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# REVIEW OF THE

# YOLO BYPASS SALMONID HABITAT RESTORATION AND FISH PASSAGE HYDRODYNAMIC MODELING DRAFT REPORT

FOR

COUNTY OF YOLO

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## Abstract

Yolo County contracted with The Center for Watershed Sciences (CWS) to review a 1D/2D combined hydrodynamic model for the Yolo Bypass. cbec ecoengineering, a consulting firm, produced the model for the California Department of Water Resources (DWR) and the Bureau of Reclamation (USBR) using the TUFLOW software. USBR and DWR developed the model to estimate potential Yolo Bypass inundation patterns resulting from the construction of an operable gate or gates in the Fremont Weir to increase the frequency and duration of flooding for juvenile salmon and to improve fish passage. USBR and DWR developed this model as part of implementation of the 2012 Yolo Bypass Salmonid Habitat Restoration and Fish Passage Implementation Plan. The Plan addresses two specific actions set forth in the Reasonable and Prudent Alternative (RPA) included in the 2009 National Marine Fisheries Service (NMFS) Biological Opinion and Conference Opinion on the Long-term Operation of the Central Valley Project and State Water Project:

- RPA Action 1.6.1: Restoration of Floodplain Rearing Habitat, through the increase of seasonal inundation within the lower Sacramento River basin; and

- RPA Action 1.7: Reduce Migratory Delays and Loss of Salmon, Steelhead, and Sturgeon, through the modification of Fremont Weir and other structures of the Yolo Bypass.

DWR and USBR intend to use the Yolo Bypass TUFLOW model for completion of the EIR/EIS for the proposed Yolo Bypass improvements. The purpose of this model review is to identify model strengths, weaknesses, and possible flaws that could compromise the results of the TUFLOW model. For the purposes of this report, “weaknesses” are areas where improvement should increase the accuracy of the model but are not mandatory to produce useful model results (can produce reasonable comparative differences from boundary conditions changes). Model “flaws” could compromise model results, producing uncertainties beyond reasonable use, and invite challenges by others to the validity of the EIR/EIS. Many weaknesses are likely the lack of content or thorough explanation within the report and may not compromise modeling results. The lack of sensitivity analysis, however, could compromise the results of the model.

The work described in the cbec model report is high quality and generally acceptable. The choice of software is reasonable to produce a quality model application. Development of the digital elevation model (DEM) included great effort to collect additional data where needed. cbec’s work to develop boundary conditions is good, although the quality is greatly compromised by the lack of measured data. The modeling report is incomplete and should be updated, as it does not contain all model details and contains some unclear explanations about the purposes of the model. DWR and cbec provided this information verbally during meetings, but cbec should update the report to include this information so future model users have all information necessary to understand the model. The following is a list of weaknesses and flaws identified from the model report review:

### Strengths

The TUFLOW model for the Yolo Bypass is superior for a field-scale basis model than other

Yolo Bypass models that have been produced in the past, such as MIKE-21. There have been many flood models produced for the Yolo Bypass, but most were only investigations into the maximum flood capacity of the system and the protection the Bypass provided to areas along the Sacramento River between Verona and Rio Vista. The MIKE 21 model of the Yolo Bypass looked at finer scale resolution than the earlier flood capacity models, but still included with issues and did not provide predictions based on the current level of information (Northwest Hydraulic Consultants *et al*. 2012). The TUFLOW software chosen for application to the Yolo Bypass lacks significant peer reviewed literature, but has proven itself in multiple applications and by the European Union benchmark tests (Neelz and Pinder 2013). In the preparation of the TUFLOW Yolo Bypass model, newer LiDAR was included to better define the topography along with significant ground surveys where other topographic detail was critical. Significant effort was made to ensure the topography was bare earth and included required drainage channels to capture needed drainage patterns as determined from the recent cbec (2014) drainage report.

## Weaknesses:

1. **The lack of boundary condition data with quantifiable uncertainty.** The lack is not a deficiency with cbec's work, but of the general lack of reliably measured historical data needed to fully develop boundary conditions within reasonable and better quantifiable uncertainty. cbec made a good effort in the model review report to quantify the inflows using regression analysis, but the report has not fully quantified the uncertainty the boundary conditions produce and the resulting uncertainty of the model predictions has not been adequately evaluated. The boundary conditions are uncertain because of 1) the complete lack of measured data for Putah Creek and Willow Slough; and 2) the errors associated with calculating boundary conditions of Knights Landing Ridge Cut, Cache Creek, Feather and Sacramento Rivers and Sutter Bypass. Consequently, the work should do more to quantify this uncertainty and conduct and present a more thorough sensitivity analysis for all flows and the timing of these flows. Responsible agencies need to recognize the need to reduce the future uncertainty and begin properly monitoring these inflows.
2. **The lack of calibration details.** cbec should update the model report to include a clear description or evidence of any low flow calibration for the Sacramento River channel. cbec provided this information during meetings, but not in the model report. While roughness coefficients for the floodplain were assigned by vegetation types, there is no clear description of modification for calibration. This includes whether the modification is by vegetation type for the entire floodplain or only locally. The report mentions DEM modifications, but does not detail them. There is no demonstration of matching Tule Canal flows (only a statement that it did), nor explanation of what was changed to create the match. There is also no description of other model parameter settings, such as implicit/explicit solution variable, wetting and drying tolerances. There is also no information in the report indicating that truncated models used in calibration are representative of full model.

3. **The lack of detail on the Fremont Weir.** DWR and cbec indicated during meetings that the Fremont Weir is not explicitly represented in the model. cbec instead gave more attention to the roadway, which is between the river and the weir and is higher than the weir. Using the roadway as the control structure for floods into the Yolo Bypass does not account for the earlier and later flows that circumvent the roadway and spill over the weir. The model results will have a slightly higher peak elevation with a shorter flooding period. If the model is only used for comparison purposes of differences between events and not specific durations, then the introduced errors will not be too significant. Use of the model for exact dates of Last Day Wet (LDW) would be influenced by this issue. Providing quantification of uncertainty, as described in item 1, would correct this issue.
4. **No structures included on the Sacramento River.** The reports indicates that cbec made some modifications to channel cross-sections to account for the absence of including structures to improve stability, such as bridges. Including the structures is a more appropriate solution. Again, if the model is only used for comparison purposes of differences between events and not specific durations or timing then the introduced errors will not be too significant and would be accounted by proper uncertainty analyses.
5. **Use of additional storage in 1D channels.** The report states that calibrations verify that storage was shown not attenuate flood hydrographs. The report should present evidence to support this claim.
6. **Use of 0.05 inches/hour for infiltration**. Researchers have found that infiltration values between 0.02 - 0.03 inches/hour are more accurate for the Yolo Bypass (Graham Fogg, pers. comm.) than the .05/inches per hour used in the model. The higher infiltration values will drain the floods faster than realistic and produce early LDW dates
7. **Use of 70/30% to predict LDW**. The 70% assumption assumes that a cell is dry when the center is dry. The cell will only be dry if the field is flat, which may not be a realistic assumption in the Yolo Bypass. This assumption is critical to the calculation of when a fiels in 70% dry, and therefore ready to plant. This assumption should be tested.
8. **Pre-processing Cache Creek Settling Basin data**. cbec pre-processed Cache Creek Settling Basin Data by doing the calculation outside the flood model and used a input to the flood model and did not provide a description of the work in the report. Handling the input data in this manner and not providing the work provides a potential challengeable issue for the EIR/EIS since others will not know the inputs used. Pre-processing of the data will make it more difficult to model future years. The complete work should be included in the report and the data provided with the EIR/EIS.
9. **Clarification of time series figures**. It is not indicated on the report figures whether the output of results and measured data in the figures is daily, maximum daily, hourly, or shorter time steps. The issue was clarified in personal meetings with DWR and cbec but should also be properly defined in the report.
10. **Fremont Weir spills**. The inconsistency of removing spills in the 2011 calibration while provided graphs indicating spills must be adequately addressed to avoid any challengeable issue in the EIR/EIS.
11. **Wetting and drying estimates.** There is poor detail on whether wetting and drying was calculated on a grid-cell basis or on a DEM raster resolution. The issue should be better addressed in the report.

## Flaws:

1. **Insufficient grid convergence work.** Grid convergence testing is necessary to ensure the solution provided by the model is accurate. DWR and cbec (pers. comm.) have stated some grid convergence testing was completed. Without inclusion of results in the report, however, it is still not clear that the grid size was chosen for any reason other than to make the solutions times more manageable, or even just stable. The report itself states, "The number and length of simulations greatly constrained cell sizes and time steps." At no time should the number and length of the simulations be allowed to override finding an accurate solution. The report also acknowledges water surface elevation oscillations at points along the 1D/2D border. Here again, inadequate resolution is likely a major contributor. By standards today, the absence of a thorough convergence test is a significant flaw in the work. If DWR and cbec provide information that the grid size chosen provides a convergent solution, this item would be removed from the list of flaws.
2. **No model validation**. There was no validation of the calibrated model with an independent data set. Running a separate data set from the data used in calibration is crucial to demonstrating that the assumptions made during calibration will remain valid for other flows. The report does acknowledge that other flood year data are available for validation of the calibrated model but does not cover any effort in this regard.
3. **Insufficient sensitivity analysis.** The model relies on assumptions that are uncertain and not tested with rigorous sensitivity analysis. These assumptions are: 1) the 10% variation in the boundary conditions; 2) the infiltration rate; and 3) the assumption that a cell is dry when the center is dry, which is critical to the calculation of when a field in 70% dry (and therefore ready to plant). The 10% sensitivity analysis shown for the inflow hydrographs is insufficient to cover the broad uncertainties in the boundary condition calculations. The infiltration rate is likely high. The 70% assumption assumes that a cell is dry when the center is dry (and therefore the cell will only be dry if the field is flat), which may be and unrealistic assumption in the Yolo Bypass. The sensitivity analysis should consider the full variation of errors shown in the calculated versus known inflow data. The infiltration rate should test at 0.01 inches/hour and 0.03 inches/hour. The lower end of the range accounts for potential reduction in infiltration due to ponding and the 0.03 inches is the higher end of the range provided by Graham Fogg. The 70% assumption should be tested.

The prudent use of any model is the comparison of differences in results to various inputs, not the absolute values predicted. The differences should be provided to cover the full uncertainty ranges of the input values. DWR and the USBR developed the TUFLOW Yolo Bypass model to estimate potential inundation scenarios resulting from the construction of operable gates in the Fremont Weir and fish passage improvements and for use in the EIR/EIS for implementation of these improvements. The reviewer feels this model can be used as a planning tool to compare the general trends (not the discrete predicted differences) of various changes in inputs as long as those changes do not modify the flow patterns over the floodplain. In addition, the model is currently based on data that are not available to the public. An EIR/EIS document and any other similar analysis of impacts within the Yolo Bypass should be based on publicly available data to minimize challenges and increase general acceptance among stakeholders and the general public.

## Introduction

CWS prepared this model review in partial fulfillment of Agreement Number 2014-324 between the County of Yolo and The Regents of the University of California, on behalf of its Davis campus. The specific task within the contract was item 4 and stated:

> *"Review the TU-FLOW model currently under development by cbec to support the implementation of RPA 1.6.1 and CM2, including attending Hydraulic Model Technical Team meetings hosted by the Department of Water Resources and the Bureau of Reclamation."*

USBR and DWR intend to use the TUFLOW model to inform evaluations of the impacts and benefits of selected Yolo Bypass RPA alternatives identified by the Department of Water Resources (DWR) and Bureau of Reclamation (USBR), herein referred to as the Lead Agencies, including the EIR/EIS. The following review is intended to point out the strengths and weaknesses of the model for the intended use, as well as any perceived "flaws." Model "weaknesses" are areas where improvement should increase the accuracy of the model but are not necessary to ensure useful model results. Model "flaws" could, at worst, compromise model results or, at least, raise challenges to the EIR/EIS.

CWS well understands that producing a good, field-drainage-scale model of the Yolo Bypass area is complicated as a result of CWS producing two models for this purpose with two different software products over the past three years. All models are only representations of reality; they do not contain all the physical detail or physics of nature. The goal of any modeling effort is to represent enough of the physics and physical surface to adequately produce the desired answers. Anything further becomes more costly to develop and to run than desired. The simulation of a model provides a discrete answer, meaning that for a given set of inputs the same solution will always be produced. Nature, on the other hand, is not so predictable. As a result, nature would not produce the exact same result even if it could be given the same inputs. Therefore a model is always only an approximation of nature and it is impossible to create a model that fully recreates all natural functions. For these reasons, it is critical that a good uncertainty analysis be performed in order to understand the range of possible answers.

## Elements of a Useful Model

The efficacy of any model application depends on **1)** the model software utilized; **2)** the application of that software in defining the problem to the proper detail; and **3)** the calibration and validation of the application. The best hydrodynamic modeler cannot produce a truly useful model with software ill-equipped for the problem; and the best software cannot by itself produce a useful model without a talented hydrodynamic modeler to prepare the necessary input files and create the application for the software to simulate. After the application is developed, it is necessary to calibrate the model to cover the entire range of conditions the modeler will simulate with a reliable set of data. The modeler then needs to validate the calibrated model by simulating a different set of data for the full range of conditions. Only after all three elements are in place is the model application ready to examine potential alternatives. Even then, care must be taken to ensure that the alternatives do not compromise the validity of the model application and its assumptions by exceeding the calibrated flow ranges or anticipated flow patterns.

## 1) The Software

The TUFLOW Classic software tool chosen for this project solves the full Saint Venant equations describing 1D hydrodynamic flow, and couples that with a 2D shallow water solution developed by Stelling (1984) as described by Syme (1991). The software is a proprietary, commercial product and requires other proprietary, commercial pre- and post-processing packages to support it (*e.g.*, produce input files and analyze output files). The nature of this project lends itself well to the choice of a 1D/2D coupled model. The extensive river network involved outside the floodplain is suitable to 1D treatment, while the floodplain is best solved with a 2D solution. The 1D/2D choice can represent the domain well with a minimum of computational effort.

Ideally, every modeling software package would be documented with its own rigorous verification and validation exercise along with peer-reviewed publications to assure its efficacy (Wang *et al*. 2008). Code verification serves the purpose of ensuring the code is properly solving the equations and determining the order of accuracy of the numerical solution (*i.e.*, code verification ensures the solution of the coded equations is correct and accurate). The validation will then be used to determine whether the equations being solved are providing the proper solution to the physical problem (*i.e.*, validation determines whether are the correct equations are being solved). Peer-reviewed publications provide confidence in the software and demonstrate both its strengths and weaknesses.

Like many software packages, TUFLOW relies instead on the publication of graduate student theses and dissertations along with a raw underlying theory paper (Stelling 1984), without verification and validation by actual peer-reviewed journal articles. The lack of true code verification and validation is a shortcoming found in most proprietary software packages. The TUFLOW software has been extensively applied outside the United States, however, and certainly applied to the extent that any underlying fatal flaws in the code would have been uncovered. Properly applied for this application, the TUFLOW software should provide reasonable results within the bounds of its limitations.

## 2) The Application

The second step in the creation of a useful model application is the successful implementation of the chosen software to adequately describe the problem to be examined. The goal is to define the problem in sufficient physics and detail to provide reasonable answers without overly complicating the problem and wasting excess time and money in development and computational effort.

The physical elements or parameters necessary for the proper problem definition include **A)** the topography and bathymetry; **B)** a DEM created from (A); **C)** the computational grid used in the mathematical solution; **D)** channel and floodplain roughness values; and **E)** boundary conditions that will not influence the solution in the domain of interest.

### A) Topography and Bathymetry

The data sources listed for the topography of the model domain are the best available sources at this time. The lead agencies and cbec have collected additional survey data and bathymetry data expressly for this model application in some critical areas, *e.g.*, the Tule Pond area. The upper area is important in properly simulating the initial spills from the Fremont Weir or any modification to the weir. It is unclear, however, why similar efforts were not made for the lower Toe Drain-floodplain connection where a 1D/2D manipulation of the problem was made (see below). The lower region of the Toe Drain is important in predicting drainage and consequently the last day wet (LDW). Since neither the 1D cross-section information nor the actual topography were supplied for the review, there is little else that can be ascertained about the efficacy of these parts of the model.

### B) Digital Elevation Model

From the topography, and possibly bathymetry, a digital elevation model (DEM) is produced to provide input to the actual mathematical grid. TUFLOW uses nine elevation values from the DEM for each grid cell – the four corners, the four mid-sides, and the center. Only the center node is used, however, in the calculation of the stage-area-volume tables for each cell used in the mathematical solution. Further, the center elevation is also used to determine when each cell is either dry or wet on the basis of user-specified threshold values. DWR and cbec have demonstrated in the calibration that reasonable wetting and drying threshold values have been used, but this needs to be clarified in the report.

The report indicates the DEM was processed at a 3.125 ft resolution with hydro-enforced breaks. The DEM was then resampled to a 25 ft resolution to make it more manageable for TUFLOW. There is no information provided to explain how the 3.125 ft DEM was interpreted, nor any details on the resampling to 25 ft resolution. The methods used (*e.g.*, nearest neighbor, Kriging, *etc.*) will influence the results. Provided that the uncertainty of flooding extent and duration is detailed in the calibration, then the resolution is considered adequate to provide useful results.

When the grid is overlaid onto the DEM and the data interpreted into the DEM, it is critical that the grid boundaries honor the more significant natural break and enforced breaks. Failure to do so can greatly influence the results (*e.g.*, if a significant elevation is not captured by a grid line or artificially enforced break-line then it is missed altogether). DWR and cbec provided these details to the reviewer and they have been properly applied. The details need to be included in the report.

### C) Computational Grid

The computational grid as discussed here will include both the actual 2D grid as well as the 1D channel definitions. The 1D channel definitions are reported in one section to have been developed from “a combination of bathymetric and field surveys”, and in another section it is stated that cross-sections “outside of the Yolo Bypass … [were] obtained from Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS model”. Although it needs to be clarified in the report, personal meetings with DWR and cbec confirmed that the earlier statement referred to 1D cross-sections within the Yolo Bypass (these assumptions have been confirmed in personal meetings with DWR and cbec and should be included in the report). For the 1D Toe Drain channel development, the cross-sections were extended at some locations into the floodplain to better account for topography where vegetation may have interfered with the DEM bare-earth elevations. If the topography is actually known, it would be just as simple, and more accurate, to correct the DEM and not manipulate the solution by extending the 1D cross-sections. If the extended portion of the 1D cross-section had a high point within it, then flows would be seen in the 2D area before water actually topped the crest and likewise drain early, unless further 1D cross-section information is included in the model. Examination of later supplied data demonstrates an adequate application of cross-section and floodplain interactions.

In the cross-section discussion of the CVFED usage, the simple statement in the report, “Some modifications were made to individual cross-sections to improve numerical stability” suggests that there are some cross-section or grid resolution issues that need to be resolved. The report notes that none of the structures associated with the CVFED cross-sections were included, but the flow ranges simulated rarely create instabilities. The model would benefit from the inclusion of the structures to better resolve all flow ranges and to remove the issue from potential challenge.

Since the 1D portion of TUFLOW is an explicit solution scheme, the Courant number must be kept below unity. The 2D portion is an implicit scheme, so the Courant number can range from 2 for steep flows to as high as 10 for sub-critical flows. There is no mention in the report of the maximum Courant number in the simulations for either the 1D or 2D domains. Further, for explicit solutions there is typically a parameter than can be used to adjust the solution from fully explicit to a combination of explicit/implicit. No mention is made for this in the report. While these issues have been addressed in personal meetings with DWR and cbec, they should be clarified to prevent questions regarding the accuracy of other analyses that rely on the model.

The TUFLOW model uses a square cell grid, which will always have some difficulties in properly resolving curved and irregular boundaries. Fortunately in the Yolo Bypass, the majority of the major features are orthogonal to one another. Only the Fremont Weir area and the lower Toe Drain pose much issue for the grid. The majority of the 2D floodplain is using a 200 ft cell size, with 100 ft cells from the transition of Sutter Bypass to Yolo Bypass, and 400 ft cells on Liberty Island. Providing the grid convergence is addressed in more detail, there is no reason that the square grid cell representation will compromise the results.

As mentioned above, care must be taken so that the grid cells most properly align with the major features of the floodplain. The applied resolution and internal computation of the TUFLOW software will not permit a detailed field drainage representation without further extensive additions. Providing the grid convergence is addressed in more detail, further examination of the more detailed data provided demonstrate a well-designed grid for these purposes.

The 2D grid was modified in locations to produce better drainage through channels into the Toe Drain. Since these modifications are not actual representations of the natural artifacts, better documentation of these modifications is necessary. These artifacts could require additional calibration, improperly influence, or raise into question, any expanded investigations performed with the model. Several of these modifications are described in the report:

> The crown and thalweg profiles of berms (road and field berms) and gullies (ditches and drains) were restamped into the sampled DEM to overcome data loss and surface smoothing when resampling to a coarser resolution (*e.g.*, 200 feet grid).
>
> The field berms were limited to those berms and road features along the field perimeters.
>
> The digitized drainage features were 200-foot-wide rectangular channels with channel inverts often derived from ponded water elevations within the LiDAR
>
> Often via small culverts, [features] were created by adding 600-foot-long drainages that cut a 200-foot-wide swath across the field perimeter features

The report states "storage (water volumes) for the portion of 2D boundary cells not overlapping the 1D domain is ignored" and acknowledges that this will reduce total water volume. Reducing volumes here will force more water elsewhere onto the floodplain. The report states "TUFLOW manual states that adding additional storage to 1D nodes is an acceptable approach to stabilize 1D nodes but may attenuate the model results (typically attenuation will reduce the predicted stage by stretching the duration of the flow)". The model application also adds storage for the purpose of stabilizing the results which will attenuate the model results, and divert water onto the floodplain. Eventually small errors will compound into significant errors. The report acknowledges the issues but does not quantify the effects. This weakness should be examined more closely to determine whether it is becoming too influential on the solution.

While the report states, "The calibration models verify that the storage changes do not significantly attenuate flood hydrographs", this can also mean that parameter modification has mostly compensated for any storage errors remaining. It is these types of issues for which validation of the calibration is crucial. Otherwise, when flooding occurs differently than during the calibration flows, or other physical modifications are tested, these issues may become a problem.

### *D) Roughness Values*

The model application generally used vegetation mapping roughness developed by California State University, Chico prepared for the Central Valley (DWR 2011) and Sacramento-San Joaquin River Delta using the National Vegetation Classification System (NVCS). The values used were originally developed for an RMA-2 flood capacity model, so they would be expected to be low since higher flow rates and depths experience less roughness. Without modification the lower roughness values of a flood-capacity model would not attenuate flood flows and produce faster draining than expected. It would be prudent to mention whether variable roughness over flood flow depth is used.

The report mentions that roughness multipliers were applied to the ‘composite Manning roughness’ of some cross-sections. Note that there were variable Manning ‘n’ values incorporated in the CVFED cross-section data, and not composite values. A composite value would be only a single value to represent a cross-section – both laterally and vertically. The model uses CVFED values that vary across and vertically within each cross-section.

### E) Boundary Conditions

The report does a good job of developing the boundary conditions with the best possible data available, although boundary conditions remain a weakness since the available data are limited. Most of the work is an extension of the Jones & Stokes work on the Yolo Basin Management Strategy study. The modeler’s understanding of the Knights Landing Outfall Gates (KLOG) is not consistent with the physics. The flow does initially go into the Sacramento River, but there is an elevation of the river at which flow is then reversed and flows down the Knights Landing Ridge Cut (KLRC) into the Yolo Bypass. It is possible that this accounts for some of the difference discussed in the two calculation methods for FEA+SUT flows. Regardless, at lower flows the comparison of the two methods shown in Figure 4-10 of the report demonstrates there is up to a 200% variability between the two equations solving for FEA+SUT flows.

The boundary condition locations are selected well and located sufficiently far enough from the area of interest to be suitable for the intended purpose. It is unfortunate, and certainly no fault of the modeler, that the boundaries are not better monitored. The lead agencies should be planning ways to better monitor the west-side tributaries to improve confidence in future work.

The northern boundaries could be located farther from the domain of interest to reduce some of the calculations needed for the boundary conditions; but moving boundaries farther north would create a larger, less manageable, and more computationally demanding model. The reviewer does not believe the model is compromised by the decision not to locate the northern boundaries farther from the domain of interest.

The Fremont Weir is an internal boundary and not explicitly represented in the TUFLOW model, but the reviewer’s information differs slightly with the report on the height of the weir. The height certainly is not constant across the nearly 2-mile long weir, and the gage lists it at 33.5 feet USED datum. Correcting for NGVD29 and the NAVD88 conversion (according to Vertcon[1] a correction of 2.454 ft) the weir would be 32.945 ft NAVD88. Rounded to the nearest tenth gives 33.0 ft versus the 32.8 feet listed in the report. The Lead Agencies should work to ensure that different State agencies don’t supply contradictory values.

The Natomas Cross Canal (NCC) flows are estimated with a scaling factor calculated from regression with the Steelhead gage. The associated error for the scaling factor is +/-13%.

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[1] From the NOAA web site: http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

The KLRC flows have good correlation at very low flows, but exhibit up to a 100% difference at moderate flow rates (Figure 4-14 of the report). The differences at higher flow rates may also be associated with the KLOG flows mentioned above.

It is not made clear why the boundary data for the Cache Creek Settling Basin were pre-processed with a different software rather than just implemented into the model. Perhaps it was felt that it would be too computationally intensive for TUFLOW or maybe just not something TUFLOW does easily, or well. When applying the model for any other use or modeling time periods, it would be more straightforward if the work was incorporated into the computations in the model application. Regardless, the flow calculation has a tendency to over-predict the peaks of the lower flows by up to 100% (Figure 4-18).

Although the author of the Jones & Stokes Management Strategy believes the hydrology work was not fully developed for use in planning and design (Gus Yates pers. comm.), better data still do not exist for Willow Slough and Putah Creek. There is not enough information for these two inflows to even develop an error estimate. Fortunately, the flow rates for Willow Slough and Putah Creek are smaller and have less effect than other tributaries where better information is available. Over- or under-estimated inflows of these two boundary conditions, however, will influence upstream flood coverage and the effect should be analyzed to quantify the uncertainty. Better monitoring of the west-side inflows are needed.

The existence of only Dayflow data for use at the Delta Cross Channel (DCC) and the Georgiana Slough boundaries can produce problems. Certainly for the most recent years there are USGS flow data on a more refined time scale that could be used at least to examine the effects of using the daily values at these locations, which are so close to the lower tidal boundary. Using daily values here always provides a net outflow where tidal reversals certainly occur, except for extreme floods where the DCC would always be closed and Georgiana Slough a more likely outflow.

The information provided for the Delta Sloughs and North Bay Aqueduct are not clearly described. However, it seems like a lot of effort for something that has so little influence. It is difficult for the reviewer to understand why the upper most boundaries of Haas and Upper Cache Sloughs would have negative flows during flooding events, or why they would have a sinusoidal pattern during these events.

While not clear in the report, DWR and cbec have made assurances that a more appropriate time step for tidal stage has been used in the calculations. Aside from the shortcoming of the daily time step of the inflows, the boundary conditions are reasonable. An uncertainty is produced by the lack of detailed measured data for each of the boundary conditions. These uncertainties will compound themselves throughout the results and will remain a weakness in the results. The only solution to this weakness is prudent monitoring of the boundaries. The overall modeling effort falls short, however, in considering the error bounds of the boundary conditions. A single look at +/-10% of the inflows does not likely cover the error associated with gage measurements, and certainly not the extent of error associated with the calculated boundary conditions.

## *Conclusions - Elements of a Useful Model*

The TUFLOW software package, appropriately developed for an application of this nature, can be expected to produce acceptable results. The topography work for the model included all the most recent information and additional survey data were taken where increased understanding was necessary. The actual techniques for incorporating the additional survey data and the methods of interpolating all the data into the DEM are not provided. Various interpretation methods will produce differing qualities of DEMs and the methods used should be defined in the report. The technique for the choice of roughness coefficients is prudent, although no specific values for the channels or floodplains are provided subsequent to calibration. The best possible development of the boundary condition inputs has been made, although great uncertainty exists due to lack of available measured data. The uncertainty of the boundary conditions should be more fully developed in the EIR/EIS work and the results presented as a range of possible values.

### Model Calibration

During any calibration procedure, it is necessary to determine if the grid size is sufficiently small to properly resolve the problem. To make this determination, it is necessary to perform one simulation and then reduce the grid size (normally by half) and re-run the simulation. If the solutions have not converged, then the grid should continue to be reduced until the solutions agree (converge). Checking to ensure the results converge as the discretization size in time and space is decreased is crucial to knowing whether the problem is properly resolved. Many today even feel the observed order of convergence should be compared to the formal order of convergence of the scheme (Roache 1997, 2009; Knupp and Salari 2003; Wang *et al*. 2008; Graziani 2008; Oberkampf and Roy 2010; Ateljevich *et al*. 2011; Zamani and Bombardelli 2014), but few formally follow this ideal.

While the TUFLOW manual suggests that convergence testing is not needed for an ADI solution (Alternating Direct Implicit), this suggestion is only referring to the convergence of the mathematical solution, not the convergence of the solution for any given grid size. DWR and cbec (in communications) have confirmed some grid convergence testing was done; but without inclusion of results in the report it is still not clear that the grid size was chosen only to make the problem more manageable, or even just stable. The report itself states, “The number and length of simulations greatly constrained cell sizes and time steps”. At no time should the number and length of the simulations be allowed to override finding an accurate solution. The report also acknowledges water surface elevation oscillations at points along the 1D/2D border. Here again, inadequate resolution is likely a major contributor. By standards today, the absence of a thorough convergence test is a significant flaw in the work.

After convergence testing, calibration proceeds by finding the flaws in the results (when compared to observed data) and correcting the grid elevations, structures, and modifying roughness coefficients until an acceptable difference is produced. Calibration and validation of a flood model brings additional complications. First, there is often not very accurate, or limited, data available for these purposes. Second, it is necessary to calibrate for a broad range of flows to ensure the model is capable of handling both the rising and receding limbs of the flood, including drainage. To properly accomplish the calibration it is necessary to start with the low, in-bank flows to be certain that the model will properly handle these low flow drainage periods. This analysis of low, in-bank flows is particularly important for the Yolo Bypass since the lower boundary is tidal in nature and also can be influenced by drainage other than the Sacramento River. If the flood flows are first calibrated, modifications made for subsequent low flow calibrations can influence, possibly very significantly, the earlier flood calibration.

It is not clear from the report that the calibrations were done in a proper order, but subsequent conversations with DWR and cbec have demonstrated the calibration was completed better than reported. The report needs to be modified to clear up any issue raising questions with the order of the calibration.

### 1) High Flow – 1997

The high flow flood calibration of 1997 relied heavily on high water marks (HWM). The use of HWMs is universal because they are physical observations that are often made; however, HWMs are also understood to be highly inaccurate. Along with different personal judgments, HWMs are hugely influenced by wind and waves, particularly on such a wide-open floodplain as the Yolo Bypass. In the Yolo Bypass, storm winds are from the west. The calibration Figure 5-3 (misstated as 5-33 in the report) suggests that the west side HWMs were lower than predicted and the east side higher than predicted. Considering the predominant wind direction, the solution bias would be expected to be in the opposite direction. The other question is why most of the Toe Drain water surface elevations (WSEs) below the Lisbon Weir are predicted lower than the HWMs while the few above are higher than observed. At the same time, there are water surfaces in the lowest part of the Toe Drain that are predicted 1 to 2 ft too high. If the HWMs are accurate representations of WSEs, the results suggest that something is inaccurately represented in the lower Toe Drain. Such an inaccurate representation will influence both flood extent and drainage times.

The calibration graphs of WSE are more difficult to interpret. It is unclear whether the observed data are also hourly reports of daily values. If the observed values are event-based (1-hour or less) then the peaks would be higher than an hourly averaged output stage. On the Sacramento River all the predictions are lower than observed for the receding limb except for Walnut Grove which is predicted higher than observed for the entire period. Tidal elevations as close as Walnut Grove to the input of the lower boundary condition at Rio Vista should be getting more accurate rather than less. The stages specified at Rio Vista input will have great influence on Walnut Grove because it is so close.

The graphs depicting calibration near Woodland (Figure 5-16 in the report) demonstrate that the model over-predicts the stage by nearly 3 ft in the rising limb of the flood, while the west side of the bypass also is higher than the HWMs. The field measurements of flow at this location and the discrepancies with USGS reported values suggest this location should be discounted. The error uncovered by the flows measured by cbec would indicate that the reported calculated stages from the USGS flow data would be lower than actual observed conditions.

### 2) Low Flow – Feb 2010

Obtaining data during the period when the Tule Canal/Toe Drain was full but not spilling was a great opportunity and provides invaluable data. A model intended to supply guidance for use in an EIR/EIS document, however, should be made with public data. CWS recommends making this data public to improve EIR/EIS transparency.

The observed WSE data shown in Figure 5-20 of the report were recorded over a period of time. This presentation leaves some important questions unanswered. Does the predicted profile represent the same times or is it a given snapshot in time? Were the comparisons provided made with a snapshot of output or based on actual time the observed data were collects? Answers to these questions should be included in the report as they would help characterize model performance by indicating areas of uncertainty.

The measured flows along the Toe Drain are provided in Table 5-2 of the report, but there are no modeled flows presented for comparison. The report states that flows were "based on measured flows, as shown in Table 5-2, with incremental flows added or subtracted from the channel". That suggests that the measured flows were used as local boundary conditions to test the measured stages versus the predicted stages. A more complete and clearer explanation of the actual process and measured flows would greatly benefit the validity of the model.

Truncating the model for calibrating the low flows and then using more proprietary data to establish a relocated boundary condition, removes the influence of the actual boundary condition and all hydrodynamic effects between the old and the new boundary. Evidence should be presented in the report to show that the data collected, and used at the new boundary condition, would have been reasonably replicated by the full model. Otherwise, using the newly measured data at the relocated boundary can be overly influencing the solution.

Calibration proceeded by adjusting roughness coefficients and energy losses within the 1D channel. Only a single graph of Toe Drain elevations was presented. For such a low flow simulation, it would be expected that a time series of the propagation of tidal flows in the Toe Drain, Deep Water Ship Channel and Sacramento River would have been demonstrated. Inclusion would greatly improve the significance of the model results.

### 3) Flood Recession – March/April 2011

Again, truncating the model for calibrating the recession flows and then using more proprietary data to establish a relocated boundary condition is not ideal. It removes the influence of the actual boundary condition and all hydrodynamic effects between the old and the new boundary. It needs to be demonstrated that the data collected at the new boundary condition can be reasonably replicated by the model to eliminate this doubt and weakness of the model. Obtaining data for this period also was a great opportunity and significantly improves the ability to produce a solid model. Similar to the Tule Canal/Toe drain data, CWS recommends providing these data to the public.

The results section of this calibration item makes it sound as though berms were applied randomly where necessary just to match the aerial drainage photos. Meetings with DWR and cbec have shown that is not the case, but rather certain berms that do exist on the bypass were found necessary to be included in the topography to reasonably match the photos. There needs to be clarification made on this point. Only including the existing berms and ditches where they are needed for this calibration is a typical procedure and provides the simplest and most efficient grid for the problem as defined. It is likely that the model will be asked to consider other locations for the inflows, however, or even barrier modifications. This will then create a need for additional calibration. These types of future uses are rarely considered *a priori* by the client and always create additional work, or errors, as the uses are needed.

The effort included an infiltration rate of 0.05 inches/hour where 1-foot of water would infiltrate in 10 days. There is no specific reference cited for this choice. The particular silty clay to clay soils found in the bypass has a broad range of infiltrations rates ranging from 0.14 – 0.0014 inches/hour with the slower ranges associated with more clay (Fetter 1994). In groundwater models for the Yolo Bypass developed by Graham Fogg at UC Davis, infiltration of rainfall into the root zone is 0.02 in/hr and 1 foot of water would take 25 days to infiltrate. In agricultural areas the infiltration due to irrigation is 0.03 in/hr and would take 16 days to infiltrate 1 foot of water (pers. comm. Graham Fogg). Under full flooding conditions the infiltration rate is reduced further because air is restricted from escaping (multi-phase flow). The infiltration rates used in the TUFLOW model are too high and reduce the drainage time. The result is either earlier LDW dates or higher resistance to inhibit runoff.

The assumption that there was no flow over the Fremont Weir is not supported by the Fremont Weir stages or the physical configuration of the weir. The stages on the weir are reported as 33.06 and 32.52 ft for April 9th at 4:00pm and 12th at 1:45pm respectively. The data for the west and east end of the levee are exactly identical to the nearest 100th of a foot. That would suggest that one of the gages was not operational for the flood and the data from one was duplicated for the other. The report states that the photographs indicate there was no weir flow, but the measured stage for the 9th is definitely high enough to spill over the weir, while the photographs suggests there is minimal spill. The flow on the 12th is marginal to spill over the weir, but certainly high enough to still flow through the existing fish passage, which is approximately 6 ft below the weir height. Further, the data presented in Figure 5-24, which was presented to depict the modifications to Fremont Weir flows, still indicates spills for the 9th, but both the observed and modified lines have no spills by the 12th. As a side note, the estimated Fremont flows using the YBY gage minus the KLRC and CCSB flows demonstrate the magnitude of errors compounded here for the YBY gage, which the report authors demonstrated has problems, and errors in the KLRC and CCSB calculations. Here, once again, is evidence that the measured data are not always correct. The lead agencies should be working with all the relevant organizations to improve the information being recorded.

## *Calibration Conclusions*

The most significant shortcoming of the calibration work is the absence of any grid convergence testing. Rather, grid resolution seems to have been chosen for the convenience of computer simulation times. No evidence has been provided to demonstrate that the grid resolution is sufficient for the numerical solution to converge. Further, the calibration uses truncated models which are not shown to replicate results of the full model. The figures provided do not specify the actual time steps of the modeled or measured data, and the low flow calibration does not demonstrate that flows are matched. Without supplementing the report with documentation that the truncated models do not obfuscate issues within the omitted areas, the calibration will remain a weakness of the model.

## Model Validation

After calibration of the model, validation is performed where a completely separate data set is then simulated with the model to establish credibility of the calibration. While the purpose section of the report states that it covers the validation of the model, no such validation is presented. The report does acknowledge that other flood year data are available for validation of the calibrated model but does not cover any effort in this regard.

## Existing Conditions Analysis

The graphs of Figure 6-1 in the report represent a comparison of modeled versus observed flows (gage estimates) for the three water year categories chosen – dry, normal, and wet years. Normal and wet water year types show a bias toward under-predicting Fremont Weir spills for spills less than 50,000 cfs. Since the goal is to control flooding in these less-wet year types, or lower Fremont Weir spills, this tendency should be kept in mind. Modeled stage predictions at the Fremont Weir has a bias to predicting higher stages than observed data, except in the wettest of years (Figure 6-2). It is somewhat incongruent that lower flows would be predicted at the same time higher than measured stages are predicted. The report should specify whether the values in the figure are reported on a daily maximum basis for all time steps, at a daily fixed time, or whether it was selective.

The predicted flows on the Sacramento River at Verona do an excellent job of matching the observed flows (Figure 6-3 in the report). Since the sum of the upper inflows of the model would be represented by the sum of the Sacramento River at Verona and the Fremont Weir spills, the results suggest that the majority of the error in the upstream boundary conditions is spilling into the Yolo Bypass. Once again the Yolo Basin gage near Woodland demonstrates the likely USGS calibration error or the tendency of the gage location to be corrupted easily by debris.

Figures 6-7 and 6-8 in the report were prepared to demonstrate the effect of the incorrect lower stage boundary condition being applied before 2006. The use of a dry year, 2002, produces the minimum effect the error would represent. During higher inflows to the bypass the increase of stage values in the lower bypass would cause some additional flooding on more northern parts of the bypass, with an expected increase in LDW acreage.

## Alternatives Analysis

The use of the HEC-RAS program to create operating rules for the various gates and canals of the alternatives is perfectly acceptable and the assumptions are reasonable. For future model use it would be better if the process could be incorporated into the full model. Removal of the agricultural crossings is appropriate as any significant flood eliminates them quickly. All gates and channels and their operation are properly handled.

The TUFLOW model handles wetting and drying by a user-specified tolerance value on the depth at the center of the cell. If the water depth is below this tolerance then the cell is instantly dry. Wetting may use a different tolerance, or the same, and the cell goes from dry to wet when this depth is exceeded. Since most cells are 200 ft by 200 ft, then the model represents wetting and drying of these areas in approximately 1-acre increments. The report discusses applying wetting and drying to raster cells. The DEM used in the grid is a raster with resolution of 25 ft. It is not clear whether there was a post-processing effort to disaggregate the cell wetting and drying to the raster scale, but either method would produce reasonable relative results. Determinations of wetted areas need to have a much clearer explanation in the report so that the process can be understood. The ultimate issue here would be whether the field could be considered dry when 30% of it was still wet and how those data are used in determining when farming can begin.

## Sensitivity Analysis

A sensitivity analysis was performed to examine the effects of removing structures within the bypass and increases and decreases in boundary condition flows. The low flow calibration did not fully address the lowest portion of the Yolo Bypass, the area that would be the ultimate downstream control of draining. The model needs to include a better low flow calibration to address this issue, with subsequent calibrations on increasing flows.

A 10% increase and decrease in the estimated boundary condition flows do not nearly reach the level of uncertainty of the calculated boundary conditions. Some of the calculated values show a difference of up to 200%. A better statistical error estimate should be made of all the compounding errors and applied as the sensitivity analysis. The use of a fixed infiltration rate must also be tested in a sensitivity analysis, and within ranges found on Yolo Bypass. The 70/30% assumption of when the field is dry and ready for use should also be tested in a sensitivity analysis. The subsequent results should be provided as a range and not a discrete value. The unexpected LDW results discussed in the report sensitivity analysis demonstrate that an additional error is introduced by the modeling method.

## Conclusions

The TUFLOW model for the Yolo Bypass is superior for a field-scale basis model than other Yolo Bypass models that have been produced in the past, such as MIKE-21. An analysis of the hydrodynamic modeling report and additional data requested and received, however, reveals several significant model flaws. DWR and cbec did not present grid convergence work to demonstrate the applied resolution will produce the desired solution. Validation of the calibration has only been discussed, and not quantifiably demonstrated. Finally, the model relies on assumptions that are uncertain and not tested with rigorous sensitivity analysis. These assumptions are: 1) the 10% variation in the boundary conditions; 2) the infiltration rate; and 3) the assumption that a field is dry when the center is dry, which is critical to the calculation of when a field is 70% dry (and therefore ready to plant). A reasonable effort has been made here to quantify the inflows, but it falls short in quantifying the uncertainty that the boundary conditions introduce. Assumptions on infiltration significantly over-estimate the present knowledge of losses to groundwater. The 70/30% assumption that a cell is dry when the center is dry needs to be tested. Other issues are less critical but still bring uncertainty to the predicted results. These weaknesses are further described in the abstract, including the need for more information about calibration and the lack of detail of certain structures in the Yolo Bypass.

All models are representations of reality and the goal is to include enough of the physics and physical surface to adequately represent the system for specific objectives. The simulation of a model provides a discrete answer, meaning that for a given set of inputs the same answer will be produced. Nature is not so predictable and would not produce the exact same result even if it could be given the same inputs (*e.g*., consider error ranges in controlled flume experiments). The most prudent use of any model is in the comparison of various results to different inputs. For comparison purposes the reviewer feels this model can be used as planning tool to predict the general trends (not the discrete predicted differences) of various changes in inputs as long as those changes do not modify the flow patterns over the floodplain. To produce quality results, however, all input data will require full transparency and a much more rigorous effort in grid convergence, calibration and validation. Sensitivity analyses should be undertaken. Simulations should include the full extent of possible error ranges of inputs and the results presented with the ranges of predicted values.

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