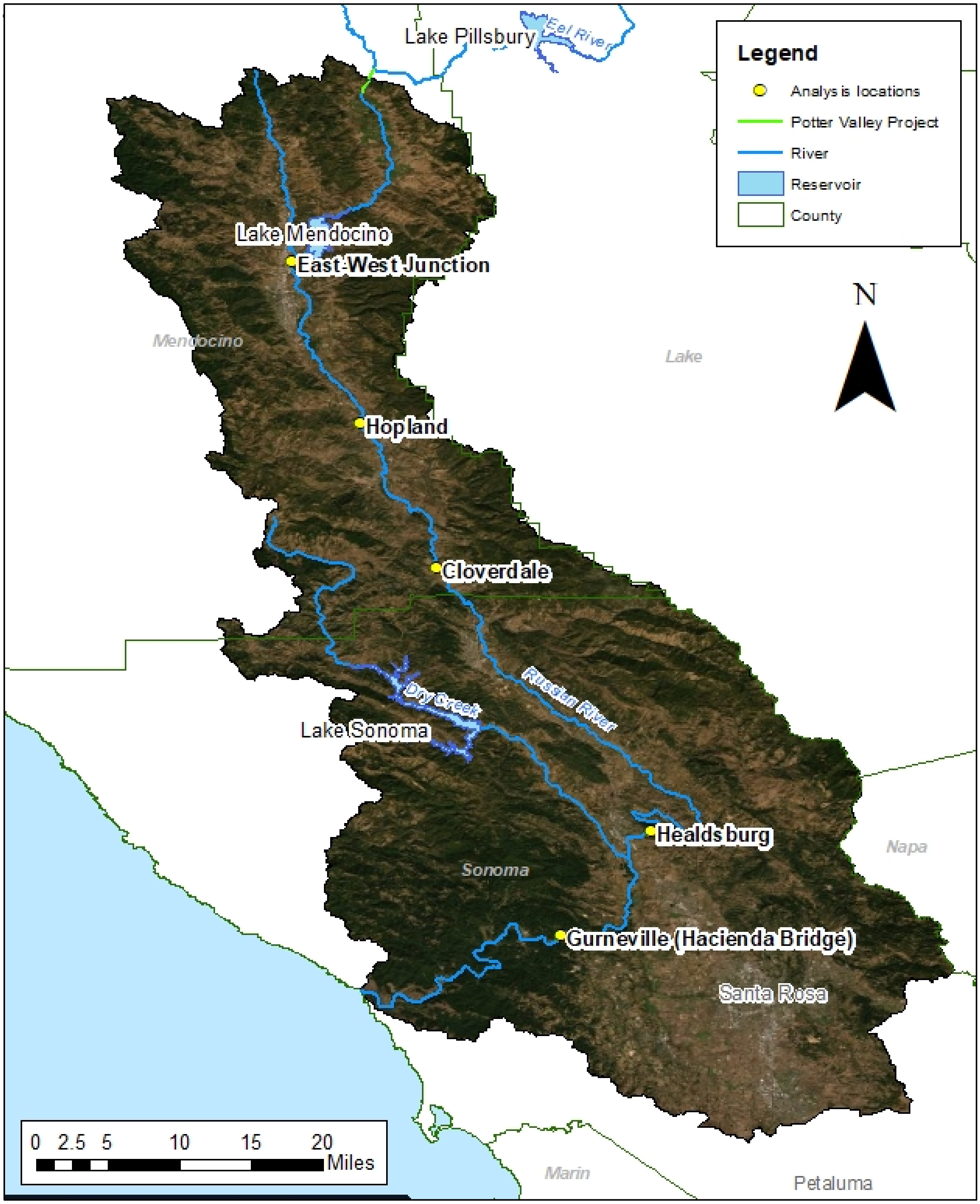


Figure 1. Map of Russian River watershed, including Lake Mendocino

Table 1. Design events

ID (1)	Event Year (2)	AEP/Scaling (3)
1	1986	p=0.005 (200-year)
2	1986	p=0.002 (500-year)
3	March 1995	p=0.005 (200-year)
4	March 1995	p=0.002 (500-year)
5	1997	p=0.005 (200-year)
6	1997	p=0.002 (500-year)
7	2006	p=0.005 (200-year)
8	2006	p=0.002 (500-year)

Hydraulic considerations

HEC and SW have developed a one-dimensional HEC-RAS model of the Russian River system. HDR obtained the model and completed test routings for 4 historic flood events (1986, March 1995, 1997, and 2006). We found that the flow-stage relationships at various points in the system vary based on reservoir releases and downstream local inflows. For this reason, unique channel stage-frequency relationships for each event pattern and operation alternative are required as input to the consequence analysis.

Methodology

Overview

Our proposed methodology will use historical streamflow information and hydrologic datasets from CNRFC hindcasts in addition to scaled event datasets (including associated ensembles) as input to HEC computer programs HEC-ResSim, HEC-RAS, HEC-FIA, and HEC-FDA. We will use these programs to compute consequences for the baseline condition and proposed alternatives in the FVA. Figure 2 shows the general overall workflow for each alternative. Each of the steps listed below are discussed in greater detail in the following sections.

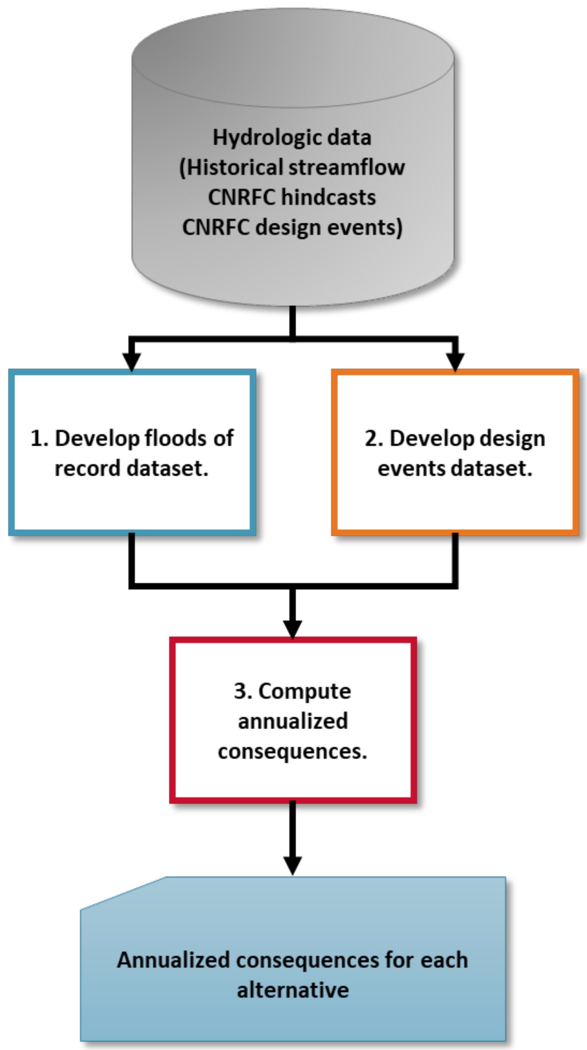
- **Step 1. Develop Floods of Record Dataset.** Reservoir outflows and local inflows from historical streamflow data will be used to identify annual peak flow events for the POR from WY 1985-2017. These floods of record will be hydraulically routed and consequences (flood damage and life loss) for each annual peak flow will be computed. For WCP alternatives that require forecast information, the hindcast dataset will be used as forecast information.

- **Step 2. Develop Design Events Dataset.** Design events (based on 2 historical event patterns scaled to match outflows for the p=0.005 (200-yr) and p=0.002 (500-yr) events will be used to determine reservoir outflow for the baseline condition and proposed alternatives. Reservoir outflows and local inflows will be hydraulically routed and consequences (flood damage and life loss) for each design event computed. For WCP alternatives that require forecast information, the ensembles associated with each event will be used.

- **Step 3. Compute Annualized Consequences.** The outputs from Steps 1 and 2 will be combined to create the necessary HEC-FDA input functions for each of the 4 event patterns. These will be used to calculate EAD/EALL for each of the 4 event patterns. The EAD/EALL for the 4 event patterns will be averaged to determine the final EAD/EALL of the chosen alternative.

This methodology will be repeated for each alternative.

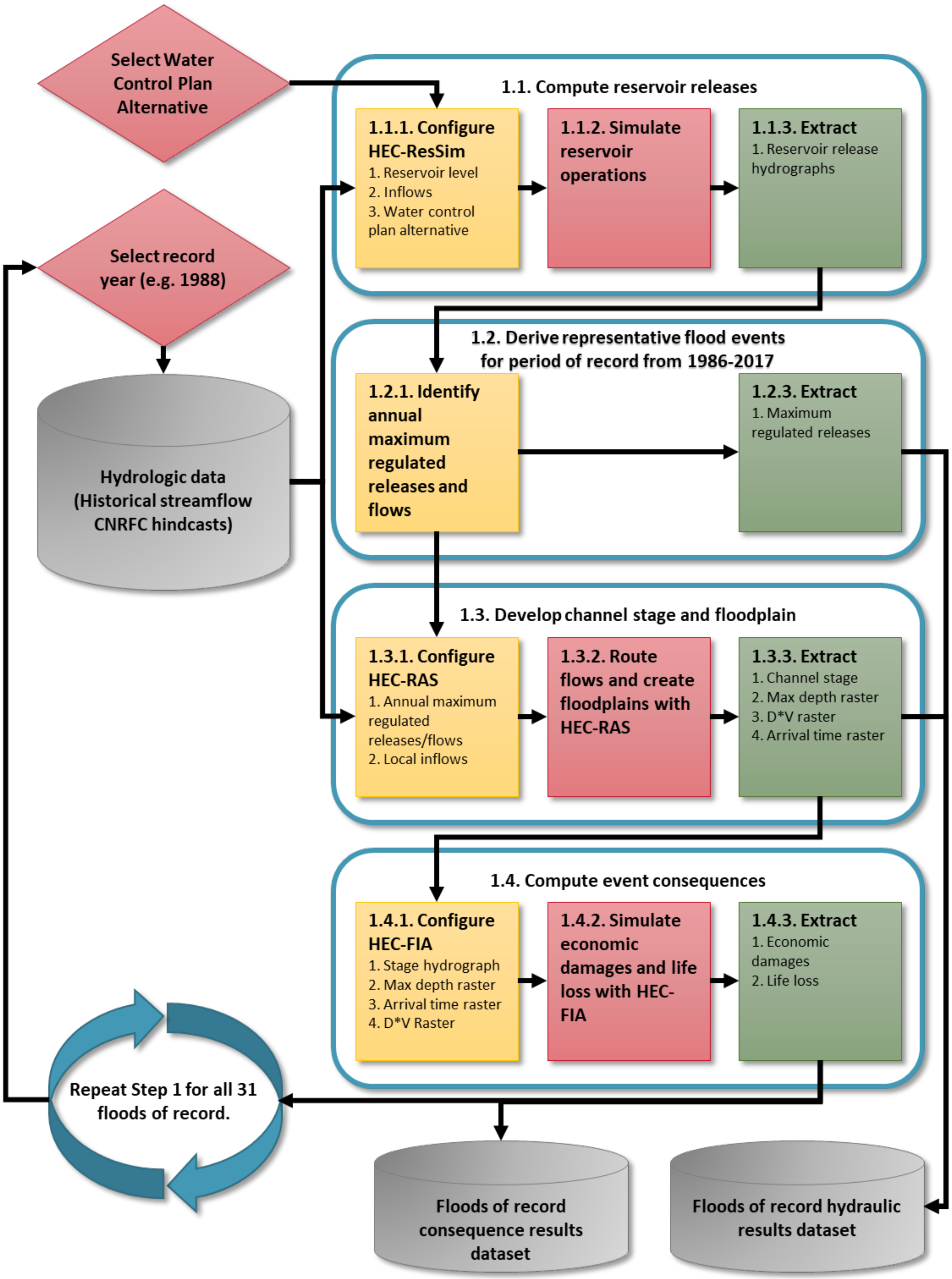
Figure 2. Overview of proposed consequence analysis methodology for Lake Mendocino FVA



Step 1: Develop Floods of Record Dataset

Step 1 relies on input data from historical streamflows and CNRFC hindcasts for the POR from WY 1985 to 2017. Figure 3 shows the proposed detailed workflow for Step 1, including required input data, processes, and output data.

Figure 3. Proposed workflow for Step 1. Develop floods of record dataset



1.1 Compute reservoir releases

The HEC-ResSim model (version 3.3) developed by HEC will be used to determine the reservoir releases from Lake Mendocino and Lake Sonoma for the POR from WY1985 to 2017 for each WCP alternative. HEC and SW will be responsible for configuring and running the HEC-ResSim model. Specifically, HEC will configure the baseline and 5-day deterministic forecast alternatives, and SW will configure the EFO, Hybrid (2019 Major Deviation), and Modified Hybrid alternatives. An HEC-DSS file with the reservoir releases from Lake Mendocino and Lake Sonoma from WY 1986 to 2017 will be used as input to the HEC-RAS model described in section 1.3 below.

1.2 Derive representative flood events for POR from WY1985-2017

The POR reservoir releases for Lake Mendocino from Step 1.1 will be reviewed to identify the largest flood event in each WY based on unregulated reservoir inflows.

The start and end date and time for each annual event will be determined from reservoir inflow and release hydrographs. The start points in the hydrograph will be set when inflow exceeds the baseline inflow and end points in the hydrograph will be set when outflow returns to the baseline outflow. This will be used as the simulation window for each of the HEC-RAS simulations described in Step 1.3.

1.3 Develop channel stage and floodplains

The HEC-RAS model (version 5.0.3) developed by SW will be used to route reservoir releases from Lake Mendocino and Lake Sonoma and downstream local flows (provided by the CNRFC). Reservoir releases determined in Step 1.1 for annual flood event durations and determined in Step 1.2 will be routed down Dry Creek and the Russian River to the Pacific Ocean. SW will be responsible for configuring and running the HEC-RAS model for the 31 annual events for each alternative using data supplied by CNRFC and HEC from Steps 1.1 and 1.2. HEC-RAS Mapper will be used to develop the following results for each simulation:

1. Maximum depth raster.
2. Maximum Depth*Velocity raster.
3. Arrival time to 2 ft raster.
4. An HEC-DSS file with the stage and flow hydrograph outputs for all cross sections in the model.

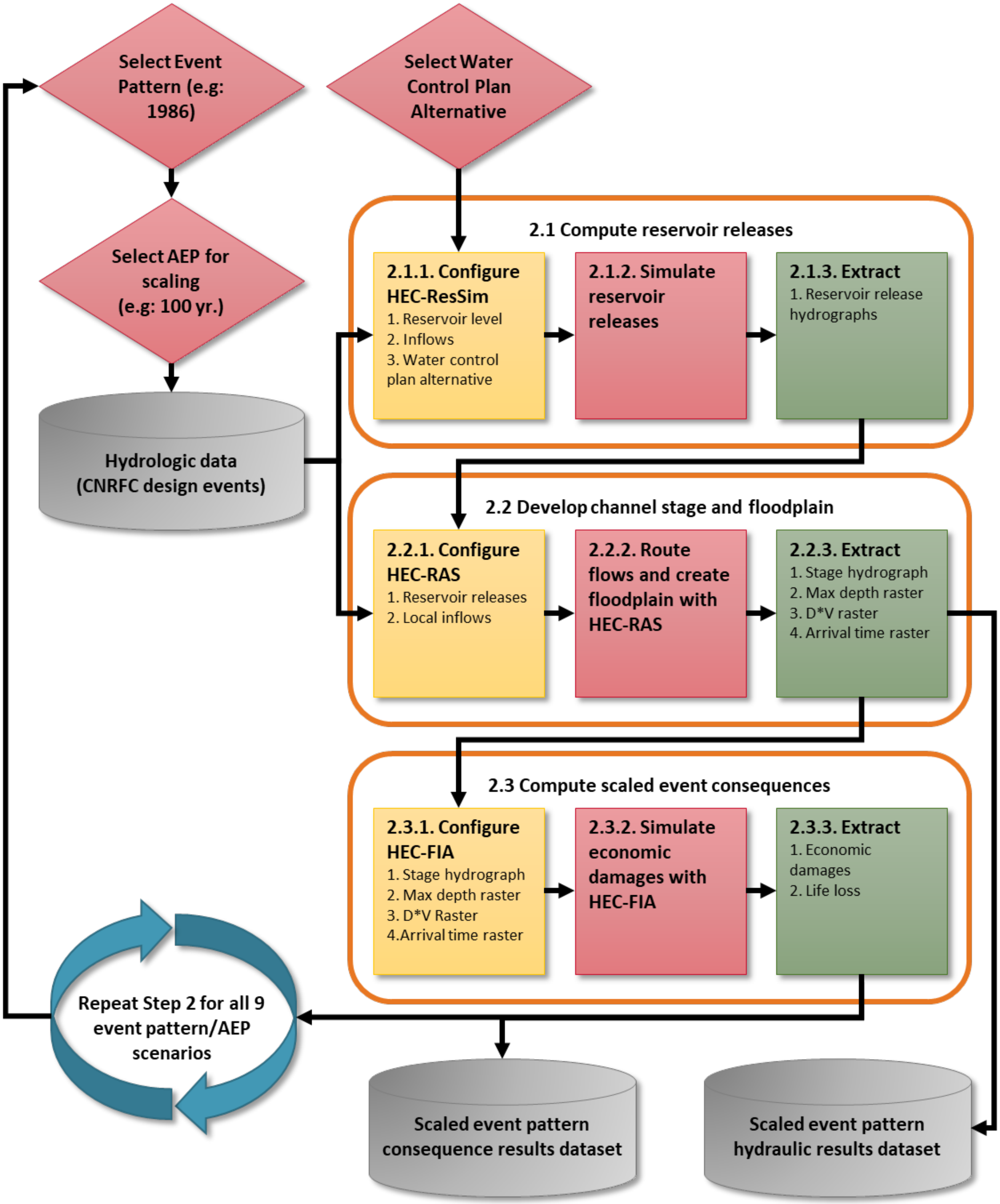
1.4 Compute event-specific consequences

The HEC-FIA model (version 2.2) developed by HEC will be used to compute event-specific consequences, specifically flood damages and life loss. HDR will be responsible for configuring and running the HEC-FIA model for the 31 annual maximum flow events for each alternative using the data supplied by HEC and SW from Step 1.3. Flood damages and life loss for each damage reach will be computed for each alternative.

Step 2: Design Events Dataset

Step 2 methodology for computing consequences is similar to methodologies presented in Step 1. The 9 design events chosen for the analysis represent rarer events than those seen in the POR events used in Step 1. Figure 4 shows the proposed workflow for Step 2.

Figure 4. Proposed workflow for Step 2. Develop design events dataset



2.1 Compute reservoir releases

The HEC-ResSim model developed by HEC will be used to determine reservoir releases from Lake Mendocino and Lake Sonoma for the design events. HEC and SW will be responsible for configuring and running the HEC-ResSim model. Specifically, HEC will configure the baseline and 5-day deterministic forecast alternatives, and SW will configure the EFO, Hybrid (2019 Major Deviation), and Modified Hybrid alternatives. An HEC-DSS file with the reservoir releases from Lake Mendocino and Lake Sonoma for each of the design events will be used input to the HEC-RAS model described in Step 2.2 below.

2.2. Development of channel stage and floodplains

The HEC-RAS model developed by SW will be used to route reservoir releases from Lake Mendocino and Lake Sonoma and local flows for each of the 9 design events down Dry Creek and Russian River to the Pacific Ocean. SW will be responsible for configuring and running the HEC-RAS model for each alternative using the data supplied by CNRFC and HEC from Step 2.1. HEC-RAS Mapper will be used to develop the following results for each simulation:

1. Maximum depth raster.
2. Maximum Depth*Velocity raster.
3. Arrival time to 2 ft. raster
4. An HEC-DSS file with stage and flow hydrograph outputs for all cross sections in the model.

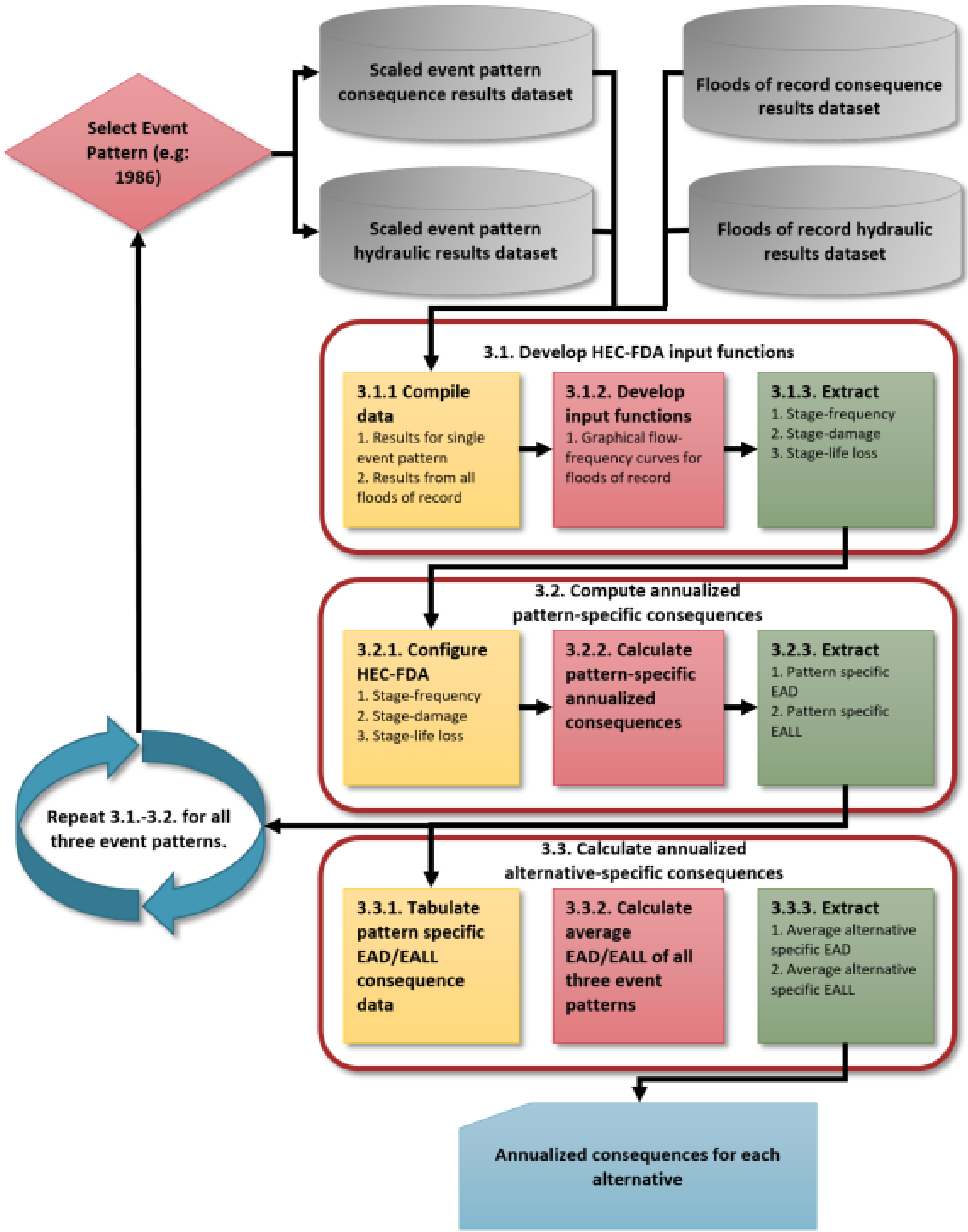
2.3 Compute event consequences

The HEC-FIA model developed by HEC will be used to compute event specific flood damages and life loss. HDR will be responsible for configuring and running the HEC-FIA model for the 9 design events for each alternative using data supplied by SW form Step 2.2. The flood damages and life loss for each damage reach will be computed for each simulation.

Step 3: Compute Annualized Consequences

Step 3 involves combining the stage, damage, and life loss outputs from the HEC-RAS and HEC-FIA models from Steps 1 and 2 to develop stage-frequency, stage-damage, and stage-life loss functions used as input to HEC-FDA. HEC-FDA will be used to calculate EAD/EALL for a given event pattern and alternative. Figure 5 shows the proposed detailed workflow for Step 3.

Figure 5. Proposed workflow for Step 3. Compute annualized consequences



3.1. Develop stage-frequency, stage-damage, and stage-life loss functions

The EAD and EALL will be determined for each of the 4 historical patterns using HEC-FDA. Stage-frequency, stage-damage, and stage-life loss functions will be developed using the POR and design event results from steps 1 and 2. These functions will be developed outside of HEC-FDA before being used as inputs to the model for each damage reach analyzed. HDR will be responsible for developing the suite of functions for each the 4 historical patterns required for input into HEC-FDA using the results provided by HEC-RAS and the HEC-FIA models.

Stage-frequency curves

The floods of record provide 31 stage-frequency points from Steps 1.2 and 1.3. The annual maximums will be used to develop a graphical stage-frequency relationship for each alternative corresponding to the POR of 1/1/1985 through 9/30/2017; Water Years (WY) 1985-2017. This will entail ranking the annual maximum flows; assigning plotting positions based on rank and POR; and plotting the flow-frequency relationship.

The design events provide 2 discrete stage points for the p=0.005 (200-yr) and p=0.002 (500-yr) events for each of the 4 historical patterns from Step 2.2. The results of the design events for each historical pattern will be plotted along with the floods of record to create a stage-frequency curve for each of the historical patterns for a total of 34 points. The 31 stage frequency points from the floods of record will be the same for each of the historical patterns.

The uncertainty in a stage-frequency relationship in HEC-FDA is described using an equivalent record length. Therefore, we will adjust the equivalent record length to account for the uncertainty in both the flow-probability and flow-stage relationships. Equivalent record length will be determined by identifying the total uncertainty in the flow-probability and flow-stage relationships for the p=0.01 (100-yr) annual exceedance event, and then iteratively adjusting the stage-frequency equivalent record length until the uncertainty matches the total uncertainty identified for the p=0.01 exceedance event.

Stage-damage curves

The stage damage function will be developed by combining the stage at the index locations with the total damages for the damage reach. For each of the 4 historic patterns (1986, March 1995, 1997, and 2006) the 31 POR events from Steps 1.3 and 1.4 will be combined with the 4 design events (corresponding to the p=0.005 and p=0.002 scalings) to create a unique stage-damage function.

Stage-life loss curves

The stage-life loss function will be developed by combining the stage at the index locations with the total life loss for the damage reach. For each of the 4 historical patterns (1986, March 1995, 1997, and 2006) the 31 POR events from Step 1.3 and 1.4 will be combined with the 4 design events (corresponding to the p=0.005 and p=0.002 scalings) to create a unique stage-life loss function. For the purposes of this analysis life loss will be treated as a “damage” for use in the HEC-FDA model.

Additional points

HEC-FDA requires stage-frequency relationships to span from p=0.999 (1-yr) to the p=0.001 (1,000-yr) events. To accurately capture the full range of damages and life loss, the stage-damage and stage-life loss relationships should extend from the stage equivalent to no damage/life loss to the damage/life loss at the maximum possible stage of the stage-frequency curve. In order to provide the required functions, additional points will be added at the lower and upper limits of the stage-frequency, stage-damage, and stage-life loss functions using the following assumptions:

- The lower end of the stage-frequency relationship will be set to p=0.999 at a stage 0.1 ft. above the channel invert
- The lower end of the stage-damage relationship will be set to damage of $0 at a stage 0.1 ft. above the channel invert.
- The lower end of the stage-life-loss relationship will be set to damage of 0 lives lost at a stage 0.1 ft. above the channel invert.
- The upper end of the stage-frequency relationship p=0.001 (1,000-yr) stage will be set to p=0.002 (500-yr) stage.
- The upper end of the stage-damage relationship p=0.001 (1,000-yr) stage will be set to p=0.002 (500-yr) damage.
- The upper end of the stage-life loss relationship p=0.001 (1,000-yr) stage will be set to p=0.002 (500-yr) loss.

3.2. Compute annualized pattern-specific consequences

HEC-FDA will be used to compute EAD and EALL for each damage reach for the 4 historical patterns analyzed. HDR will be responsible for configuring and running the HEC-FDA model (version 1.4.2). The stage-frequency, stage-damage, and stage-life loss functions developed in Step 3.1 will be input into HEC-FDA for each historical pattern.

3.3. Calculate annualized alternative specific consequences

The EAD and EALL for the 4 event patterns will be averaged for each damage reach to develop the overall EAD/EALL for each alternative.

References

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