An assessment of changes to physical habitat resulting from the 2017 Oroville Dam spillway incident: An application of a 2D sediment transport model to characterize potential effects

John Stofleth, MS, PE, Engineer, cbec, Inc., Wadesville, IN, j.stofleth@cbecoeng.com
Doug Shields, PhD, PE, Scientific Advisor, cbec, Inc., Oxfords, MS, d.shields@cbecoeng.com
Gavin Downs, MS, Engineer, cbec, Inc., Santa Cruz, CA, gspdowns@gmail.com
Toby Stegman, MS, Geomorphologist, cbec, Inc., Logan, UT, t.stegman@cbecoeng.com
Chris Bowles, PhD, PE, President, cbec, Inc, West Sacramento, CA, c.bowles@cbecoeng.com

Introduction

This paper presents a concise overview of the development and application of a computer model by cbec eco engineering (cbec) for the California Department of Water Resources (DWR) of the reach of the Feather River between the Fish Barrier Dam at Oroville, CA and the Twin City's Memorial Bridge in Yuba City, CA. Of particular interest within the model domain is the reach that is referred to as the Low Flow Channel (LFC) because of aquatic habitat resources within the LFC (Figure 1). The LFC draws its name from the fact that a significant portion of the Feather River flow is diverted around this reach through the Thermalito Complex and returned to the river channel at the Thermalito Afterbay Outlet. The model is based on a sophisticated hydrodynamic and sediment transport software package developed by the Danish Hydraulic Institute (DHI), MIKE 21C, and data sets provided by DWR or by field studies conducted by cbec during 2017-2019. The purpose of the model was to assess impacts of the 2017 Oroville Dam spillway erosion event on the sediment regime and physical habitat in the Feather River relative to a baseline condition that would have occurred without the incident.

Model software

The MIKE 21C model represents the river channel as a spatial domain divided into four-sided grid cells. Grid cells are approximately rectangular, but their sides may have moderate curvature, characteristic of a curvilinear grid model. The model assumes conditions that are uniform within a given grid cell and computes water depth, velocity, bed elevation, and bed sediment characteristics for each grid cell at a specified time step. The model simulates continually changing conditions during flood events. The model domain cbec developed is composed of ~1.8 million cells. The average grid spacing for the entire model domain is 10.2 m in the streamwise (downstream) direction and 6.8 m in the normal direction with an aspect ratio of ~1.5:1. In the main channel, the grid spacing averages 11.1 m in the streamwise direction and 4.4 m in the normal direction with an aspect ratio of ~2.5:1. The model computational timestep for hydrodynamics and morphological conditions were set to 0.4 seconds and 30 seconds, respectively. Hourly computational outputs were written to result files.

MIKE 21C has been widely used worldwide to successfully describe the transport of sediments and morphological behavior of fluvial systems ranging from fine sand to cobbles (https://www.mikepoweredbydhi.com/products/mike-21c). Examples of model study reports published in refereed literature are found here.

It should be noted that the MIKE 21C model simulates the movement of water and sediment coarser than silt according to the basic laws of physics. The behavior of finer sediment (silts and clays) is more complex than for coarser sediment and is not considered within the model. During the spillway erosion incident, near-surface concentrations of suspended sediment, primarily silts and clays, in the river below the dam were monitored by DWR by measuring the concentrations of total suspended sediment (TSS) and turbidity at several locations. Additional documentation regarding the capability and functionality of the MIKE 21C hydrodynamic and sediment transport model can be found at the following web links:

- https://manuals.mikepoweredbydhi.help/2020/Water_Resources/M21C_User_Guide.pdf
- https://manuals.mikepoweredbydhi.help/2020/Water_Resources/MIKE21C_Scientific_documentation.pdf

Figure 1. Subreach delineation for sediment and habitat area analysis

Model input data

Channel and floodplain geometry

The model topography and bathymetry were derived from multiple data sources. The channel bathymetry was incorporated and converted to a digital elevation model (DEM) by interpolating between cross sections surveyed in 2010. These cross-sectional data were initially used to support the development of the Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS hydraulic model, which has been reviewed and accepted for numerous flood studies concerning rivers in California's Central Valley, including the Feather River (DWR 2014). The bathymetric surface was quality checked and merged with another, more detailed bathymetric survey of the LFC completed by DWR in 2009. The bathymetric surface was then merged with CVFED 2008 LIDAR, which was used to characterize the floodplain topography. These 2008-2010 era topographic and bathymetric datasets were selected as they serve as the best available representation of the river geometry prior to the 2017 flood event.

Hydrology

Inflow boundary conditions for the LFC reach of the Feather River model were located at the Fish Barrier Dam and at the Thermalito Afterbay Outlet (Figure 1). Three scenarios were simulated: the observed 2017 event, the 2017 event that would have occurred had there been no spillway erosion incident, and the 2017 event that would have occurred in the absence of Oroville Dam. The first two scenarios were simulated using the MIKE 21C hydrodynamic and sediment transport model. No numerical simulation was performed for the third (without dam scenario), but the suspended sediment flux for the 2017 event in the absence of Oroville Dam was computed using rating curves.

Observed event
The 2017 15-minute discharges for the Fish Barrier Dam and the Thermalito Afterbay Outlet were provided by DWR (Figure 2). At the outlet of the model, a water level boundary condition was defined using 15-minute stage data from the Yuba City gage, which was obtained from the California Water Data Library (https://wdl.water.ca.gov/).

Without incident event
The "without incident" inflow water hydrograph represented Oroville Dam releases that would have occurred if there had been no spillway erosion and therefore no bed-material (sand) sediment load entering the LFC from upstream. This hydrograph was based on an Oroville Dam outflow hydrograph provided by the DWR (Figure 2). DWR developed the "without incident" hydrograph, which had a peak discharge of 150,000 cfs, using observed inflows to Lake Oroville and the rules that constitute standard procedure for operating the reservoir (USACE 1970). The observed Oroville Dam outflow hydrograph had a lower peak (about 100,000 cfs) but flows in March, April and May were elevated relative to the without incident hydrograph.

Without dam event
As discussed below, the Lake Oroville inflow hydrograph, which was obtained from the California Data Exchange (cdec.water.ca.gov) was used as the Feather River at Oroville discharge hydrograph for a hypothetical "without dam" scenario (Figure 2). This "without dam" hydrograph and the observed hydrograph for flow at Oroville based on data provided by DWR for flows passing the Thermalito Diversion Dam.

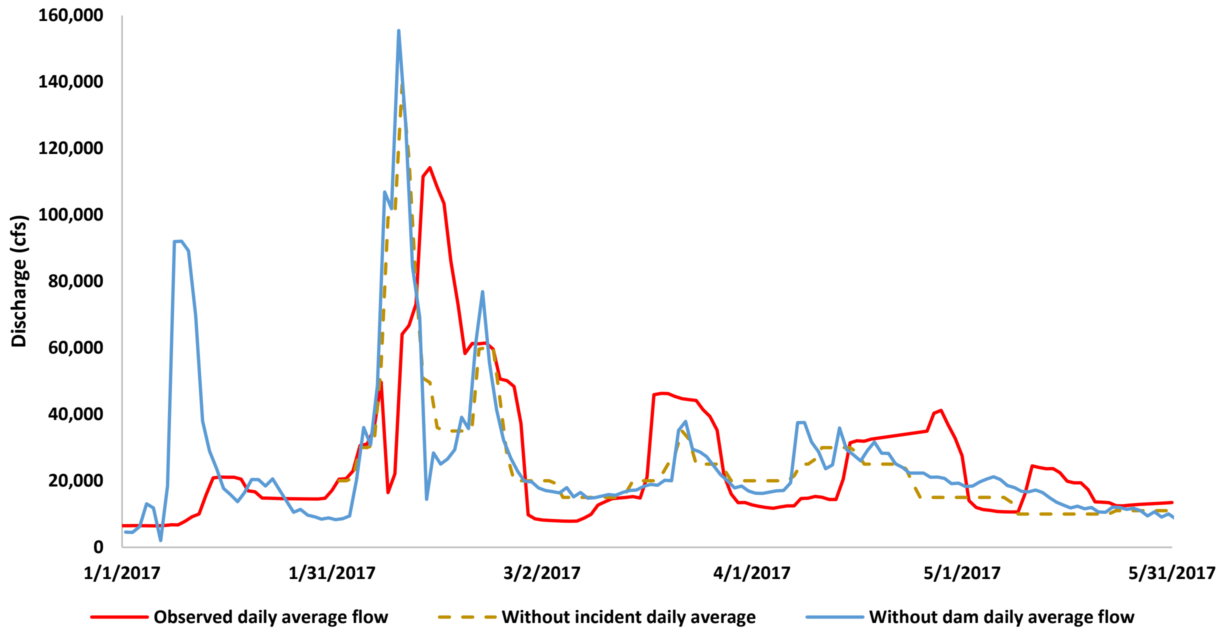

Figure 2. Early 2017 discharge hydrographs for Lake Oroville and Thermalito Diversion Dam

Bed and bank sediment size

Bed sediment sampling was performed in the summer of 2017 by cbec along the Feather River within the model domain through a combination of digital grain size sampling (computer analysis of digital photographs) and standard sieve analysis to quantify the particle size distribution of the bed material. Sampling was performed on exposed bars and the banks of the river. Grain size analysis results were used to map sediment sizes throughout the model domain. Specific gravity of the LFC bed materials was set equal to 2.65, which is typical for alluvial sands and gravels.When armoring was observed, the surface and subsurface sediments were sampled separately. Additionally, the presence of bedrock was observed just downstream of the Fish Barrier Dam and Table Mountain Road Bridge. Bedrock was represented in the model by limiting the erodible layer thickness of the channel bed to only 0.03 ft (0.01 m) in the immediate area where bedrock was observed. The erodible layer thickness was then transitioned back to the thickness set for the rest of the domain (33 ft or 10 m) over the distance downstream to the Highway 70 Bridge by assuming a linear variation with distance.

The mapping of the grain size distribution of the bed material included an aggregation of samples into characteristic zones. Surface and subsurface sediment zones were considered separately when determining zone boundaries. Within each zone, sample grain size distributions were aggregated into a representative distribution. Bank sediment gradation was determined using the same method. Bank samples showed little difference longitudinally with respect to gradation; therefore, all bank sediment samples were aggregated.

Bed and bank sampling produced a valuable dataset that provided a basis for realistic representation of the spatial variability of channel boundary sediment sizes within the LFC. Realistic representation of boundary sediment characteristics was necessary to produce reasonable simulated morphological changes and sediment transport results.

Sediment inflow

The incoming load of sediment at the upstream boundary of the model was specified at each time step using output from a similar but separate MIKE 21C model of the Thermalito Diversion Pool (TDP). The TDP model simulated transport of sediment eroded from the spillways through the Diversion Pool and released through the Diversion Dam spillways. All of the sediment eroded from the Oroville Dam spillways but not removed from the TDP by dredging was available for transport. Furthermore, to be conservative[1], it was assumed that the undredged, eroded sediment was fine sand (0.074 mm to 0.420 mm). Based on laboratory analysis of samples of the parent materials, specific gravity of the sands derived from spillway erosion was set equal to 2.89. Sediment flow from the eroding spillways into the TDP was specified as a power function of water discharge.

Model coefficients and calibration

The model was successfully calibrated for both hydrodynamics (water movement) and sediment transport parameters. Calibration of the hydrodynamics was completed first by adjusting Manning n-values ("roughness values") to achieve agreement between modeled and observed water surface elevations. Initial, uncalibrated roughness values were derived from a comprehensive mapping effort of the Sacramento River Valley (DWR 2011, MBK 2011). In-channel roughness values were then calibrated to (1) a water surface profile survey of the LFC conducted by DWR during high flows in March of 2011 and (2) water surface elevations measured by cbec along the entire river during high flows that occurred in April of 2019. Both sets of high-water surface elevation data were collected using standard techniques. The calibrated model was validated by comparing the observed and simulated 2017 water surface elevations at the Gridley gage.

MIKE 21C offers the user the option of using one of several sediment transport equations. While sediment as large as cobbles were mobilized during the 2017 event and are represented in the model, the modeled reach bed material is largely composed of fine sands to coarse gravel. Therefore, Engelund and Hansen's (1967) total load transport formulation, using several sediment size classes and the Egiazaroff hiding function, was selected (Yang 2001, Wu 2008). After hydrodynamic calibration, the sediment transport parameters required by the Engelund-Hansen equations were set to recommended values per model documentation. These values were informed by the characteristics of the computational mesh, the characteristics of the channel, and the range of flows for the study domain. Finally, parameter values were adjusted by calibrating model output to suspended sediment concentration measurements collected throughout the model domain by cbec during high flows in April 2019 using standard techniques (Edwards and Glysson 1999).

Interpretation of model results

Model results from the MIKE 21C hydrodynamic and sediment transport model are valuable tools that aid in the understanding of physical processes and trends associated with erosion and deposition of sediment in the lower Feather River. MIKE 21C is a dynamically-linked, unsteady, two-dimensional hydrodynamic and sediment transport model that provides continuous results for sediment transport over the course of a complete hydrograph for a given flood event. The

[1] "Conservative" as used herein refers to assumptions that tend to increase the amount of sediment that is transported downstream. In reality, much of the sediment eroded from the spillways and deposited in the TDP was much coarser than fine sand.

model output allows a dynamic visual representation (video / animation) of the changing bed level over the course of a complete flood hydrograph, which illustrates erosion and deposition through the course of the event. By examining these dynamic visual representations, results can be reviewed at a single location or for the entire reach to develop a better understanding of the sediment transport processes. At the completion of a given simulated flood event, the resulting cumulative erosion or deposition may be mapped as change in the channel/floodplain topography. It should be noted that despite efforts to construct a comprehensive and functional model, the precision of the modeling results (e.g., computation of bed level change to the closest 0.01 meter [0.03 feet]) do not equate to absolute predictions, because the accuracy of the model is much lower than the precision. The modeling results presented herein result from depth-averaged, two-dimensional representations of complex, three-dimensional processes, and the results have been interpreted to imply probable trends (not absolute values). However, model results for the two scenarios examined may be compared to reveal relative differences in scour, deposition, and bed material size change associated with the 2017 event.

When examining sediment transport modeling results, it is generally advisable to interpret these results at the reach scale. When assessing and interpreting relative differences in model output between scenarios, relatively small, local differences should not be considered significant. Instead, larger magnitude differences over the broader spatial domain are reliably significant.

Simulation scenarios and results – observed versus without incident

After the model was constructed as described above, it was used to simulate several scenarios. Two key scenarios are outlined below. All scenarios involved simulation of the same spatial domain (the LFC) and the same temporal domain (February 1, 2017 through May 31, 2017).

Hydrology

The inputs described above were used in a 2017 “observed” scenario simulation. The same inputs except for the water and sediment inflows at the upstream end of the model were used in a “without incident” scenario simulation. The purpose of comparing the two scenarios was to disaggregate the effects of the spillway erosion event from the effects of the flood event.

As discussed in the preceding section, the “without incident” inflow water hydrograph represents Oroville Dam releases that would have occurred if there had been no spillway erosion and no bed-material (sand) sediment load entering the LFC from upstream.

Sediment flux

Over the simulated period, the observed scenario flux of sediment at the downstream end of the LFC was approximately 372,000 yd^3 or 540,000 tons assuming a porosity of 0.35. This mass is an order of magnitude higher than influx of coarse sediment (sand) to the LFC from spillway erosion. This is a clear indication that native bed sediments within the LFC that are typically mobilized during high flows and not spillway erosion were the dominant source of sediment transported from the LFC to the lower Feather River.

Under the without incident scenario, model results indicated that the flux of sediment at the downstream end of the LFC was 248,000 yd^3 or 359,000 tons assuming a porosity of 0.35. It should be noted that estimates of the sediment flux at the downstream end of the LFC under both scenarios exclude sediment transported into the Oroville Wildlife Area D-unit. When assessed at several points along the LFC, the peak sediment transport rate for the "without incident" hydrograph ranged from about 25% greater to 20% less than for the observed scenario. The observed hydrograph produced a higher sediment load during the elevated flows that occurred in March, April, and May of 2017 subsequent to the major peak in February.

Under both scenarios, the dominant source of the sediment exiting the LFC was the channel bed, as detailed below.

Bed level change

The 2017 flood event resulted in erosion and deposition that caused some re-arrangement of LFC bed topography when viewed at the scale of tens to hundreds of feet. However, visual examination of bathymetric contour maps based on model output did not reveal changes in spatial patterns of physical habitat at the scale of the entire LFC. Results show local bed level changes across the time domain ranging from -4.0 m to +3.0 m (-13.1 to 9.8 ft). While sustained elevated flows influenced the amplitude of erosion and deposition, an active low flow channel was still present at the end of the simulation. High flow events such as the 2017 observed event work to increase the heterogeneity of geomorphic features, which is reflected in the bed level change results, most notably in Subreach 3.

The without incident simulation displayed similar patterns of erosion and deposition. Visually, it was difficult to distinguish between contour maps based on the two scenarios, but the extent and amplitude of bed level change in the without incident simulation was generally damped. The resulting bed topography maintained a low flow, active channel, and heterogeneous geomorphic features.

Spatial patterns in erosion and sedimentation were examined by dividing the LFC into three subreaches and comparing the change in volume of sediment stored in the LFC bed (mainstem channel and entire corridor) at the end of the simulation under both scenarios (Figure 1,3-4). In the 2017 observed simulation, the mainstem channel was net degradational in all three subreaches, with between 174,000 and 359,000 yd^3 of material being exported from each subreach (Figure 3). The entire LFC mainstem channel lost a total of 722,000 yd^3 in the observed scenario, which equates to an average scour depth of 0.9 ft. There was a net loss of sediment volume over the entire flood corridor also, except in Subreach 2, where there was net deposition (Figure 3).

The same pattern of results occurred in the without incident simulation; however, magnitudes were lower, ranging between 104,000 and 293,000 yd^3 of bed material lost from the mainstem channel in each subreach (Figure 3). Net loss of bed volume for the entire LFC mainstem channel under the without incident scenario was 545,000 yd^3 or about 25% lower than for the observed scenario, which equates to an average scour depth in the channel of 0.7 ft (Figure 3). Also, the amount of sediment retained over the entire flood corridor in Subreach 2 was reduced (Figure 4) compared to the observed scenario. Net degradation and sediment export were lower for the entire flood corridor than for the channel alone because sediment was retained on the floodplain and in other off-channel areas. Despite the influx of sediment from spillway erosion in the as observed scenario, higher levels of channel erosion/degradation relative to the without incident occurred. This difference is clearly due to differences in the hydrographs (Figure 2).

Figure 3. Net change in mainstem channel bed material volume

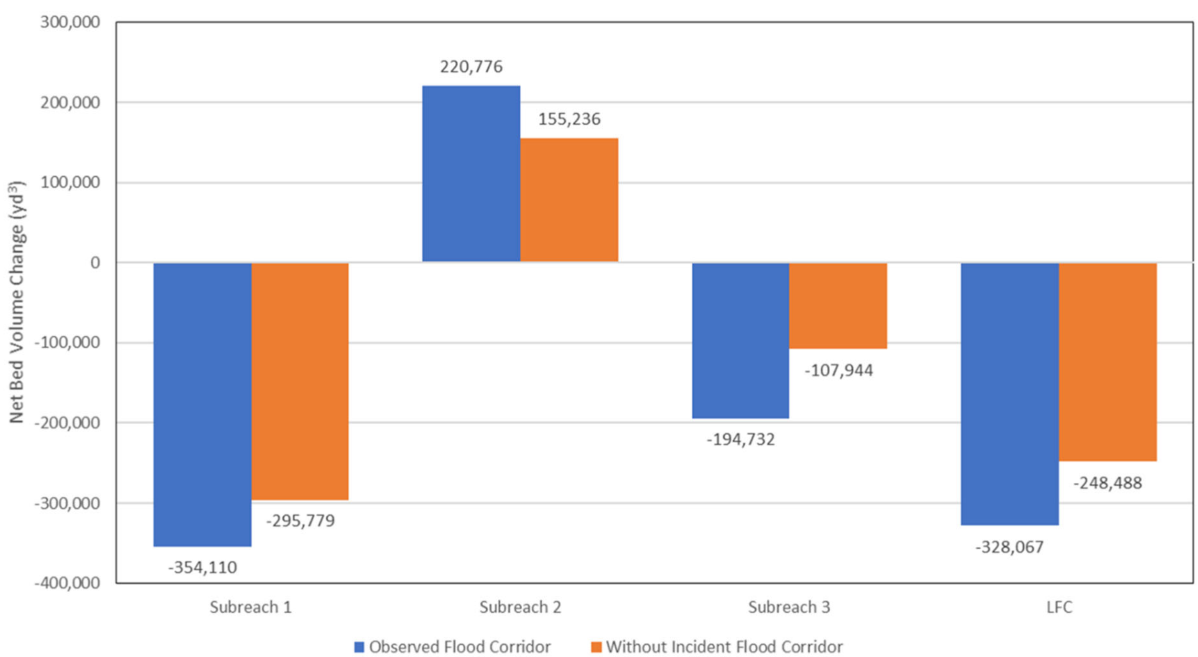

Figure 4. Net change in channel and floodplain bed material volume

Bed composition

During extreme flood events, elevated flows and high velocities tend to mobilize armor layer sediments[2]. When this armor layer is mobilized, finer bed material under the armor layer may

[2] Surface layers of river beds often comprise coarser material than the subsurface. These armor layers are formed as finer particles are winnowed away during normal to high flow.

be exposed, resulting in a finer particle size distribution in the surficial bed sediments following a flood event. In order to disaggregate the potential effects of armor mobilization and sand introduction from upstream, the area-weighted average sand content of the top 5 inches of the bed at the end of the 2017 flood event (May 28, 2017) was extracted from model output for spawning sites within each LFC subreach for both scenarios (Figure 5). Area-weighted average spawning site sand content varied from 2.2% to 7.8%. Results for both scenarios indicated higher levels of sand in Subreach 1. Differences between the two scenarios were quite small, ranging from 0.1% for Subreach 1 to 2.9% for Subreach 3 and averaging 1.0% for the entire LFC. Given the complexity of simulating the evolution of sediment size distribution in armored beds and the lack of pre-2017 event sediment size data, these differences between scenarios are likely insignificant.

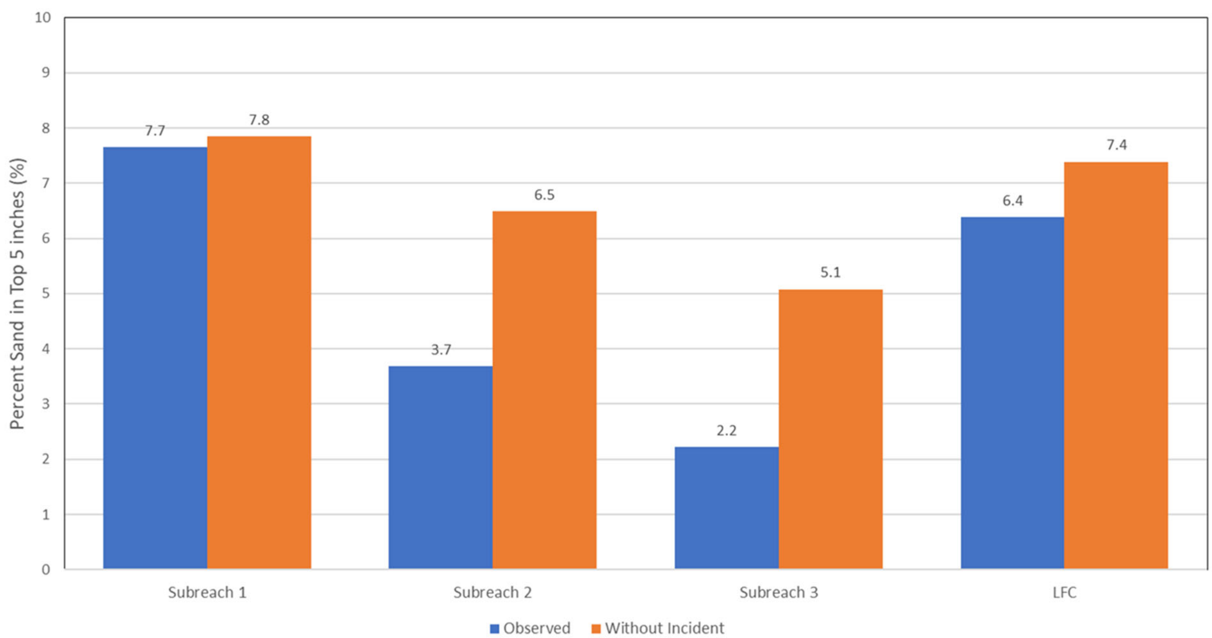

Figure 5. Area weighted average sand content in surficial layer of spawning sites by subreach

Large sediment transport and maximum velocities

The relative difference in the mobility of the bed sediments between the "observed" and "without incident" scenarios within the LFC was further examined by comparing the transport of the largest bed sediments (≥ 128 mm). The total transport of these large sediments varied widely along the LFC, ranging from 50% more to 30% less in the observed scenario relative to without incident. This spatial variation reflects the heterogeneity in the availability of the coarser sediment and local hydrodynamic conditions.

Model simulations also included water velocity and depth for both scenarios. An examination of the simulated current velocity output under both scenarios indicates slightly higher velocity at peak discharge for the without incident hydrograph. This is intuitive, because the peak discharge for the without incident scenario was about 150,000 cfs, while the maximum observed discharge at Oroville gage during the 2017 event was about 110,000 cfs.

Fate of fine sediment eroded from spillways

A significant quantity of fine (clay and silt) sediment entered the LFC during the first week of the spillway erosion event as observed by TSS and turbidity data collected by the DWR and images and video posted online. These sediments were likely derived from soil overlying bed rock in the spillway erosion zones. USDA NRCS web soil survey information for the erosion zone indicates a mantle of soils 10 to 40 inches thick with gradations of about 60% finer than sand size. Turbidity levels reached a peak about February 10 and rapidly declined afterward. Since sediment this fine is present only in very small quantities in the LFC bed, this sediment was transported as wash load. Recent findings regarding wash load transport indicate that fine clay and silt particles often form flocs in freshwater rivers and that these flocs exhibit settling velocities of about 0.34 mm/s (0.0011 ft/s) regardless of their size (Lamb et al. 2020). The mode of sediment transport (in contact with the bed, as suspended load, or as wash load) is indicated by the Rouse number, P, which is defined as:

$$P = \frac{w_{eff}}{\beta k u*_{sk}} \tag{1}$$

In which w_{eff} is the effective settling velocity, β is a factor that accounts for difference in the fluid turbulence and sediment diffusivities, and turbulence damping due to stratification, κ = von Karman's constant = 0.41, and $u*_{sk}$ = the skin-friction portion of bed shear velocity. Although β is often assumed equal to 1.0, Lamb et al. (2020) computed β as follows:

$$\beta = 16.82\left(\frac{u*_{sk}}{w_{eff}}\right)C_f^{0.3} \tag{2}$$

In which $C_f = \frac{u_*^2}{U^2}$ and $u*$ is the total shear velocity while U is the average flow velocity. Rouse numbers < 0.8 are associated with sediment transport as wash load, in which sediment moves through the reach with little net deposition or exchange with the bed. Rouse numbers between 0.8 and 2.5 indicate fine sediment grains move in suspension, but there is active exchange between the bed and water column. Rouse numbers > 2.5 indicate fine sediment either moves in contact with the bed (bedload) or is immobile.

Using model output and an assumed effective settling velocity for fine sediments of 0.34 mm/s, the Rouse number, P, was calculated for a range of LFC flow conditions (in channel) as shown in Table 1.

Table 1. Calculation of Rouse number and inferred sediment transport mode for fine sediment in Feather River Low Flow Channel for selected periods during the observed 2017 event.

Start	End	Condition	Average flow velocity, ft/s - (m/s)	Average flow depth ft - (m)	Skin-friction shear velocity, ft/s - (m/s)	β	Rouse No., P	Sediment transport mode
2/12 18:00	2/16 9:00	High flow	7.9 (2.4)	20.7 (6.3)	0.620 (0.189)	0.09	0.077	Wash load
2/19 0:00	2/27 3:00	Medium flow	5.9 (1.8)	15.4 (4.7)	0.484 (0.147)	0.115	0.090	Wash load
2/27 18:00	3/7 10:00	Low flow	0.3 (0.1)	3.6 (1.1)	0.060 (0.018)	0.323	0.455	Wash load

These calculations indicate that the fine sediment moved through the LFC as wash load even under extreme low flow conditions. Deposition of silts and clays was likely limited to quiescent and near-quiescent regions on floodplains, in riparian vegetation or in extremely sheltered zones at flow obstructions.

Estimated sediment load that would have occurred in early 2017 in the lower Feather River in the absence of the Oroville Dam

Oroville Dam was completed in 1968. Since that time, the reservoir has exerted a significant influence on downstream flows of water and sediment. In general, peak water flows have been damped and the sediment flux has been greatly reduced. The likely magnitude of water and sediment flows passing the dam site in 2017 if the dam had not been present is of relevance for at least two reasons:

1. Since impacts to aquatic habitat that might have occurred during the 2017 spillway erosion event and its aftermath are partially a consequence of the presence of the dam, such impacts may be assessed relative to conditions that would have occurred without a dam in place.
2. Since biota native to the Feather River below Oroville Dam are adapted to flows of water and sediment that occurred there for centuries if not millennia prior to the dam closure, potential ecological impacts of the spillway erosion event should be assessed in light of natural, pre-dam conditions or to conditions on natural salmonid inhabited rivers that lack dams / flow regulation.

Simulation modelling of flood flows occurring in the reach of the Feather River presently occupied by Lake Oroville, Oroville Dam and the Thermalito Diversion Pool indicates that very little attenuation of the flood hydrograph occurs due to floodplain storage or valley constriction. Accordingly, the Lake Oroville inflow hydrograph, which is available from the California Data Exchange (cdec.water.ca.gov) was used as the Feather River at Oroville discharge hydrograph for a hypothetical "without dam" scenario. (Figure 2).

Total suspended sediment flux for the Feather River at Oroville was determined by integrating the concentration of suspended sediment and water discharge:

$$m_{ss}(t) = \int_{t_0}^{t} C_{ss} Q \, dt \tag{3}$$

In numerical terms, this equation is

$$m_{ss}(t) = \sum_{i=1}^{n} C_{ss_i} Q_i \Delta t \tag{4}$$

in which $m_{ss}(t)$= suspended sediment flux between time t_o and time t, C_{ss} is the cross-sectional average suspended sediment concentration at time t, and Q is the water discharge at time t. This integration was applied for the period February 1, 2017 to May 31, 2017 for the observed conditions and the "without dam" condition. The "without dam" condition represents what would have happened if the observed flows in the reservoir watershed had occurred, but without the dam and the reservoir in place. Rating curves developed by the USGS (Porterfield et al. 1978) as described below were used to obtain C_{ss} for total suspended sediment concentration and for suspended sand concentration.

The USGS collected suspended sediment data for the Feather River at Oroville (USGS 11407000) beginning in 1956. These data included depth-integrated suspended sediment samples collected daily or more often during high flows and 2 to 5 days each week during low flows with low sediment concentrations (Porterfield et al. 1978). These data are archived by the USGS at https://waterdata.usgs.gov . Daily data[3] are available for the period 1956-1979, and 54 discrete[4] samples from the period 1957-1975 are available. Data from the 1957-1962 period were judged to be representative of the pre-dam conditions by Porterfield et al. (1978), and there were 19 discrete samples during this period. Although reservoir storage did not begin until November 14, 1967, construction impacts likely began about June 1962. Daily and discrete values of suspended sediment load are plotted versus discharge for the periods 1957-1962 and 1963 in Figure 6. Sediment grain sizes were determined for a limited number of discrete samples. These data are plotted in Figure 7. Figures 6 and 7 show that data are much more numerous for lower flows, and a regression based on all data would be biased toward the lower flows. Porterfield et al. (1978) addressed this problem by constructing rating curves based on averaging all of the daily loads for small increments of the discharge range (Figure 8). The curves shown in Figure 8 were digitized and fit with power functions to the digital data with results as follows for total suspended sediment flux in tons/day:

$$Q_{sst} = 3.3932Q^{2.6304} \tag{5}$$

and for suspended sand flux in tons/day:

$$Q_{sss} = 0.7574Q^{2.6304} \tag{6}$$

These rating curves were applied to the Lake Oroville inflow ("without dam") daily discharge hydrograph plotted in Figure 2 using Equation 4 above. Results were compared to suspended sediment flux computed for observed conditions using the MIKE 21C model. The total sediment discharge for the Feather River at Oroville during the period February 7 – May 31, 2017 was about 5% of the estimated load that would have occurred under pre-dam conditions and that the discharge of sediment coarser than silt (sand) was about 2% of the pre-dam condition load. In other words, the pre-dam total sediment discharge would have been about 20 times greater and the discharge of sand about 50 times greater if the Oroville Dam had not been present. The difference between the observed sediment load and the pre-dam or "without dam" load was greater for coarser (sand) sediments than for finer (silt and clay) sediments because sands are preferentially retained by the reservoir.

[3] Daily-record sediment data are daily mean estimates of suspended-sediment concentration and (or) load and are computed at sites in which suspended-sediment concentration samples are collected approximately daily or more frequently.

[4] Discrete sediment data are results from samples collected at a certain time on a certain date.

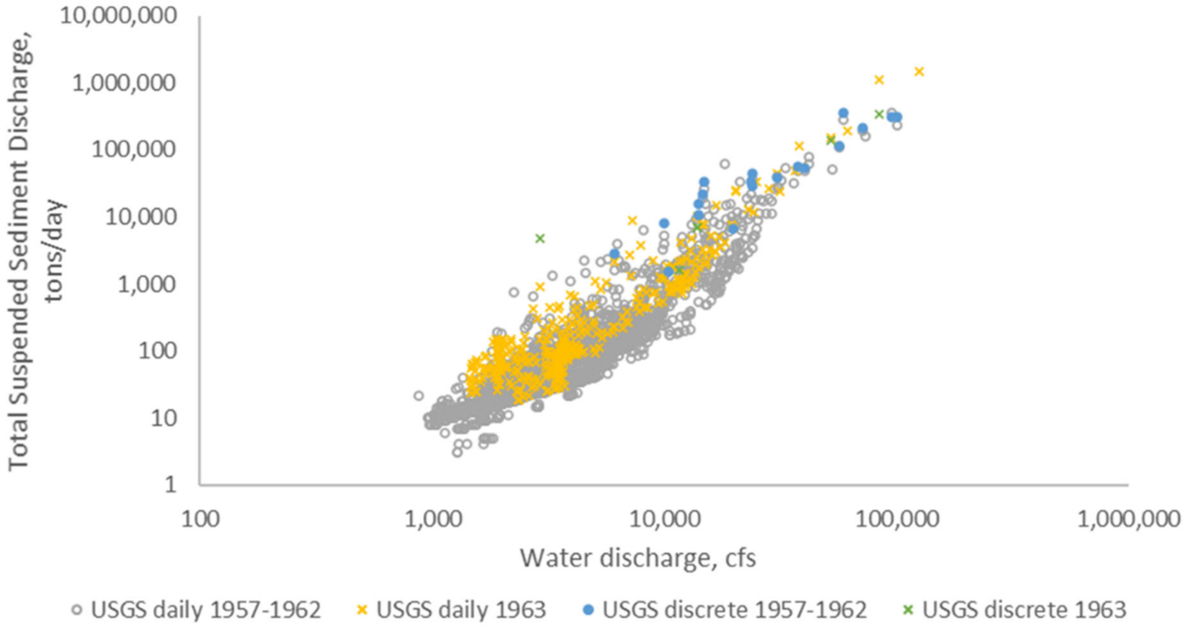

Figure 6. Daily and discrete total suspended sediment load versus discharge, Feather River at Oroville

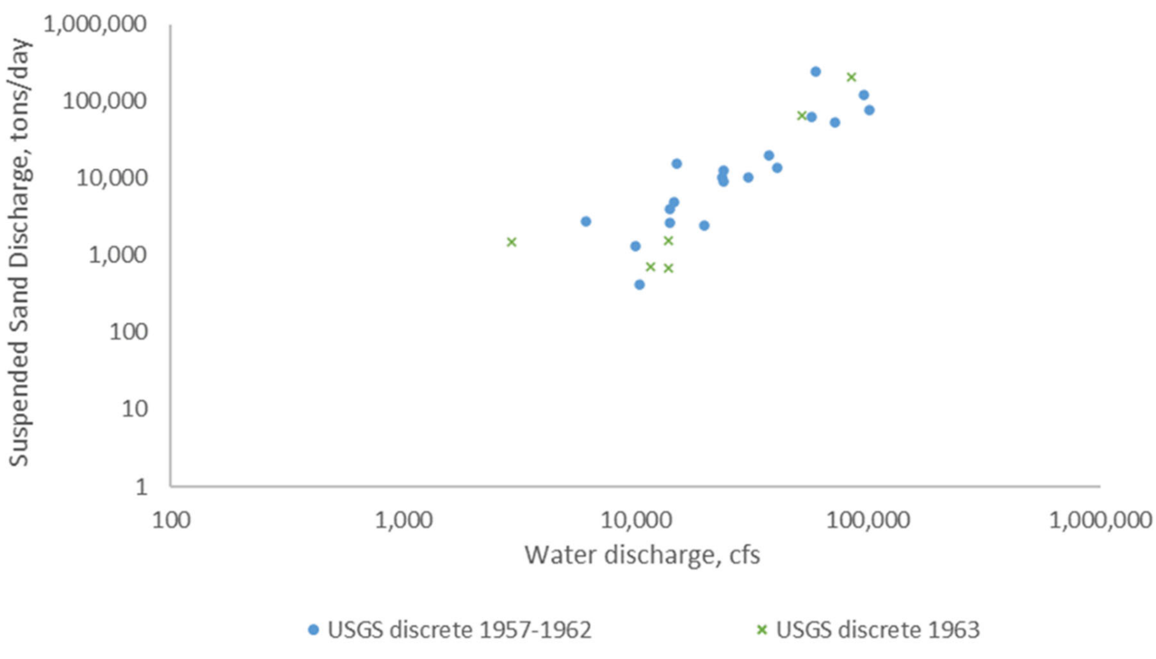

Figure 7. Discrete suspended sand load versus discharge, Feather River at Oroville

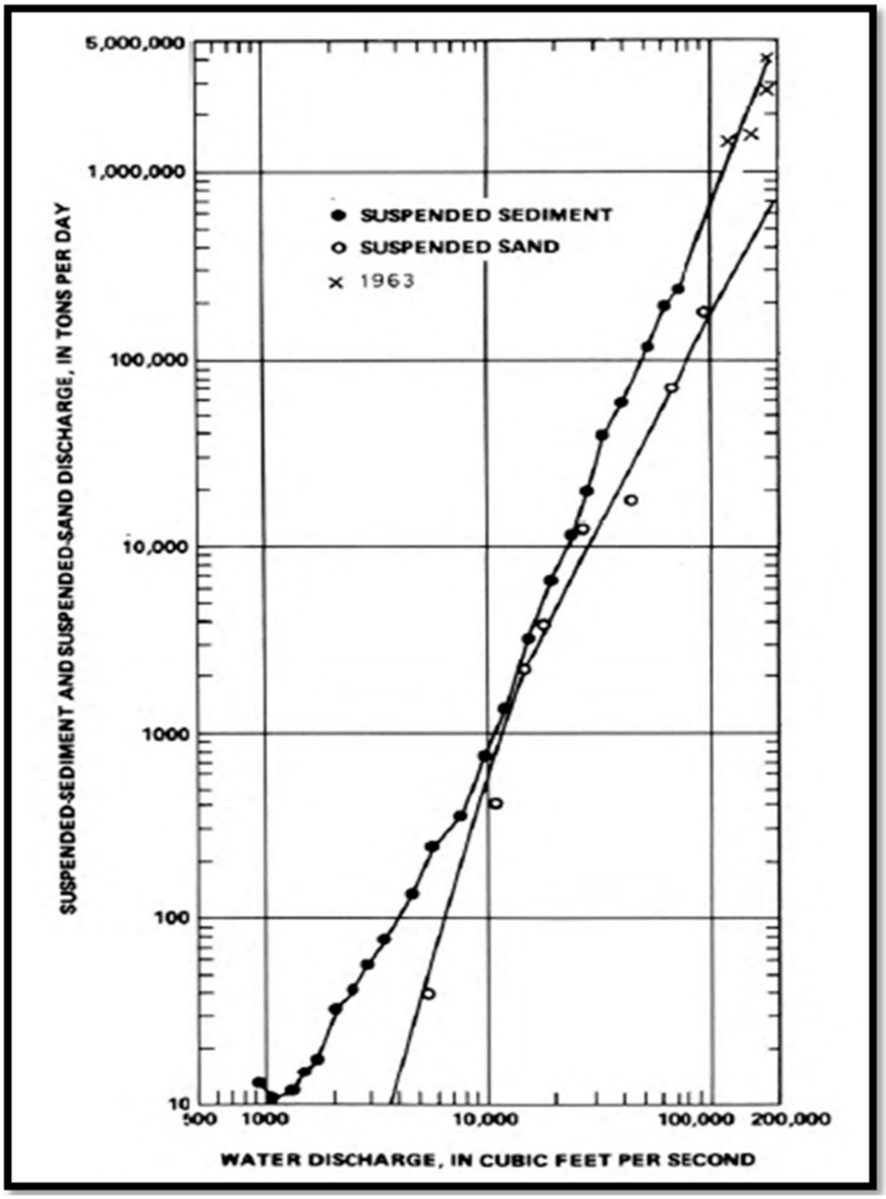

Figure 8. Suspended sediment and suspended sand rating curves

Summary

MIKE 21C two-dimensional numerical simulation models were constructed to simulate water and sediment movement in the Feather River between Oroville Dam and Yuba City, CA during the 2017 spillway erosion event (February 1, 2017 to May 31, 2017). Herein we focus on model inputs and outputs for the spatial domain comprising the reach between the Fish Barrier Dam and the Afterbay Outlet, also known as the Low Flow Channel (LFC). Compilation of model input and model calibration followed standard practice. Model simulations included two scenarios: one using the observed inflows of water and sediment, and one with the inflows that would have occurred in the absence of spillway erosion. Model output was quite detailed with respect to both temporal and spatial variations, and a wide range of graphical and numerical products have been analyzed in this study. Total bed-material sediment flux varied considerably along the LFC reflecting the heterogeneity in bed sediment sizes and local hydraulic conditions. Simulations of both scenarios indicated net export of sediment (erosion) from the LFC during the simulation period with minimal change in habitat quality and habitat type distribution.

The MIKE 21C model cannot simulate transport of sediments finer than sand. However, computation of the Rouse number for a range of hydraulic conditions observed in the LFC indicates that these fine sediments moved through the reach as wash load with limited interaction with the channel bed.

Comparison of the observed sediment load to historic data collected prior to closure of Oroville Dam indicates that the LFC was subjected to total sediment load in during the 2017 event that was only about 5% of the load that would have occurred for this event during pre-dam conditions. The same figure for coarser (sand) sediments is about 2%. The difference between the observed sediment load and the pre-dam or “without dam” load is greater for sands than for finer (silt and clay) sediments because sands are preferentially retained by the reservoir.

References

[DWR] Department of Water Resources. (2014). Feather River Regional Flood Management Plan. Retrieved from http://frrfmp.com/wp-content/uploads/2013/02/FeatherRFMP-MainReportDraftFinal7-11-14-clean.pdf

[DWR] California Department of Water Resources. (2011). Mapping Standard and Land Use Categories for the Central Valley Riparian Mapping Project. Developed for the Central Valley Flood Protection Program (CVFPP) Systemwide Planning Area (SPA), major rivers and tributaries. Prepared by Geographical Information Center, California State University, Chico.

Edwards, T.K. and Glysson, G.D., 1999. Field methods for measurement of fluvial sediment. USGS – TWRI Book 3, Chapter C2. 1999.

Engelund, F., and Hansen, E. (1967). A monograph on sediment transport in alluvial streams. Technical University of Denmark 0stervoldgade 10, Copenhagen K.

Lamb, M. P., de Leeuw, J., Fischer, W. W., Moodie, A. J., Venditti, J. G., Nittrouer, J. A., Haught, D. and Parker, G. (2020). Mud in rivers transported as flocculated and suspended bed material. Nature Geoscience, 13(8), 566-570.

[MBK] MBK Engineers. (2011). Lower Feather River Corridor Management Plan Hydraulic Analysis—Baseline Model Documentation. 17 January 2012.

Porterfield, G., George, B., Busch, R.D. and Waananen, A.O. (1978). Sediment Transport in the Feather River, Lake Oroville to Yuba City, California. U.S. Geological Survey, Water Resources Division, California District. Menlo Park.

U.S. Army Corps of Engineers Sacramento District. (1970). Oroville Dam and Reservoir Feather River, California. Report on Reservoir Regulation for Flood Control. Department of the Army. Washington, D.C.

Wu, W. (2008). Computational River Dynamics. Taylor and Francis, New York.

Yang, C.T. and Huang, C.A.I.A.N. (2001). Applicability of sediment transport formulas. International Journal of Sediment Research, 16(3), pp.335-353.