# EXPLORATION OF FLOODPLAIN REACTIVATION AT A LANDSCAPE SCALE WITHIN THE SACRAMENTO VALLEY: BASELINE HYDRODYNAMIC MODEL DEVELOPMENT FOR THE BUTTE BASIN, COLUSA BASIN, AND SUTTER BYPASS

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# TABLE OF CONTENTS

## LIST OF TABLES



## LIST OF FIGURES

# GLOSSARY OF ACRONYMS

| Acronym | Meaning |
|---|---|
| 1D | One-dimensional |
| 2D | Two-dimensional |
| AFP | Adult Fish Passage |
| BNP | Big Notch Project |
| cbec | cbec eco engineering, inc. |
| cfs | Cubic feet per second |
| CNRFC | California Nevada River Forecast Center |
| CVFED | Central Valley Floodplain Evaluation and Delineation Program |
| CVFPP | Central Valley Flood Protection Project |
| DEM | Digital elevation model |
| DWR | Department of Water Resources |
| ft | Feet |
| NWR | National Wildlife Refuge |
| RMSE | Root mean square error |
| SBMP | Sutter Bypass Management Plan |
| SPFC | State Plan for Flood Control |
| SRFCP | Sacramento River Flood Control Project |
| USDA | United States Department of Agriculture |
| USGS | United State Geological Survey |
| WSE | Water surface elevation |

# 1 OVERVIEW

Large-scale hydrodynamic models were developed to assess the existing conditions (baseline conditions) of the Sacramento Valley floodplain regions in the Butte Basin, Colusa Basin, and Sutter Bypass. Coupled one-dimensional (1D) / two-dimensional (2D) models were developed for the Butte and Colusa Basins and an existing model of the Sutter Bypass was enhanced to support hydro-spatial analyses in these basins and bypasses. These models simulate existing hydraulic conditions including timing, inundation characteristics (depth and velocity) and hydrologic variability across multiple water years. The baseline hydraulic conditions simulated by the model establish a reference point by which future actions will be compared regarding ecological outcomes and potential impacts.

This modeling effort aims to support the Floodplains Reimagined Program (Program) goals of understanding the Sacramento River Valley's potential for voluntary measures to increase the frequency and duration of shallow inundation in the winter months through increased connectivity with the Sacramento River. Increasing shallow inundation has the potential to 1) improve juvenile salmon migration and access to productive rearing habitat, 2) reduce adult fish passage impediments, 3) improve Pacific Flyway bird populations, 4) improve groundwater recharge, while respecting flood management functions and protecting existing property uses and water rights.

The results from these hydrodynamic models will feed into other models and habitat analyses to help meet the overarching goals of the Program (Figure 1). The hydrodynamic models will produce depth, velocity, inundation area, and duration information, which are inputs into hydrospatial and bioenergetic habitat models to assess habitat suitability for juvenile salmon, waterfowl, and shorebirds. The hydrodynamic model outputs are also used to assess land use impacts for agricultural production, wetland management, and waterfowl hunting. The metrics produced by these tools will be used to understand the baseline habitat conditions and land use impacts in the basins. The next step will be to compare the model results between the baseline conditions and potential future actions that fall within four major categories:

- Floodplain Connectivity
    - Modification or addition of connections between the river and the floodplain
- Floodplain Flow Corridors
    - Modification of water management infrastructure
- Floodplain Reactivation for Fish Food
    - Modification of water management within the field units
- In-river Function
    - Improve existing floodplain habitats within the river corridor

# 2 MODEL SETTING

Three hydrodynamic models were developed to represent the baseline hydraulic conditions from October to June for the Butte Basin (Butte Model), Colusa Bains (Colusa Model) and Sutter Bypass (Sutter Model). Baseline conditions in these models assume that some recent and near-future construction projects have been completed and are operating in all baseline model runs. This includes the Fremont Wier Adult Fish

Passage Project (built), the Fremont Weir Big Notch Project (in construction), Tisdale Weir Adult Fish Passage (scheduled for construction), Lower Elkhorn Basin Levee Setback Project (in construction), and the Sacramento Weir Widening (in construction). The baseline conditions also include winter water management on fields, but not water management during the agriculture season.

The Butte, Colusa, and Sutter models were developed using the 2020-10-AE TUFLOW model version. This model version uses the TUFLOW HPC solver for the full 2D Shallow Water Equations. All project data are referenced to the NAD 1983 State Plane California Zone 2 (FIPS 0402 US Feet) horizonal projection and the NAVD88 vertical datum (Feet).

Unless otherwise noted, model development information for the Sutter Model is documented in "Tisdale Weir Rehabilitation and Fish Passage Project: Flow Analysis – Baseline Model Calibration and Validation Report" (DWR, 2020) and the cbec Technical Memorandum "Enhancements to the Tisdale Weir Rehabilitation and Fish Passage Project TUFLOW HPC Model," (Appendix A).

## 2.1 MODEL DOMAIN

Figure 2 shows the three modeling domains. Each of the three basins has an associated 1D/2D TUFLOW model. The Butte model encompasses the northernmost domain, representing the Sacramento River in 1D from Hamilton City to Wilkins Slough. The 1D Sacramento River is connected to the 2D basin / floodplain areas through overflow areas/structures. The 2D basin encompasses an area that was estimated to be inundated by the 100-year flood as delineated by previous modeling studies (Central Valley Floodplain Evaluation and Delineation Program, CVFED model) (DWR, 2014). The Colusa model domain includes the 1D Sacramento River from Wilkson Slough to below the Knights Landing Outfall Gates (KLOG). The 2D basin area includes the area along the Colusa Drain that is potentially inundated by the 100-year flood from the Delevan Wildlife Refuge south to the connection with the Yolo Bypass. The Sutter model encompasses the Sutter Bypass from just north of Highway 20 down to the Yolo Bypass in a combination of 1D and 2D elements; the Sutter model also includes the Sacramento River from north of Tisdale Weir to Verona, CA.

Most of the basins' area, including natural overflows (Butte model) and channels (apart from the East and West Borrow Canals in the Sutter model), are modeled in 2D, while the Sacramento River and hydraulic structures (e.g., river connection weirs and outfall gates, internal basin management structures) are modeled in 1D. The 2D grid uses quadtree grid refinement to provide higher computational resolution in complex terrain and coarse resolution in other areas. For the Butte and Colusa models, the base computational grid resolution is 400 ft in fields and is refined down to 25 ft along the drains and canals. Areas of natural sloughs in the northern region of the Butte Basin were refined to 100 ft grid cells to help characterize the complex drainage network. In the Sutter model, the base computational grid resolution is 100 ft and is refined to 25 ft along the drainage network. The models also use sub-grid sampling, which allows coarse grid cells to incorporate finer resolution terrain data into the hydraulic calculation.

## 2.2 TERRAIN

### 2.2.1 1D TERRAIN DATA

The Sacramento River was modeled in 1D utilizing bathymetry derived from cross-sectional surveys collected as part of CVFED and later used to support the Central Valley Floodplain Protection Plan (CVFPP) integrated 1D-2D system model (DWR, 2014; DWR, 2017c). Cross-sections from this study were surveyed in 2010 with an accuracy of ±3 to ±6 ft horizontally and ±0.5 to ±1.0 ft vertically depending on the water depth. (Table 1).

### 2.2.2 2D TERRAIN DATA

The base terrain surfaces for the Butte and Colusa models are a combination of the 2018 USGS 3DEP and the 2008 CVFED LiDAR surfaces (Table 1). To create a complete terrain surface that best represented the bare-earth elevations of the basins and reduced the potential errors due to the presence of vegetation and water, a merged Digital Elevation Model (DEM) was created, which selected the lowest elevation from either dataset for each 3.28 ft cell (Figure 3-4). Areas where land use had changed between the two LiDAR datasets (prioritizing the newer 2018 land use) or where one LiDAR set was missing data were filled with other data. For example, a large area of the southern part of the Colusa Basin was inundated during the 2018 LiDAR collection and hydroflattened to a single elevation in the LiDAR DEM, so the area was patched with 2008 data. The Sutter Model terrain was developed for the Sutter and Tisdale Bypasses Flood & Multi-Benefit Management Plan and is shown in Figure 5 (RD 1500 & DWR, 2023).

**Table 1. Terrain Development Datasets**

| Terrain Dataset | Source | Year Collected | Coverage area | Resolution |
|---|---|---|---|---|
| LiDAR DEM | USGS 3DEP | 2018/ 2019 | Butte and Colusa 2D Basins, missing some patches along Sacramento River | 3.28 ft (1 m) |
| LiDAR DEM | DWR/CVFED | 2008 | Butte and Colusa 2D Basins, missing southern end of Butte Basin and the farthest western extent of the Colusa Basin | 3.125 ft, resampled to 3.28 ft (1 m) |
| Cross-Sections | DWR/CVFED | 2010 | Full Length of Sacramento River in modeling area, and Lower Colusa Drain | Cross-section spacing around 0.25 miles |
| RTK GPS and Cross-Sections | cbec | 2022 | Butte Creek, Upper Colusa Drain, larger canals, and drains | Butte Creek cross-section spacing every 1 mile, other spacing as needed |

### 2.2.3 2D TERRAIN ADJUSTMENTS

***Breaklines***

Many features in the models are too small to be captured and properly represented by grid cells. Therefore, important features such as levees, berms, roads, creeks, and canals are enforced in the grid through breaklines that assign elevations to the nearest grid cell edge or center. Levees, roads, and field berms were manually delineated as polylines in GIS based on the 2018 LiDAR DEM (except for along the southern end of the Colusa Drain where large areas of wetlands and fields were completely obscured by hydroflattening, in these area 2008 LiDAR was used) and aerial imagery (Figures 6-8). The 2018 LiDAR was used to represent the most recent berm layout and elevations in the model. The vertices along these lines were densified to at least 50 ft spacing. Drains were also manually delineated in a similar fashion, but vertices were only placed in the lowest elevations of the drains to closely represent the thalweg channel elevations (Figures 9-11). The highest or lowest elevations, for berm and drains respectively, within 10 ft of each vertex were extracted from the 2018 LiDAR. These elevations were enforced along the berm and drain lines in the 2D modeling areas and elevations between vertices were linearly interpolated.

All delineations were performed at the 'field scale' to appropriately represent the locations of publicly and privately owned field units within the model areas. Field-level networks of canals and drains were incorporated into the model domains to allow for sufficient field drainage to main waterways. Interior field berms (e.g. rice checks) and smaller drainage network features (e.g. highline delivery canals, field culverts/structures) were generally not included because this level of detail was unnecessary to meet Program goals and would have substantially increased computation times. Additionally, drainage outlets were added to agricultural fields that do not have winter water management to allow for positive drainage to be maintained.

***Elevation Adjustments***

The majority of the topographic data that define the 2D areas within the model domains are derived from LiDAR data. The LiDAR surveys were collected when many areas, including creeks, canals, and wetlands, were inundated. LiDAR cannot penetrate water; therefore, the LiDAR DEM surface does not represent the bathymetry of the wetted channels and wetland areas. In the smaller inundated drains, cross-sections were surveyed in the field (Appendix B). At data collection points, elevations from the surveys were linearly interpolated to adjust the drain elevations and bathymetry (Table 1). Most of the drains are represented as 25 ft wide rectangular channels (the finest grid resolution of the model). For drains wider than 25 ft, the channel widths in the model were increased. For the larger creeks (Butte Creek, Sanborn Slough, and the Colusa Drain), field-surveyed and bathymetric data from other modeling studies (DWR, 2017c) were used to create DEM surfaces along the drains (Appendix B). These surfaces were patched on top of the LiDAR derived terrain and clipped to blend well with the underlying topographic surface (Figures 9-11).

The majority of wetlands and winter-managed rice fields were also inundated during the LiDAR acquisition. Because water is actively managed on these fields in the models (see Section 2.5), the field bottom elevations and the surrounding field berms were adjusted to allow fields to hold water at an appropriate depth and freeboard in the model. Elevations for all inundated wetlands and rice fields were flattened and assigned a single, adjusted elevation. For wetlands, where berm elevations were generally inundated or obscured by unfiltered vegetation, berm heights around each field were adjusted to a single elevation (Figures 12-14). Information on how these fields were adjusted is discussed in Appendix C.

## 2.3 LANDCOVER AND MODEL ROUGHNESS

### 2.3.1 1D SACRAMENTO RIVER

The Sacramento River has several key flood control structures (M&T, 3B's, and Goose Lake Natural Overflows; Moulton, , Colusa, and Tisdale Weirs) that allow floodwaters to enter the Butte Basin at a range of flow conditions (Table 6); therefore, it is important that the mainstem of the Sacramento River is well calibrated to flow conditions that corresponds to activation of these structures (~22,500 to +80,000 cfs). Additionally, the Program aimed to accurately model entire water years to provide a reference point by which future actions can be compared regarding ecological outcomes and potential impacts, it was vital the roughness values worked for these entire water years as well.

Since roughness values utilized in the CVFPP study were calibrated for high flow conditions, new roughness values for the Sacramento River in the Butte Basin model were developed based on bed material grain size using a methodology developed by Arcement and Schneider (1984) and grain size data from Singer (2008). These roughness values were adjusted locally to account for the additional form drag due to sinuosity. The initial floodplain roughness within the river corridor relied on calibrated values from CVFPP. The roughness values were adjusted to achieve calibration as described in Section 3.1.1.

For the Colusa model, the mainstem Sacramento River relied upon roughness values derived from the CVFPP model study (DWR, 2017c, calibrated for high flow events). These values were not adjusted in the calibration processes since these reaches only served to route flows and did not influence floodplain inundation within the basins.

### 2.3.2 2D BASINS

Roughness values for the Butte and Colusa Basins were based on vegetation and land cover mapping from the California Department of Fish and Wildlife Biogeographic Information and Observation System (Bios) for the Great Valley Ecoregion (CDFW, 2018) (Figures 15-16), which is consistent with previous modeling efforts in the Yolo Bypass (DWR, 2017d). Manning's roughness values for each vegetation classification developed for the Yolo Bypass hydrodynamic model were utilized as baseline roughness values in the Butte and Colusa models (Table 2) (DWR, 2017d).

**Table 2. Butte and Colusa Models 2D Domain Landcover and Manning's Roughness Values**

| Map Class | National Vegetation Classification System | Manning's Roughness Value |
|---|---|---|
| AGR | Agriculture | 0.03 |
| BGS | Bare Gravel/Sand | 0.035 |
| CAI | Mediterranean California Naturalized Annual and Perennial Grassland | 0.03 |
| CAP | California Annual and Perennial Grassland | 0.03 |
| CFP | California Annual Forbs and Grasses | 0.03 |
| CSS | Central and South Coastal California Seral Scrub | 0.055 |

| | | |
|---|---|---|
| FEM | Freshwater Emergent Marsh | 0.05 |
| IMF | Introduced North American Mediterranean Forest | 0.08 |
| NRW | Naturalized Warm-Temperate Riparian/Wetland | 0.055 |
| NTF | Naturalized Temperate Pacific Freshwater Vegetation | 0.03 |
| RIS | Riparian Introduced Scrub | 0.045 |
| RWF | Southwestern North American Riparian Evergreen and Deciduous Woodland | 0.08 |
| RWS | Southwestern North American Riparian/Wash Scrub | 0.055 |
| TFF | Temperate Freshwater Floating Mat | 0.03 |
| URB | Urban | 0.03 |
| VPG | California Vernal Pool and Grassland Matrix | 0.03 |
| VRF | Vancouverian Riparian Deciduous Forest | 0.08 |
| WAT | Water | 0.03 |
| WTM | California Warm Temperate Marsh/Seep | 0.03 |
| WVO | California Broadleaf Forest and Woodland | 0.08 |

For the Sutter Bypass model the baseline roughness values included adjustments for water depth (depth variable) (DWR, 2020). The Sutter model's baseline roughness values were updated for the areas of the Fremont Weir Big Notch Project (BNP) and the Adult Fish Passage (AFP) structures. Revised landcover and roughness values are shown in Figure 17 and Table 3.

**Table 3. Sutter Bypass Model 2D Domain Landcover and Manning's Roughness Values**

| Landcover Class | Base Manning's roughness | Shallow Water Manning's roughness for Depth Variable Roughness |
|---|---|---|
| Agriculture | 0.028 | 0.17 |
| Adult Fish Passage (AFP) Channel | 0.034 | -- |
| Adult Fish Passage (AFP) Inlet | 0.038 | -- |
| Big Notch Project (BNP) Downstream Channel | 0.03 | -- |
| Big Notch Project (BNP) Upstream Channel | 0.034 | -- |
| Dense Vegetation | 0.1 | 0.8 |
| Feather River Channel | 0.024 | -- |
| Feather River Floodplain | 0.032 | -- |
| Feather River Confluence Weir and Riparian | 0.06 | 0.4 |
| Fremont Weir Crest | 0.016 | -- |
| Fremont Weir Trough | 0.016 | -- |
| Fremont Weir Wildlife Area | 0.035 | -- |
| Gilsizer Slough | 0.04 | -- |
| Medium Vegetation | 0.08 | 0.6 |
| Natomas Cross Canal | 0.035 | -- |
| Natural grasses | 0.045 | 0.15 |
| Nelson Slough | 0.05 | -- |

| | | |
|---|---|---|
| Riparian Habitat | 0.06 | 0.4 |
| Sacramento River | 0.035 | -- |
| Sparse Vegetation | 0.06 | 0.4 |
| Sutter National Wildlife Refuge Marsh | 0.037 | 0.24 |
| Sutter National Wildlife Refuge Watergrass | 0.037 | 0.15 |
| Toe Drains | 0.03 | -- |
| Willow Slough | 0.04 | -- |

## 2.4 SOIL CLASSIFICATION AND INFILTRATION

Soil classification data from the USDA's Soil Survey Geographic Database (SSURGO) (USDA, 2023) was used in the TUFLOW models to derive spatially variable infiltration rates for the 2D areas. These data include the soil types and characteristics for each soil profile layer (at least 60 inches deep) within each soil type polygon. Infiltration in each SSURGO polygon was determined based on the soil profile layer with the most limiting hydraulic conductivity, i.e., utilizing the assumption that the least permeable soil layer will control infiltration (Figures 18-20).

The Green-Ampt method was used to compute infiltration rates. This method allows for variable infiltration based on soil saturation. The model used soil parameters for each soil type (suction, porosity, and hydraulic conductivity) computed by TUFLOW (Table 4), that can be further altered for each soil type as needed. Based on subsurface and deep percolation estimates provided in regional groundwater sustainability plans (Butte Subbasin, 2022; Colusa and Glenn Groundwater Authority, 2021; Sutter Subbasin Groundwater Management Coordination Committee, 2022), simulated infiltration rates were reduced by approximately 80%. The adjusted hydraulic conductivity rates used in the models are shown in Table 4.

**Table 4. Soil Type Infiltration Properties**

| USDA Soil Type | Suction (in) | Porosity (fraction) | Hydraulic Conductivity (in/hr) | Hydraulic Conductivity (in/hr) 80% reduction |
|---|---|---|---|---|
| Clay | 12.453 | 0.385 | 0.012 | 0.0024 |
| Silty Clay | 11.504 | 0.423 | 0.02 | 0.004 |
| Sandy Clay | 9.409 | 0.321 | 0.024 | 0.0048 |
| Clay Loam | 8.22 | 0.309 | 0.039 | 0.0078 |
| Silty Clay Loam | 10.748 | 0.432 | 0.039 | 0.0078 |
| Sandy Clay Loam | 8.602 | 0.33 | 0.059 | 0.0118 |
| Silt Loam | 6.567 | 0.486 | 0.134 | 0.0268 |
| Loam | 3.5 | 0.434 | 0.299 | 0.0598 |
| Sandy Loam | 4.335 | 0.412 | 0.429 | 0.0858 |
| Loamy Sand | 2.413 | 0.401 | 1.177 | 0.2354 |
| Sand | 1.949 | 0.417 | 4.638 | 0.9276 |

## 2.5 WINTER INUNDATION MANAGEMENT

Many fields within the model boundaries are flooded in the winter to provide waterfowl and shorebird habitat. These fields include public wetlands (both state and federal), private wetlands (duck clubs and conservation easements on private lands) and rice fields. A technical memorandum that documents the modeling decisions and framework for winter water management is included in Appendix C. The implementation of this approach is discussed in the following sections.

### 2.5.1 FIELD IDENTIFICATION

The first step in implementing field scale water management in the model was to identify the fields that are managed to flood during the winter. Figures 21-23 show the fields with managed winter flooding in the models. These figures represent the typical inundation condition, which does not include year-to year variability in managed inundation extent. To identify the federal public wetlands that are typically flooded in the winter, the National Wildlife Refuge (NWR) Management Plans for each refuge in the study area were reviewed. These plans contain management information on the timing, duration, and frequency of field flooding as well as the species being managed for each year. For the state wetlands, flood management maps were available online, while others were assumed to be flooded based on discussions with land managers. For private wetlands, all conservation easements in the Wetland Reserve Program and all duck clubs were assumed to be flooded in the winter.

For rice fields, a review of available spatial data was completed to identify winter managed (flooded) rice fields. Crop data from 2007 to 2021 were reviewed to identify fields in rice production; fields were classified as rice if they were in rice production for at least 8 of the 15 years or if it appeared management had changed to be consistently rice in the last four years. Next, water inundation maps from satellite imagery were evaluated from four drier years (2014, 2015, 2016, 2018) to identify if the rice fields were subject to managed flooding during the winter. If a field was flooded in the winter for more than half of the dry years analyzed, it was considered a managed rice field for all years modeled.

### 2.5.2 FLOOD SCHEDULES

Winter flooding schedules were identified for each managed wetland and field type through discussions with practitioners and review of habitat management plans (Table 5). More information on these selections is discussed in Appendix C. Some managed wetlands in the Sutter Bypass have different schedules than those in the Butte and Colusa Basins; the Sutter Bypass schedules were determined based on stakeholder discussions and the local National Wildlife Refuge management plans in Sutter and Tisdale Bypasses Flood & Multi-Benefit Management Plan effort (KSN, 2021). For consistency with the Management Plan, these schedules were preserved in the updated model.

**Table 5. Winter Wetland Management Schedules for Each Field Type**

| Management type | Category | Acro-nym | Target Species | Flood-up Start Date | Flood-up Duration (weeks) | Target depth (ft) | Draw-down Start Date | Draw-down Duration (weeks) |
|---|---|---|---|---|---|---|---|---|
| Managed Rice Fields | Rice fields | MRF | Ducks | 15-Oct | 2 | 0.833 | 1-Feb | 1 |
| Sutter Bypass Managed Rice Fields | Rice fields | MRFS | Ducks | 1-Oct | 1 | 0.833 | 28-Feb | 2 |
| Duck Clubs | Private Wetlands | DC | Ducks | 15-Sep | 2 | 0.833 | 1-Mar | 6 |
| Conservation Easements | Private Wetlands | WRP | Ducks | 1-Oct | 4 | 0.833 | 15-Mar | 4 |
| Sutter Fish and Wildlife Service Conservation Easements | Private Wetlands | FCE | Ducks | 1-Oct | 1.4 | 0.833 | 22-Mar | 1.4 |
| State Wildlife Areas | Public Wetlands | SWA | Ducks | 15-Sep | 2 | 0.833 | 1-Mar | 4 |
| State Wildlife Areas | Public Wetlands | SWA | Ducks | 15-Oct | 2 | 0.833 | 1-Mar | 4 |
| National Wildlife Refuges | Public Wetlands | NWR | Ducks | Variable | Variable | 0.833 | Variable | Variable |
| National Wildlife Refuges | Public Wetlands | NWR | Shore-bird | Variable | Variable | 0.292 | Variable | Variable |

### 2.5.3 MODELING SETUP

Land managers within the basins employ a variety of methods to manage inundation in winter. Water sources for flooding can be delivered via a drainage/water delivery network, provided onsite (e.g., groundwater pumping, on-site running water), or a combination of the two. The source can vary in space (e.g., proximity to main channels or by landowner) and time (both from year to year and within a year). The identification of the specific water source for each field was beyond the scope of this Program and was not necessary to achieve Program goals. To simplify the modeling process, it was assumed that the managed flooding used water from sources external to the model domain (for example, fall rice field drainage and diversions from Thermalito Afterbay to Western Canal). This was implemented in the model via operational pumps configured to meet and maintain managed water levels on each field. Each of these pumps pulls water from outside the model domain and therefore does not affect the modeled surface water in the basins including drainage networks that landowners may divert from in reality. During drawdown, the water on the field is released back into the drainage network, and the pumps on the fields are configured to match infiltration and meet the appropriate drawdown schedule for each field. Each pump is located near the centroid of the field to distribute water evenly across the field. The pumps maintain the managed water level for each field using stage observed at a designated monitoring point located between the pump and the outlet structure, as described below.

An initial estimate for the pump flow rate needed to meet the field's flood-up duration was calculated using field area, the intended flood-up duration for that field, and the average infiltration rate on the field. During drawdown, the pump flow rate drops to a rate initially calculated to match the average infiltration rate on the field to make sure infiltration does not cause fields to drawdown faster than the specified duration for each field type (Table 5).

To maintain the desired water depth and allow fields to drawdown at the end of the managed flood season, each field has an outlet structure represented as an operable weir. These structures have a base elevation equal to the field flattened elevation such that when they are lowered the field can fully drain. During the managed flood season, outlets are raised to a height equal to the respective field management depth plus one inch to allow for target depths to be maintained without incurring water level instabilities near the outlet structure.

Generally, field outlet structures were connected to nearby drains or channels. However, in some instances, outlet structures could not directly connect to the drainage network and instead were linked to a neighboring field. Additionally, outlet structure weir coefficients were adjusted to increase drainage efficiency at lower water depths.

In the original Sutter Bypass model (DWR, 2020; Appendix A), there were drainage structures throughout the Sutter NWR and some of the rice fields near Tisdale Bypass that control how inundation moves through the local drainage network and fields. Since managed wet season inundation was added to some of these fields during this effort, some of these structures were altered or removed to support managed inundation remaining on those fields at appropriate levels. In the previous Sutter Bypass model, the wetland terrain was represented by the LiDAR surface, but this was updated in the current version with the flattening of all field bottoms (see Section 1.2.3) to make sure the inundation management scheme was implemented correctly within the model.

### 2.5.4 CALIBRATION

Field management calibration was performed so that each field met its intended managed flood schedule and water depth. To meet these requirements, model runs were performed under low flow conditions such that the drainage network and channels could support the water released during drawdown throughout the basins. All fields began flood-up at the beginning of the model simulation and transitioned to drawdown approximately 44 days later. The 44-day timeframe between flood-up and drawdown was used to accommodate fields with the longest flood-up periods (WRP fields with 28 days, see Table 5), and provide ample time to meet their flood-up duration such that deviations from the intended duration could be calculated.

Calibration results were analyzed on a field-by-field basis. To meet the appropriate flood-up duration, the management pump flow rates used during flood-up were adjusted based on the deviations from the intended flood-up durations. To adjust the drawdown duration, the rate at which the field outlet structures were lowered was adjusted.

Following calibration, 99% of managed fields in all three basins were within one day of the intended flood-up duration. Drawdown, however, was more difficult to calibrate since the methods of calibration were less direct than adjusting pump flow rates for flood-up. Thus, drawdown duration results were less accurate than flood-up, with 88% of managed fields in all three basins being within one week of the intended drawdown timing. Inaccuracies in flood-up timing were typically associated with flooding up too quickly. Conversely, inaccuracies in drawdown timing mostly occurred with fields drawing down more slowly than their intended schedule due to the lack of topographic relief on the field surface (flat fields). Further uncertainty is expected to occur in each modeled water year based on hydrologic conditions that influence field flood-up and drawdown timing. This variability in drawdown is acceptable as it reflects the natural inconsistency in the timing of field drainage.

## 2.6 HYDRAULIC STRUCTURES

The Butte Basin, Sutter Bypass, Tisdale Bypass, facilities within the Colusa Basin, and several overflow weirs (described below) are part of the Sacramento River Flood Control Project (SRFCP) and therefore considered to be SRFCP facilities. The State Plan for Flood Control (SPFC) is defined by the SPFC Descriptive Document as “Collectively, the facilities, lands, programs, conditions, and mode of O&M for the State-federal flood protection system in the Central Valley.” The SRFCP was originally authorized by the Flood Control Act of 1917. This act made the flood system along the Sacramento River and its tributaries part of the SPFC. These SPFC facilities include dams, bypass channels, levees, canals, sloughs, weirs, and water control structures.

A variety of hydraulic structures are present throughout the basins and bypasses for flood control and surface water management These structures include Sacramento River flood relief structures, via natural overflows, weirs, and outfall gates; and in-basin structures including culverts, weirs, sluice gates, dams, and fish ladders. Due to the scale of these models, the finer details of the water control system were not explicitly represented in the model (e.g., road crossing, individual field gates and water delivery). Instead, the models include only the large structures that control water diversions in the main tributaries and maintain water levels throughout the drains. More detail was included in the Butte Sink area due to the complex nature of water control in the wetland areas, but many simplifications were applied. Most hydraulic structures were modeled in 1D; Table 6 summarizes the model structures, purpose, and intended operations and Figures 24-26 show the structure locations.

The Butte Basin, located to the east of the Sacramento River and upstream of the Sutter Bypass, is a major flood relief basin for the Sacramento River and surrounding area that receives flood flows from natural (Table 6: M&T, 3 B’s, and Goose Lake Natural Overflow Areas) and engineered (Moulton and Colusa Weirs) flood release structures. The flow activation of the flood release structures from the Sacramento River varies with the highest activation located in the north and decreasing in the downstream direction (California Nevada River Forecast Center (CNRFC) as of 2/1/2024, M&T, 3B’s & Goose Lake Natural

Overflow Areas: 86,000 cfs at Ord Ferry; Moulton Weir: 66,200 cfs; Colusa Weir: 33,700 cfs). Upstream from the overflows, the Sacramento River has a channel capacity of 260,000 cfs. The channel capacity systematically decreases downstream as water is spilled into the Butte Basin: to 160,000 cfs downstream from the natural overflows, to 135,000 cfs downstream from Moulton Weir, to 65,000 cfs downstream from Colusa Weir, and finally to only 30,000 cfs below Tisdale Weir. The natural overflows have the capacity to spill 100,000 cfs into the Butte Basin, and Moulton, Colusa, and Tisdale weirs have spill capacities of 25,000 cfs, 70,000 cfs, and 38,000 cfs, respectively. Thus, the majority of Sacramento River flood flows are diverted through the Butte Basin and ultimately into Sutter Bypass, which has a channel capacity of 180,000 cfs upstream from the Feather River. For further information on facilities and channel capacities, refer to the State Plan for Flood Control Descriptive Document (DWR, 2022). The overflow weirs begin spilling into the Butte Basin at different flow levels, reflecting the downstream decreases in channel capacity of the Sacramento River. As flows rise on the Sacramento, weirs begin activating from downstream to upstream, with Tisdale spilling first, then Colusa, then Moulton, and finally the natural overflows, depending on the specifics of the flood hydrograph.

The Butte Basin also receives and routes flows via major sources like Little Chico Creek, Butte Creek, Little Dry Creek, and Cherokee Canal. Several sloughs (Angel, Sanborn, and Drumheller) along with a complex agricultural drainage network also conveys flows through the basin and into the Butte Sink, located at the southern end adjacent to the Sutter Buttes. Within the Butte Sink, numerous surface water management and conveyance structures (Table 6: Bifurcation Structure, North Weir, End Weir, White Mallard Dam, Morton Weir, Field and Tule Turnout, Mile Canal Turnout, Driver’s Cut Weir, and Drumheller Slough Complex) divert flows to privately-owned hunting clubs as well as State and Federal wildlife areas. On the north end of the Sink, the Bifurcation Structure controls the seasonal flow split between Butte Creek and Sanborn Slough. North and End Weirs, located along Sanborn Slough, are used to control the water surface elevation (WSE) in Sanborn Slough and its outflow to Cherokee Canal, and to divert water into the hunting clubs for flooding up the wetlands. White Mallard Dam also controls the WSE for Butte Creek and the Drumheller Slough complex (discharges into Butte Creek) downstream of the Bifurcation Structure. The Morton Weir, Field and Tule Turnout, and Mile Canal Turnout control WSE in Cherokee Canal downstream of End Weir and are used to route water to the hunting clubs in the Sink. The structures also control the outflow from Cherokee Canal into Butte Creek. Driver’s Cut Weir serves a similar purpose by managing the drainage of several major hunting clubs back into Butte Creek on the southern end of the Sink. The surface water control structures are aided by a network of secondary channels (Crosscut Canal, Mile Canal, and North Butte Canal) and minor infrastructure that enables the hunting clubs and wildlife areas to manage wetland flood up and drawdown seasonally to achieve various goals. Flow-through weirs, between managed fields, provide hydraulic connection throughout the Sink during winter flooding. Diverted flows eventually accumulate downstream within Butte Slough which conveys surface water into the Sutter Bypass or to the Sacramento River via the Butte Slough Outfall Gates.

The Sutter Bypass also receives flood flows via the Tisdale Weir (Sacramento River Activation: 23,000 cfs, CNRFC 2/7/2024) the diverts flows from the Sacramento River through the Tisdale Bypass. Drainage flows also enter the Bypass from the east near Yuba City via the Wadsworth Canal and multiple pumping plants. Flows are routed south through the 35-mile-long, man-made channel starting at the south side of the Sutter Buttes, near Highway 20, and continuing south to the Fremont Weir just northeast of the City of Woodland. Within the bypass, several structures (Willow Slough Complex, Nelson Weir and Management

Unit Culvert, and Weirs 1-3) are used to manage surface waters for agricultural purposes during non-flood periods. Several additional structures (Tisdale Weir and Notch, Weir 4 and 5, East West Diversion Weir, and the Freemont Weir) are used to aid in flood control through the Bypass during high flow periods. Flood flows are then transferred to the Yolo Bypass near the town of Verona, CA.

Within the bypass, several structures (Tisdale Weir and Notch, Weir 4 and 5, East West Diversion Weir, and the Freemont Weir) are used to aid in flood control through the Bypass during high flow periods. Flood flows are then transferred to the Yolo Bypass near the town of Verona, CA. During non-flood periods, several structures (Willow Slough Complex, Nelson Weir and Management Unit Culvert, and Weirs 1-3) are used to manage surface waters for agricultural purposes during non-flood periods.

The Colusa Basin is an agricultural basin delivering the largest single source of agricultural return flows to the Sacramento River and contains several SPFC facilities within it. The basin's main channel, the Colusa Drain, is supplied by water delivery canals, agricultural drainages, and natural streams (Stone Corral Creek, Powell Slough, Lurine Creek, Salt Creek, Cortina Creek, North Sand Creek, South Sand Creek, Salt Creek 2, Petroleum Creek, Buckeye Creek, Dunnigan Creek, Oat Creek, and Willow Spring Creek) and mirrored by an SPFC levee (Design Capacity: 20,000 cfs) on its left bank that operates as a back levee for RD 108 and 787 (DWR, 2022). Flows within the drain are managed by four main structures (Davis Weir, Knights Landing Outfall Gates (SPFC), Wallace Weir, and Knights Landing Ridge Cut - design capacity: 20,000 cfs (SPFC)) that control water surface elevations and outflows to the Sacramento River (via Knights Landing Outfall Gates) and Yolo Bypass (via Knights Landing Ridge Cut and Wallace Weir) with support from secondary structures located along the drainage network of the basin. The Knights Landing Outfall Gates operates with unidirectional flap gates that inhibit backwater from the Sacramento River into the basin, reducing flood risk for the basin.

**Table 6. Modeled Hydraulic Structures and Operations**

| ***Butte Basin*** | | | |
|---|---|---|---|
| **Structure** | **Purpose** | **Intended Operations** | **References** |
| M & T Natural Overflow Area (modeled in 2D) | Sacramento River Connection | Overflow spills at ~ 80,000 cfs | DWR, 2017a |
| Ord Ferry Road / County Road 32 Bridge | River Crossing | - | DWR, 2017c |
| 3 B's Natural Overflow Area (modeled in 2D) | Sacramento River Connection | Overflow spills at ~ 80,000 cfs | DWR, 2017a |
| Goose Lake Natural Overflow Area (modeled in 2D) | Sacramento River Connection | Overflow spills at ~ 80,000 cfs | DWR, 2017a |
| California Highway 162 Bridge, Butte City | River Crossing | - | DWR, 2017c |
| Moulton Weir | Sacramento River Connection | Weir spills at ~65,000 cfs | California Nevada River Forecast Center, cnrfc.noaa.gov |

| | | | |
|---|---|---|---|
| Colusa Weir | Sacramento River Connection | Weir spills at ~30,000 cfs | California Nevada River Forecast Center, cnrfc.noaa.gov |
| Bridge Steet / River Road Bridge, Colusa | River Crossing | - | DWR, 2017c |
| Butte Slough Outfall Gates (Unidirectional culverts) | Sacramento River Connection | Spills from Butte Slough to the Sacramento River when Stage is higher in Butte Slough | USACE, 2016a |
| Tisdale Weir | Sacramento River Connection | Weir spills at ~ 25,000 cfs | California Nevada River Forecast Center, cnrfc.noaa.gov |
| Bifurcation Structure (Culverts, fish ladder, and weir overflow structure) | Diverts water between Butte Creek and Sanborn Slough | Sept 1- Jan 15: 30%-70% flow split between Butte Creek and Sanborn Slough<br>Jan 15- Apr 30: structure fully open<br>May 1- Sept 1: 70%-30% flow split between Butte Creek and Sanborn Slough | Ducks Unlimited, 2009 |
| North Weir (Bladder dam) | Manage wetland water levels | Diverts water into Wild Goose Club and other connected private wetlands | Conversations with Wild Goose Club Manager (JP Stover) |
| End Weir (Screw gates and fish ladder) | Manage wetland water levels | Maintain Upstream Water surface elevation to 57.65 ft. Does not flow when stage on Cherokee canal is higher than Sanborn Slough | Conversations with Wild Goose Club Manager (JP Stover) |
| White Mallard Dam (Weir, overshot gate, and fish ladder) | Manage wetland water levels | Managed for upstream water surface elevation of 56.77 ft for pumping operations. | California Waterfowl Association, 2001 and conversations with RD 1004 manager |
| Morton Weir (Bladder dam) | Manage wetland water levels | Managed to maintain upstream water surface elevation of 51.88 ft until March 1$^{st}$. After Mach 1$^{st}$, water surface elevation managed to | California Waterfowl Association, 2001 |

| | | | |
|---|---|---|---|
| | | 48.06 ft to allow duck clubs to drain. | |
| Field and Tule Turnout (Flashboard weir) | Divert water into wetlands and manage water levels | Opened until March 1st to allow flow through to Field and Tule Club. Closed after March 1st for drawdown. | California Waterfowl Association, 2001 |
| Mile Canal Turnout (Culvert and weir) | Divert water into wetlands and manage water levels | Opened until March 1st to allow flow through to Field and Tule Club. Closed after March 1st for drawdown. | California Waterfowl Association, 2001 |
| Driver's Cut Outfall (Flashboard weir) | Retention of diverted water into wetlands and manage water levels | Opened until March 1st to allow flow through to Field and Tule Club. Closed after March 1st for drawdown. | California Waterfowl Association, 2001 |
| Driver's Cut Weir (Screw gates) | Retention of diverted water into wetlands and manage water levels | Manages the shoot level for Sacramento Out Duck Club. | California Waterfowl Association, 2001 |
| Flow Through Weirs | Connect Butte Sink Wetlands and promote flowthrough | Overflow and connect wetlands when water levels are above management level | California Waterfowl Association, 2001 |
| Drumheller Slough Complex (Weir, sluice gate, and culverts) | Retention of diverted water into wetlands and manage water levels | Managed with White Mallard Dam to maintain 56.77 ft WSE for pumping operations | Ducks Unlimited, 2009 |
| ***Colusa Basin*** | | | |
| **Structure** | **Purpose** | **Intended Operations** | **References** |
| Davis Weir (Bladder dam) | Maintain upstream water level | Maintain water level ~36.93 ft in Colusa Drain. | cbec survey and personal communications with Glenn-Colusa Irrigation District |
| Knight Landing Outfall Gates, KLOG (Unidirectional operated gates) | Maintain upstream water level | Maintain water level of 22.4 ft in Colusa Drain. Does not operate when downstream Sacramento River stage | USACE, 2016b and gage analysis |

| | | | |
|---|---|---|---|
| | | in higher than upstream stage. | |
| Wallace Weir (Badder dam and fish ladder) | Maintain upstream water level when KLOG cannot operate | Maintain water level of 22.4 ft in Colusa Drain. | DWR, 2019 |
| ***Sutter Bypass*** | | | |
| **Structure** | **Purpose** | **Intended Operations** | **References** |
| Tisdale Weir and Notch | Sacramento River Connection (Notch for additional Fish Passage) | Weir spills at 22,500 cfs, notch opens on Tisdale Weir overtopping and remains open until water level recedes to inflection point below notch invert | DWR, 2020 and RD 1500 and DWR, 2023 |
| Willow Slough Complex (Unidirectional culverts & fish ladder) | Maintain water level on East Borrow Canal (EBC) while allowing fish passage through Willow Slough | 1) Culvert that maintains water level of 28.9 ft at Pumping Plant 1 in EBC<br>2) Fish Ladder allowing flow above 28.4 ft | DWR, 2020 |
| Nelson Weir | Maintain water level on EBC | Maintain water level of 28.74 ft | DWR, 2020 |
| Nelson Management Unit Culvert | Allow water to pass between Nelson Management Unit and Sutter Bypass | 2 x 4 ft culverts open year-round with invert 23.8 ft | DWR, 2020 |
| Weir 1 | Maintain water level on West Borrow Canal (WBC) | Maintain water level of 29.3 ft | DWR, 2020 |
| Weir 2 | Maintain water level on East Borrow Canal | Maintain water level of 36.5 ft | DWR, 2020 |
| Weir 3 | Maintain water level on WBC | Open before April 1, maintains water level of 35.7 ft after April 1 | DWR, 2020 |
| Weir 5 | Maintain water level on WBC | Open before April 1, maintains water level of 39.2 ft after April 1 | DWR, 2020 |

| | | | |
|---|---|---|---|
| East-West Diversion Weir | Control flow split between EBC and WBC on North end of Sutter Bypass | Open before April 1 to allow majority of flow into EBC, after April 1 maintain water level of 36.2 ft | DWR, 2020 |
| Fremont Weir Big Notch Project (BNP) (3 Operable Sluice Gates) | Increase fish passage into Yolo Bypass in Fremont Weir | Gates open to allow up to 6000 cfs from Nov 1 to Mar 15 | DWR, 2017d |
| Fremont Weir Adult Fish Passage (AFP) | Increase fish passage into Yolo Bypass in Fremont Weir | Gates open upon Fremont Weir overtopping and close below invert | DWR, 2017d |

## 2.7 BOUNDARY CONDITIONS

Boundary conditions for the three models are shown in Figures 27-29 and summarized in Table 7. Boundary conditions in these models included upstream inflows (flow time series), downstream outflows (enforced as: flow or stage time series or stage-flow rating curves), internal boundary conditions (flow time series added at different locations within the model, i.e. groundwater), call water (flow time series added in Butte Creek) and precipitation/evapotranspiration (applied uniformly throughout the TUFLOW models based on daily data). The Colusa Basin tributaries are generally ungaged. Therefore, the model inflow boundary conditions for these tributaries were based on HEC-HMS model output (for HEC-HMS model development documentation, see Appendix D).

**Table 7. Boundary Conditions and Data Sources**

| ***Butte Model*** | | |
|---|---|---|
| **Boundary Location** | **Data Type** | **Data Source** |
| Sacramento River 1D Inflow | Gaged | DWR Gage A02630, Sacramento River at Hamilton City |
| Big Chico Creek 1D Inflow | Gaged | DWR Gage A042105, Big Chico Creek near Chico |
| Stoney Creek 1D Inflow | Gaged | USACE Black Butte Reservoir Outflows |
| Butte Creek 2D Inflow | Gaged | DWR gage A04265, Butte Creek near Durham |
| Little Chico Creek 2D Inflow | Watershed Scaling | Butte Creek inflows * 0.18 |
| Little Dry Creek 2D Inflow | Watershed Scaling | Butte Creek inflows * 0.16 |
| Cherokee Canal 2D Inflow | Gaged | DWR Gage A02984, Cherokee Canal near Richvale |
| Butte Creek, Little Dry Creek, Angel Slough, Cherokee Canal 2D Internal Groundwater Inflows | Monthly Average estimates from report | Butte Subbasin, 2022 |

| | | |
|---|---|---|
| Precipitation and Evapotranspiration | Gaged | CIMIS gage at Durham |
| Call Water 2D Inflow | Requested | Butte Sink Signatory Clubs – Water Master, Annual call water requests for 2011-2021 |
| Call Water 2D Internal Sink | Estimate | Calculated for each year as 70 % of call and ground water inflows upstream of North Weir |
| Tisdale Weir 1D Outflow | Stage/Flow rating curve developed from gage data | DWR gage A02960, Tisdale Weir Spill to Sutter Bypass |
| Sacramento River 1D Outflow | Stage/Flow Rating Curve developed from gage data | USGS gage 11390500, Sacramento River Below Wilkins Slough |
| Butte Slough 2D Outflow | Stage/Flow Rating Curve developed from Sutter Model | Stage and Flow extracted at Highway 20 in the previous version of the Sutter Bypass Model (this accounts for backwatering from downstream weirs) |
| ***Colusa Model*** | | |
| **Boundary Location** | **Data Type** | **Data Source** |
| Sacramento River 1D Inflow | Gage | USGS gage 11390500, Sacramento River Below Wilkins Slough |
| Colusa Drain 2D Inflow | Modeled | HEC-HMS Model |
| Stone Corral Creek 2D Inflow | Modeled | HEC-HMS Model |
| Lurline Creek 2D Inflow | Modeled | HEC-HMS Model |
| Salt Creek 2D Inflow | Modeled | HEC-HMS Model |
| Powell Slough 2D Inflow | Modeled | HEC-HMS Model |
| Cortina Creek 2D Inflow | Modeled | HEC-HMS Model |
| North Sand Creek 2D Inflow | Modeled | HEC-HMS Model |
| South Sand Creek 2D Inflow | Modeled | HEC-HMS Model |
| Salt Creek 2 2D Inflow | Modeled | HEC-HMS Model |
| Petroleum Creek 2D Inflow | Modeled | HEC-HMS Model |
| Buckeye Creek 2D Inflow | Modeled | HEC-HMS Model |
| Dunnigan Creek 2D Inflow | Modeled | HEC-HMS Model |
| Oat Creek 2D Inflow | Modeled | HEC-HMS Model |
| Willow Spring Creek 2D Inflow | Modeled | HEC-HMS Model |
| Yolo Bypass 2D Inflow | Stage Time Series | 1997-2017: Extracted from Yolo Bypass Model<br>2018-2020: Stage shifted upstream from USGS gage 1145300, Yolo Bypass near Woodland |
| Precipitation and Evapotranspiration | Gaged | CIMIS gage at Davis |
| Sacramento River 1D outflow | Stage Time Series | 1997-2017: Extracted from Yolo Bypass Model |

| | | |
|---|---|---|
| | | 2018-2020: Stage shifted downstream from DWR gage A02200, Sacramento River at Knights Landing |
| Yolo Bypass 2D Outflow | Stage Time Series | 1997-2017: Extracted from Yolo Bypass Model<br>2018-2020: Stage shifted upstream from USGS gage 1145300, Yolo Bypass near Woodland |
| ***Sutter Model*** | | |
| **Boundary Location** | **Data Type** | **Data Source** |
| Sacramento River 1D Inflow | Flow Time Series | Extracted from Butte Model |
| Wilkins Diversion 1D Sink | Flow Time Series | Calculated extraction from Sacramento River below Tisdale Weir based on WLK and Sacramento River near Grimes Gages |
| KLOG Sacramento River 1D Inflow | Flow Times Series | Extracted from Colusa Model |
| Butte Slough 1D Inflow | Flow Time Series | Extracted from Butte Model |
| Pump Plant 1 1D Inflow | Flow Time Series | DWR, 2020 |
| Pump Plant 2 1D Inflow | Flow Time Series | DWR, 2020 |
| Wadsworth 1D Inflow | Flow Time Series | DWR, 2020 |
| Reclamation District 1660 and 70 Inflow | Flow Time Series | DWR, 2020 |
| Butte Slough Area 2D Inflow | Flow Time Series | Extracted from Butte Model |
| Feather River 2D Inflow | Flow Time Series | DWR, 2020 |
| RD 1500 canal 2D Inflow | Flow Time Series | DWR, 2020 |
| Natomas Cross Canal 2D Inflow | Flow Time Series | DWR, 2020 |
| Precipitation and Evapotranspiration | Daily grids for net rainfall depth | DWR, 2020 |
| Sacramento River 2D Outflow | Flow Time Series | USGS gage 11425500, Sacramento River at Verona Gage |
| Bypass 2D Outflow | Stage/Flow rating curve | Normal Depth based on ground slope |

## 2.8 ASSUMPTIONS AND LIMITATIONS

Due to the large and complex nature of these landscape-scale models, some simplifications were made to manage both model run times and the required level of detail for developing the model and evaluating potential actions. Simplifications include the assumption that non-winter managed fields were ‘plumbed to drain,’ where it is assumed that all fields have an open connection to an adjacent drain that allows water to flow off these fields and not pond from rainfall or berm overtopping events. Drains in these basins are typically assumed to have open connections at roadways and drain crossings due to the limited information available for small-scale drainage features.

For winter-managed wetlands and winter flooded rice, the fall water delivery system was simplified by directly pumping water into fields instead of attempting to simulate a full water delivery system. A component of this assumption included the recapture of rice drainage water by wetlands in the late fall. Additionally, a generalized management strategy for the winter wetlands is utilized for every year, and therefore does not capture the year-to-year variability in management strategy driven by annual variations in water availability.

Another simplification made for winter-managed wetlands and winter flooded rice is the leveling of field topography. Rice fields were flattened (removing the rice check berms and terraced interior fields) to best represent the volume of water that a rice field would hold. This simplification was made for other winter wetlands as well due to the lack of terrain data within these fields. To allow fields to hold water to the management depth for the target species, the field elevations were flattened and lowered. Because of these assumptions, there is no variability in field topography / water depths and the capacity of the field/wetlands to hold water may be over or under-estimated.

In the Colusa Basin, subsidence has been documented to have impacted survey monuments throughout the Sacramento Valley (DWR, 2017b). This phenomenon was confirmed with a comparison of LiDAR datasets and analysis of historic gage data in the southern end of the Colusa Basin. Ground elevations were consistently lower by 0.25 to 2 ft in the 2018 LiDAR dataset compared to the 2008 LiDAR dataset. Water surface elevations were gradually lowering in the Colusa Basin Drain at Knights Landing gage overtime, as noted in the gage report from the DWR Water Data Library (Station Number A02945). Furthermore, cbec surveys comparing the difference in water surface elevations between the KLOG gage and the nearby RCS gage 0.6 miles downstream, suggested about 1.8 ft of subsidence was possible (Appendix E). Additional surveys of the local gages and structures were also completed by KSN and the results are summarized in Appendix F.

The terrain data used in the model represents the lowest elevations between the 2008 and 2018 LiDAR datasets, which should limit the impact of subsidence on model results in the Colusa Basin. The exception to this would occur along Colusa Drain where 2008 LiDAR data had to be selectively applied due to the presence of water surface returns (inundation) in the 2018 LiDAR dataset. In addition, the Colusa Drain bathymetry relies upon 2008 era CVFED cross-sectional survey data, which is likely higher than present-day bathymetry. The elevations of the hydraulic structures in the Colusa Basin rely upon the latest design drawing reflecting recent upgrades (KLOG in 2013 and Wallace Weir in 2018). The management elevation selected for the Colusa Drain was based on the new Ridge Cut Slough gage, which is newer and has a more recent datum survey. By using the most up-to-date elevation data where available and using these models as relative comparisons between baseline and alternatives, the impact of the subsidence on model results is expected to be limited. Overall, this subsidence is important to note, and further surveying needs to be completed in the area to understand the full impact on the elevations in this region.

# 3 MODEL CALIBRATION

## 3.1 SACRAMENTO RIVER 1D CALIBRATION – BUTTE BASIN

### 3.1.1 1D CALIBRATION APPROACH

The Sacramento River has several key flood control structures (M&T, 3B's, and Goose Lake Natural Overflows; Moulton, Colusa, and Tisdale Weirs) that allow floodwaters to enter the Butte Basin and Sutter Bypass at a range of flow conditions (Table 6); therefore, it is important that the mainstem of the Sacramento River is well calibrated to flow conditions that corresponds to activation of these structures (22,500 to 80,000 cfs). Additionally, overall Program objectives dictate the need to accurately simulate entire water years to provide a reference point by which potential actions can be compared regarding ecological outcomes and land use impacts; therefore, it was vital that the model was capable of accurately simulating the full range of hydrologic conditions within the simulation period. To facilitate these objectives, the model was calibrated using a depth-varying roughness approach to a near bank full condition on the Sacramento River in 1998 as well as the high flow events in 1997 and 2006. The model was then validated using observations from the 2019 water year.

Since roughness values utilized in the CVFPP study were only calibrated for high flow conditions, updated roughness values for mainstem channel of the Sacramento River in the Butte Basin model were developed based on bed material grain size using a methodology developed by Arcement and Schneider (1984) and grain size data from Singer (2008). The main channel roughness values were also adjusted locally to account for the additional form drag due to sinuosity. Initial roughness values for overbank areas within the Sacramento River corridor (between the levees) were derived from the CVFPP model. Two sets of combined (mainstem and overbank) roughness values for low and high flow conditions were developed to facilitate the depth-varying roughness modeling approach. The first set, for low flow conditions, were calibrated to a bankfull flow condition observed in 1998 (4/15/1998 - 5/20/1998) when flows ranged from approximately 16,000 – 32,000 cfs in the Sacramento River and generally below the activation flow (~30,000 cfs) of the Colusa Weir. The second set, for high flow conditions, were calibrated to the flood events of 1997 (12/29/1996 - 1/10/1997) and 2006 (12/25/2005 - 01/04/2006). The vertical transitional/break point between the low and high flow roughness values was set to the maximum water surface elevation (WSE) from the 1998 flow event. The depth varying roughness approach was initially tested in simulations of the 1997, 1998, and 2006 calibration periods and it was determined that a 50% increase to the high-flow roughness values above the 1998 maximum WSE was needed to achieve calibration for high flow conditions (1997 & 2006). The approach was validated further by with the 2019 water year. Calibration results are presented in the following section.

Model calibration for the high flow conditions (1997 and 2006) were also aided by implementing weir calibration factors (BMT WBM, 2018) for the Moulton and Colusa Weirs to replicate weir coefficient values used in the CVFPP model. Several important bridges at Ord Ferry, Butte City, and Colusa were also incorporated into the model to enhance model accuracy in those reaches (Table 6). Structural bridge characteristics were derived from the CVFPP HEC-RAS model. Hydraulic bridge losses for the model were calibrated using the CVFPP model results.

Generally, for the TUFLOW 1D model approach, instabilities can occur when there are significant changes in the cross-sectional area or insufficient nodal storage between respective cross sections. In some instances, CVFPP model cross sections imported into the TUFLOW model were modified in density or spatial configuration at locations where successive cross sections shared similar bathymetric profiles (added nodal storage) to achieve numerical stability. Additionally, linearly interpolated cross sections were added between existing CVFPP cross sections at points of numerical instability where there was significant cross-sectional depth variation (river bends, scour holes, etc.).

### 3.1.2 1D CALIBRATION RESULTS

The evaluation criteria for the calibration process in 1998 (4/15/1998 - 5/20/1998) and the flood events of 1997 (12/29/1996 - 1/10/1997) and 2006 (12/25/2005 - 01/04/2006) are shown in Table 8.

**Table 8. Evaluation Criteria for 1D Calibration Events**

| Event | Model Period | CVFPP Model | Historical Gage Data | High Water Marks |
|---|---|---|---|---|
| 1997 Flood | 12/29/1996 - 1/10/1997 | x | x | |
| 1998 Medium-Low Flow | 4/15/1998 - 5/20/1998 | | x | |
| 2006 Flood | 12/25/2005 - 01/04/2006 | x | x | x |

For the high flow events of 1997 and 2006, previous CVFPP model results were compared with Butte Basin model at historical gage locations and longitudinally from Hamilton City to the Tisdale Weir (Appendix G, Figures 1- 22). Generally, model results showed similar agreement to historical gage data as the CVFPP model. Additionally, surveyed High Water Marks (HWM) were also used for calibration of the 2006 flood event simulation (Appendix G, Figures 23-26). Comparison of maximum stage values at gage locations with corresponding HWMs are shown in Table 9.

**Table 9. 1D Calibration Max Stage Comparisons – 2006 Flood**

| | Ord Ferry | Butte City | Moulton Weir | Colusa Weir | Colusa |
|---|---|---|---|---|---|
| HWM (ft) | 117.41 | 88.81 | 80.70 | 68.38 | 65.47 |
| Gage Max (ft) | 117.41 | 92.37 | 80.08 | 67.05 | 66.53 |

Comparison of the simulated water surface profiles from the CVFPP model results to the surveyed HWM for the first (1/1/2006) and second (lower, 1/2/2006) were also analyzed (Table 10 and Appendix G, Figures 23-26). Historical gage data (stage and flow) were used for the 1998 calibration period (Appendix G, Figures 29-34). Table 11 provides the historical gage records implemented for the calibration process. Model validation for the 2019 water year is shown in Figures 30-39. Tables 12 & 13 include root mean squared error (RMSE) values for stage and flow of the considered calibration events. Modeled stage RMSE values are less than 1.00 ft for the 1997, 1998, and 2006 calibration events and within the ~2.00 ft tolerance for the 2019 water year. The flow RMSE values also show good agreement with the gage data generally. There is disagreement between model results and the A02570, Sacramento River at Ord Ferry gage for the 1997 and 2006 flood events. This is likely due to the flow record being rated poor during these flood events when stages and flows meet or exceed 114 ft NAVD88 and ~80,000 cfs in the gage record.

**Table 10. 1D Calibration High Water Mark RMSE Values – 2006 Flood**

| HWM RMSE (ft) | | |
|---|---|---|
| | 1st Flood Peak | 2nd Flood Peak |
| CVFPP Model | 1.94 | 1.64 |
| Model | 2.21 | 2.00 |

**Table 11. Gages Used for 1D Calibration**

| Historical Gage | Source | 1997 Flood | 2006 Flood | 1998 Medium-Low Flow |
|---|---|---|---|---|
| A02570, Sacramento River at Ord Ferry | CA DWR WDL | x | x | x |
| A02500, Sacramento River at Butte City | CA DWR WDL | - | x | x |
| A02986, Moulton Weir Spill to Butte Basin near Princeton | CA DWR WDL | x | x | - |
| A02981, Colusa Weir Spill to Butte Basin near Colusa | CA DWR WDL | x | x | - |
| 11389500, Sacramento River at Colusa, CA | USGS | x | x | x |

**Table 12. 1D Calibration Stage RMSE Values**

| RMSE, Stage (ft) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Historical Gage | 1997 Flood[a] | | 2006 Flood[b] | | 1998 Medium-Low Flow | | WY2019[c] | |
| | CVFPP | Model | CVFPP | Model | CVFPP | Model | CVFPP | Model |
| A02570, Sacramento River at Ord Ferry | 0.30 | 0.47 | 0.56 | 0.63 | - | 0.80 | - | 1.18 |
| A02500, Sacramento River at Butte City | - | - | 0.62 | 0.62 | - | 0.69 | - | 1.25 |
| A02986, Moulton Weir Spill to Butte Basin near Princeton | 0.76 | 1.04 | 0.75 | 0.57 | - | - | - | - |
| A02981, Colusa Weir Spill to Butte Basin near Colusa | 1.08 | 1.00 | 0.79 | 0.68 | - | - | - | - |
| 11389500, Sacramento River at Colusa, CA | 0.75 | 0.47 | 0.52 | 0.62 | - | 0.69 | - | 2.02 |

***a** RMSE calculated from 12/31/1996 12:00 – 01/04/1997, **b** RMSE calculated from 12/29/2005 12:00 – 01/04/2006 23:00, **c** RMSE calculated from 11/1/2018 – 5/1/2019*

**Table 13. 1D Calibration Flow RMSE Values**

| RMSE, Flow (cfs) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Historical Gage | 1997 Flood[a] | | 2006 Flood[b] | | 1998 Medium-Low Flow | | WY2019[c] | |
| | CVFPP | Model | CVFPP | Model | CVFPP | Model | CVFPP | Model |
| A02570, Sacramento River at Ord Ferry[d] | 9,550 | 64,405 | 5,772 | 13,023 | - | 980 | - | 2,008 |
| A02500, Sacramento River at Butte City | - | - | 5,863 | 7,280 | - | 1,066 | - | 2,884 |
| A02986, Moulton Weir Spill to Butte Basin near Princeton | 6,534 | 5,897 | 1,923 | 2,051 | - | - | - | 1,081 |
| A02981, Colusa Weir Spill to Butte Basin near Colusa | 15,054 | 13,145 | 7,948 | 7,592 | - | - | - | 3,640 |
| 11389500, Sacramento River at Colusa, CA | 1,849 | 2,017 | 2,592 | 4,573 | - | 1,089 | - | 9,155 |

***a*** *RMSE calculated from 12/31/1996 12:00 – 01/04/1997,* ***b*** *RMSE calculated from 12/29/2005 12:00 – 01/04/2006 23:00,* ***c*** *RMSE calculated from 11/1/2018 – 5/1/2019* ***d*** *Gage discharge is rated as poor when stage reaches 114 ft NAVD88 or ~ 80,000 cfs.*

## 3.2 2D BASIN AREA CALIBRATION

The 2D model domain was calibrated with data from the 2019 water year. The hydrology in 2019 was highly variable yielding a wide range of flow conditions that inundated large portions of both basins, which made it an ideal timeframe to test the validity of simulated model results. In the Butte and Colusa Basins, two gages in each of the respective basins were used for calibration. In the northern portion of the Butte Basin, stage data from the Butte Creek (DWR A04150, Butte Creek at Colusa/Gridley Rd) gage was used while stage and flow data in the southern basin at the Butte Slough gage (DWR A02972, Butte Slough near Meridian) was used (Figure 27). Near the center of the Colusa Basin, stage and flow data from a gage on the Colusa Drain (DWR A02976, Colusa Basin Drain near Highway 20) was used while flow and stage data from the gage at Knight's Landing Ridge Cut (DWR A02939, Ridge Cut Slough at Knights Landing) was used in south (Figure 28).

In the Butte Basin, before accounting for call water inflows and groundwater contribution to streamflow to the major tributaries (see Section 2.7, Boundary Conditions), the simulated stage and flow was generally lower than observed data. The call water and groundwater contributions provided a better calibration to observed data. Further adjustments to Manning's roughness values in Butte Creek were necessary to optimize calibration to observed data, which yielded a final calibrated roughness value of 0.035 (Figure 15). It should be noted that within the Butte Basin 2D area, no adjustments to baseline roughness values outside of Butte Creek were made given the lack of observed stage data. Comparisons of flow and stage hydrographs for the 2019 water year on Butte Creek and Butte Slough are shown in Figures 40-42.

In the Colusa Basin, TUFLOW modeled flows initially under-predicted the gaged flow at Colusa Basin Drain near Highway 20 during high-flow runoff events. Boundary conditions for the basin-scale model were derived from a HEC-HMS model (Appendix D) which was calibrated to observed data at Highway 20. Because HEC-HMS flow routing routines are very simplistic, the inflows upstream of this gage do not account for floodplain water storage (attenuation) along the Colusa Drain during overbank conditions (flow > about 6,000 cfs in the Colusa Drain at Highway 20). Therefore, the inflows derived from HEC-HMS were likely underpredicted. To account for this underprediction, all Colusa Drain inflows greater than 6,000 cfs were increased by 50%. This resulted in better agreement of simulated flows with the Colusa Basin Drain near Highway 20 gage data. Stage and flow calibration for the Colusa Drain at Highway 20 gage are shown in Figures 43-44. The HEC-HMS model for the Colusa Basin was not calibrated downstream of Highway 20 because the HEC-HMS model could not represent the backwatering present in the southern end of the Colusa Drain due to structure operation, so model calibration in the southern end of the basin was limited. To improve calibration in the Colusa Drain, Manning's roughness for all drains in the model were set to 0.03 and the Manning's roughness for the lower part of the Colusa Drain and Knights Landing Ridge Cut was increased to 0.04 to account for the higher levels of vegetative density (noted during field surveys) (Figure 16). Final stage and flow calibrations for the southern portion of the model at Ridge Cut Slough at Knights Landing are shown in Figures 45-46.

# 4 BASELINE MODELING

The hydrology of the Sacramento River Valley is highly variable, as indicated by the large variability in the total volume of water in the system each year. To forecast water supplies, DWR Bulletin 120 uses the Sacramento Valley Water Year Index (i.e., wet, above normal, below normal, dry, critical) based on observed and forecasted unimpaired runoff to represent natural water production before it is altered by upstream diversions, storage, and export or import of water to or from other watersheds. However, forecasts are known to include approximate error of ±20% due to uncertainty in data, model, and weather. Forecasts are less accurate in drier years and forecast error has increased since the 1990s due to climate change. While the index may be reasonable for forecasting interannual variability in water supplies, it is not a good indicator of the hydrologic variability within a given water year.

Intra-annual variability, or the variability within a given water year, is characterized by variable flow magnitudes, timing, and durations. To characterize hydrologic variations more comprehensively within years, Cordoleani et al. (2021) classified flow events from the 1890s to 2020 into five categories (early small, intermediate, long duration, late small, and ravaging) based on the approach of Whipple et al., (2017) (see Figure 4 in Cordoleani et al., 2021). Examples of each flow event category still present in the Sacramento River are shown in Figure 47. Beginning with the construction of Shasta Dam in 1943, once common, ravaging flows (very large, long duration flows) no longer occur. Further, intermediate flows have become functionally nonexistent in recent history due to regulation and typically occurred at a critical time for juvenile salmon populations (Cordoleani et al., 2022). In general, flows are occurring progressively later in the year over time due to water management and in recent years include less dynamic events, more often falling into long duration events, as well as, the early small and late small, categories.

Although intra-annual flow variability has decreased due to regulation, the system is still punctuated by large hydrologic events resulting in flooding throughout the Sacramento Valley. In wetter years there are often multiple and/or large flood pulses. These wetter year flood pulses activate floodplains and associated habitats within the river and the flood basins and bypasses; and present opportunities on the shoulders of flood pulses to enhance river-floodplain connectivity and improve habitat conditions for salmonids and other aquatic and terrestrial species. Conversely, drier water years typically include short duration flood pulses, while most of the rest of the year is characterized by baseflows in the Sacramento River. In these drier water years, opportunities to enhance river-floodplain connectivity, at the times that juvenile salmon populations are present, can be challenging, especially with the functional loss of intermediate flows. Due to limited water availability in drier years, river-floodplain connectivity becomes more limited in extent and duration, and finding opportunities to enhance river-floodplain connectivity and associated ecological functions becomes especially important.

Five water years were selected from the period 1997 – 2020 for baseline modeling that represented a range of water year types and flow conditions within the basins. Water year selection considered hydrologic analyses and multiple water year typing methods including the Sacramento Valley Water Year Index (DWR, 2023) (Table 14). Water year selection largely considered the flow typing analysis (i.e., early small, intermediate, long duration, and late small) within years (Table 14) (Cordoleani et al., 2021). Additionally, the timing, frequency, and duration of weir overtopping events for the gaged Sacramento River flood weirs (Moulton Weir, Colusa Weir, and Tisdale Weir) and conceptual operable river connections at these flood weirs within each year were also considered in informing the selection (Figure 48). Water years were selected to provide a range of weir and conceptual operable river activation time thresholds, periods, and durations. The overall goal was to select water years with different water volumes, flood magnitudes, flood timing, and duration to represent a range of potential flow conditions in the basins.

**Table 14. Flood Characteristics for Potential Water Years**

| Water Year | Sacramento Valley Index* | Early Small | Intermediate | Long Duration | Late Small |
|---|---|---|---|---|---|
| 1997 | W | x | | x | |
| 1998 | W | | | x | x |
| 1999 | W | x | | x | |
| 2000 | W | x | | x | |
| 2001 | D | | | | x |
| 2002 | D | x | | | |
| 2003 | AN | x | x | | x |
| 2004 | BN | x | | x | |
| 2005 | BN | x | | | x |
| 2006 | W | x | x | x | |
| 2007 | D | x | | | |

| | | | | | |
|---|---|---|---|---|---|
| 2008 | C | | | | |
| 2009 | D | x | | | |
| 2010 | BN | x | | | |
| 2011 | W | x | | x | x |
| 2012 | BN | | | | |
| 2013 | D | x | | | |
| 2014 | C | | | | |
| 2015 | C | x | x | | |
| 2016 | BN | x | | | x |
| 2017 | W | x | | x | x |
| 2018 | BN | | | | |
| 2019 | W | x | x | x | x |
| 2020 | D | | | | |

**Sacramento Valley Index: W-wet, AN- above normal, BN- Below Normal, D- Dry, C- Critical.*
*Selected Baseline water years to run are highlighted in blue.*

The final selected water years for initial analysis were 2003, 2011, 2013, 2015, and 2019 (Figures 49-50). Water year 2019 was a very dynamic wet year with a large spring pulse that also included all four of the flood types identified in the UC Davis method. Further, because of the variety of flows and weir overtopping events, water year 2019 was also used for model calibration. Water years 2003 and 2011 also represent wet or above normal years with several different flood event types. Although both of these years are wetter than average, they include different patterns of Sacramento River flood weir activation; in 2003 there are frequent, short-duration overtopping events and less frequent, longer events in 2011. Water years 2013 and 2015 represent dry or critically dry years that still have some overflow activation. Although dry, 2015 was selected due to its very early season large weir activation flow followed by limited conceptual operable notch activation thereafter. Water year 2013 includes early season elevated flows and two smaller distinct pulses followed by very dry conditions for the rest of the year. These two water years were selected because they represent drier conditions and can help evaluate potential concepts in years with limited weir overtopping and/or limited operable river connections.

The Butte and Colusa Basin models were run for the five selected water years from October 1 to July 1. The boundary conditions were then developed for the Sutter Bypass model using the outflows of these models. Using these boundary conditions, the Sutter Bypass model was run for the same years.

# 5 PRELIMINARY ACTIONS

As noted above, the Program has considered potential future actions that fall within four major categories:

- Floodplain Connectivity
  - Modification or addition of connections between the river and the floodplain
- Floodplain Flow Corridors

    - Modification of water management infrastructure
- Floodplain Reactivation for Fish Food
    - Modification of water management within the field units
- In-river Function
    - Improve existing floodplain habitats within the river corridor

Evaluation of individual actions began by first investigating floodplain connectivity by considering the addition of operable gates at key river connections in the Butte Basin at Moulton and Colusa Weirs. For example, to formulate an operable gate at Moulton Weir, the model derived rating curve for the Fremont Weir Big Notch Project (cbec, 2021) was adapted to Moulton Weir and scaled based on the desired capacity of the operable gate (Figure 51). The operable gate invert was assumed at 61.0 ft NAVD88 based on review of the existing topography and downstream constraints interior to the Butte Basin and corresponds to a Sacramento River flow of 18,000 cfs. Figure 52 displays the percentage of operable gate flows relative to the total modeled flow in the Sacramento River. As configured, this suggests that the percent river flow diverted is at a maximum when the river level is half the depth of the operable gate and then drops to approximately half of the maximum percent river flow diverted just prior to weir overtopping as tailwater conditions affect inflow. The maximum increase in entrainment with a 1,000 cfs operable gate at Moulton Weir is 3.3% at a river flow of 30,000 cfs and 1.7% at 60,000 cfs. For a 2,000 cfs operable gate, the maximum increase in entrainment is 6.7% at a river flow of 30,000 cfs and 3.4% at 60,000 cfs.

# 6 FUTURE WORK

For future modeling efforts and analysis, the collection of additional terrain/bathymetric data should be considered in all managed wetlands. In the current TUFLOW models, wetland bottom elevations are estimated and flat because inundation prevented the survey of ground elevations during LiDAR data acquisition. In reality, various managed wetlands have variable topography to provide habitat diversity and recreational access. In the Colusa Basin, in addition to the reasons noted above, updated terrain data is needed to better represent current topographic conditions due to active subsidence (see Appendix F). Terrain/bathymetric data in these areas would provide a more accurate representation of the water management system (field to field water connections) and better estimation of the inundation regime, which is essential to quantifying habitat suitability under existing and potential future actions.

Collecting additional information on hydraulic structures should also be considered for future modeling efforts. Water management infrastructure (i.e., culverts, gates and weirs) within portions of the basins (e.g., Drumheller Slough Complex, various duck clubs) is complex and a more accurate representation of these structures in the model is needed to represent  water conveyance correctly. More information on structure locations, dimensions, elevations and operations will improve how the models are directing water through the systems and in turn provide more accurate information on habitat availability and quality under existing and potential future actions.

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# 9 APPENDICES

## 9.1 APPENDIX A: ENHANCEMENTS TO THE TISDALE WEIR REHABILITATION AND FISH PASSAGE PROJECT TUFLOW HPC MODEL

## 9.2 APPENDIX B: SURVEYING TECHNICAL MEMO

## 9.3 APPENDIX C: MODELING FRAMEWORK FOR MANAGED WETLANDS IN THE BUTTE AND COLUSA BASINS

## 9.4 APPENDIX D: HEC-HMS TECHNICAL MEMO

## 9.5 APPENDIX E: RECLAMATION DISTRICT NO. 108, STREAM GAUGE STAFF SURVEY RIGGS RANCH, KNIGHTS LANDING, RIDGE CUT & WALLACE WEIR

## 9.6 APPENDIX F: COLUSA BASIN DRAIN AT KNIGHTS LANDING GAGE: SUBSIDENCE SUMMARY

## 9.7 APPENDIX G: 1D CALIBRATION SUPPLEMENTAL FIGURES