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Assessment of the effects of multiple extreme floods on flow and transport processes under competing flood protection and environmental management strategies

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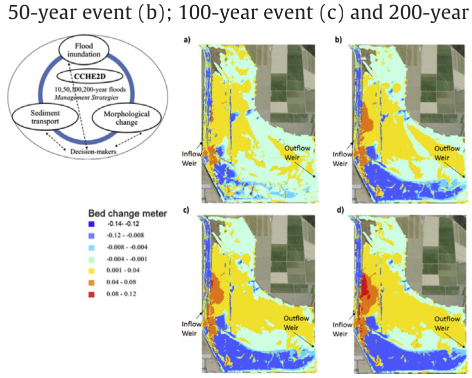
HIGHLIGHTS

- An integrated modeling approach is proposed to evaluate competing management plans.
- The proposed approach investigates flows with various return periods.
- Flood inundation and sediment transport during multiple extreme floods are explored.
- The effects of potential management strategies are evaluated for a large water body.
- The modeling approach can aid river system management.

GRAPHICAL ABSTRACT

Bed change differences within CCSB, alternative modification minus current condition, 10-year event (a); 50-year event (b); 100-year event (c) and 200-year event (d).



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ABSTRACT

Extreme floods are regarded as one of the most catastrophic natural hazards and can result in significant morphological changes induced by pronounced sediment erosion and deposition processes over the landscape. However, the effects of extreme floods of different return intervals on the floodplain and river channel morphological evolution with the associated sediment transport processes are not well explored. Furthermore, different basin management action plans, such as engineering structure modifications, may also greatly affect the flood inundation, sediment transport, solute transport and morphological processes within extreme flood events. In this study, a coupled two-dimensional hydrodynamic, sediment transport and morphological model is applied to evaluate the impact of different river and basin management strategies on the flood inundation, sediment transport dynamics and morphological changes within extreme flood events of different magnitudes. The 10-year, 50-year, 100-year and 200-year floods are evaluated for the Lower Cache Creek system in California under existing condition and a potential future modification scenario. Modeling results showed that select locations of flood inundation within the study area tend to experience larger inundation depth and more sediment is likely to be trapped in the study area under potential modification scenario. The proposed two dimensional flow and sediment transport modeling approach implemented with a variety of inflow conditions can provide guidance to decision-makers when considering implementation of potential modification plans, especially as they relate to competing management strategies of large water bodies, such as the modeling area in this study.

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1. Introduction

Extreme floods are known as rare, high-magnitude events that release a great amount of water in a short duration over the landscape. These floods can be triggered by intense or long-duration rainfall, dam failure, glacial lake outbursts, and volcanic eruptions (Alho and Aaltonen, 2008; Alho et al., 2005; Spillway, 1986; Walder and O'Connor, 1997). Extreme floods are regarded as one of the most catastrophic natural hazards that pose serious threats to property, infrastructure, and even human lives, as floodwaters running outside of the channel or river network approach areas with extensive human activities (Carrivick and Rushmer, 2006; Rickenmann et al., 2016). Such floods can carry the transport of high fluxes of sediment, resulting in significant morphological changes caused by pronounced erosion and deposition processes in the channel, river, and floodplain (Guan et al., 2015; Rickenmann et al., 2016). The modified geometry and morphology in return can greatly affect hydrodynamic features; for example, channel conveyance capacity decreases when sediment deposition occurs in the channel, making the surrounding areas more exposed to flood damage (Rickenmann et al., 2016). Furthermore, it is expected that both frequency and intensity of extreme events will change within future climate change scenarios (Easterling et al., 2000; McMichael et al., 2006). Additionally, the large amount of transported sediment can alter the physical, chemical and biological properties of waterbodies. Such changes include water temperature change, reduction in light penetration in waterbodies, and water quality change due to heavy metals and pesticides transported along with sediment (Bilotta and Brazier, 2008). As a consequence, sediment transport issues could be very important to aquatic ecosystems and environmental health (Gamvroudis et al., 2015; Johnston, 1991). Therefore, the study of extreme flood events and their associated morphological processes, which may have direct impact on transport processes in the waterbodies and have implications on environmental monitoring and management, attracts growing interests in the field of earth science (Guan et al., 2015).

Research on extreme floods and accompanied geomorphic implications together with the consideration of flow-sediment transport interactions, especially in fluvial hydrology at floodplain and basin scales, is limited and is commonly conducted on laboratory experimental scales or small field scales (Cao et al., 2004; Carrivick et al., 2011; Cooper, 2002; Lane et al., 2003). Previous work of the impact of extreme floods on the landscape at large scales can be found in Baker and Kale (1998), Korup (2012), Rickenmann et al. (2016), and Surian et al. (2016). Guan et al. (2015) explored the various sediment transport effects during floods by small-scale laboratory cases and a full-scale glacial outburst flood. Surian et al. (2016) investigated channel response in six mountain rivers during an extreme flood by studying the controlling factors and morphological changes. These studies offered fundamental insights on the complex interactions between flood events and morphological changes. However, most of the aforementioned scientific literature considers the landscape morphological response to single extreme flood event, which may be incomplete to understand the geomorphic signature and the associated transport processes behavior of extreme floods. As argued by Magilligan et al. (2015) and Smith et al. (2010), a weak link exists between return period and the immediate morphological imprint of a flood in some instances, though it is widely accepted that a single dominant flood event controls channel morphology (Milan, 2012). Consequently, to get a relatively comprehensive understanding of the morphological responses to extreme floods and the flood inundation dynamics while considering flow-sediment transport interactions in a given river or basin, floods with different recurrence intervals should be considered.

Additionally, as suggested by Costa and O'Connor (1995) and Surian et al. (2016), factors such as human interventions and structures should be incorporated in the understanding and prediction of channel and floodplain response to large floods much like hydraulic parameters are currently. Langhammer (2010) analyzed the relationship between stream modifications and the geomorphologic effects of floods and found that the relationship is limited. Holstead et al. (2017) incorporated the farmer's perspective in flood management and identified six key criteria in the implementation of flood management. However, the impact of human intervention and hydraulic structures on morphological changes within multiple extreme floods and the subsequent implication of the morphological changes on flood hazards are currently not well explored (Guan et al., 2016). Such understanding can be important for environmental management agencies, for example, when the feasibilities of potential management strategies need to be evaluated for a given river system. The potential poor correspondence between the frequency of a flood and its associated morphological changes may result in competing interests for different parties, such as the flood protection and environmental management agencies and the local community. These competing interests may make identification of potential management strategies challenging. For instance, potential management in a river system may decrease inundation extent for a given extreme flood, which is favored by the local community, but it may increase sediment erosion or deposition in the management area, which can be unwelcome to the management agency. Moreover, the flood inundation extent may be altered with the transport of sediment. Therefore, information about the morphological responses to different extreme floods is especially desirable for policy-makers to evaluate the implementation of certain management policies in the river system.

To extend the knowledge on the effects of sediment transport processes, morphological response, and the subsequent flood inundation with flow-sediment transport interaction during extreme floods at the basin scale, a coupled two-dimensional hydrodynamic and sediment transport model, which can handle unsteady flow, non-uniform sediment transport, morphological changes and the interactions between flow and sediment transport, is applied to simulate several extreme floods with variable recurrence intervals under different scenarios. The Lower Cache Creek system located in California, USA, which includes a floodplain and settling basin, is chosen as a case study. Two landscape scenarios are proposed as potential future engineering modifications within the study area. Flood inundation, sediment transport dynamics and morphological changes based on the two landscape scenarios and under four different flood conditions, 10-year, 50-year, 100-year and 200-year return periods, are of concern to local community and management agencies. The present work serves to illustrate: (1) flood inundation extent and morphological responses to different extreme flood events under current bathymetric conditions when loose bed and bank are assumed, (2) effects of potential engineering management in the floodplain and basin on these responses, and (3) comparison of modeling results from different potential engineering interventions and the implication of selecting management strategies for policy-makers.

2. Study area

The study area as shown in Fig. 1, the Lower Cache Creek system, is located in northern California, USA and covers about 400 km^2 with the inclusion of the communities of Woodland and Yolo, California. The study area is comprised of a nearly 18 kilometer reach of Cache Creek, the 14.5 km^2 Cache Creek Settling Basin (CCSB), and the remainder is a floodplain where residential housing and industrial companies are located. The study domain includes the compound reach from Rd 94B in Cache Creek through the outflow weir of the CCSB. The main channel in Cache Creek is very sinuous with steep banks. The immediate overbank area is vegetated and also bounded by levees. Channel width throughout Cache Creek is variable. Flow enters the CCSB at Road 102, where the training levee guides the flow into the basin. The outlet from the CCSB is the outflow weir, an uncontrolled 530-meter wide roller compacted concrete weir. The design capacity of the training channels and outflow weir is 850 m^3/s. The CCSB is highly heterogeneous with a mixture of vegetated wetland and agricultural land. The primary function of the CCSB is to settle a large amount of sediment load delivered from Cache Creek to avoid its deposition in the Yolo Bypass. Consequently, the CCSB helps preserve the capacity of the bypass for conveying floods and protect surrounding areas, such as Sacramento, California. Mercury issues are also a concern in the CCSB, as many abandoned, un-reclaimed and partially reclaimed mercury mines are located in the Cache Creek Watershed. Because mercury is often transported with sediment, trapping sediment within the CCSB helps reduce threats of pollution transport to the Yolo Bypass and the surrounding communities. As documented in the USACE 2007 Draft Cache Creek Settling Basin Operations & Maintenance Manual (U.S. Army Corps of Engineers, 2007), modification and additional management operations of the CCSB are required to preserve the CCSB sediment trapping efficiency when it falls below 30%.

Potential modification of the study area was proposed to contribute to reducing flood risk and the resulting damages, improving local operations and maintenance of the study area, and promoting ecosystem restoration opportunities and multi-benefit projects in cases of extreme flood events. The modification includes construction of an approximately 10-kilometer long levee as shown in Fig. 1, a new inlet weir located north of the intersection of the new levee and the existing western levee of the CCSB, and removal of a 1600-m portion of the training channel in the CCSB. A detention basin is created by the intersection of the existing west levee of the CCSB and the proposed new levee. Associated operations and management in the lower Cache Creek system during extreme events may be greatly affected by any potential modification. Flood inundation and sediment transported during extreme flooding may be significantly altered for different modification scenarios, and the modifications may also largely affect flood conveyance in the channel, and the CCSB morphology. Primary concerns about the potential effects of the project vary among different agencies. Agencies representing the surrounding communities are primarily focused on flooding issues, such as the risk of property damage, infrastructure damage from flooding of Lower Cache Creek. Other agencies are concerned with the potential modifications' effects on sediment and mercury dynamics and the associated sediment and mercury trapping efficiencies. Therefore, prior to determining a preferred recommendation of modification, the potential problems and opportunities emerging from each modification plan should be evaluated.

3. Methodology

One-dimensional or two-dimensional numerical models would be sufficient to simulate morphological changes at the basin scale, while three-dimensional models would be computationally expensive (Papanicolaou et al., 2008). Two-dimensional models can provide more details than one-dimensional models and can more efficiently simulate nearly all aspects of three-dimensional flow (Carrivick and Rushmer, 2006). As a result, two-dimensional sediment models are widely used in modeling sediment transport and morphological processes (Buttolph et al., 2006; Fang et al., 2006; Guan et al., 2015; Qian et al., 2016; Tu et al., 2015).

A depth-integrated two-dimensional hydrodynamic and sediment transport model, CCHE2D model (Jia et al., 2013), which is capable of modeling unsteady flow dynamics, sediment transport and morphological processes, was used in this study. CCHE2D has been successfully applied in many hydrodynamic and sediment transport problems (Carr et al., 2015; Ercan and Kavvas, 2015; Kantoush et al., 2008; Tu et al., 2015; Tu et al., 2017). Introduced here are three main components of

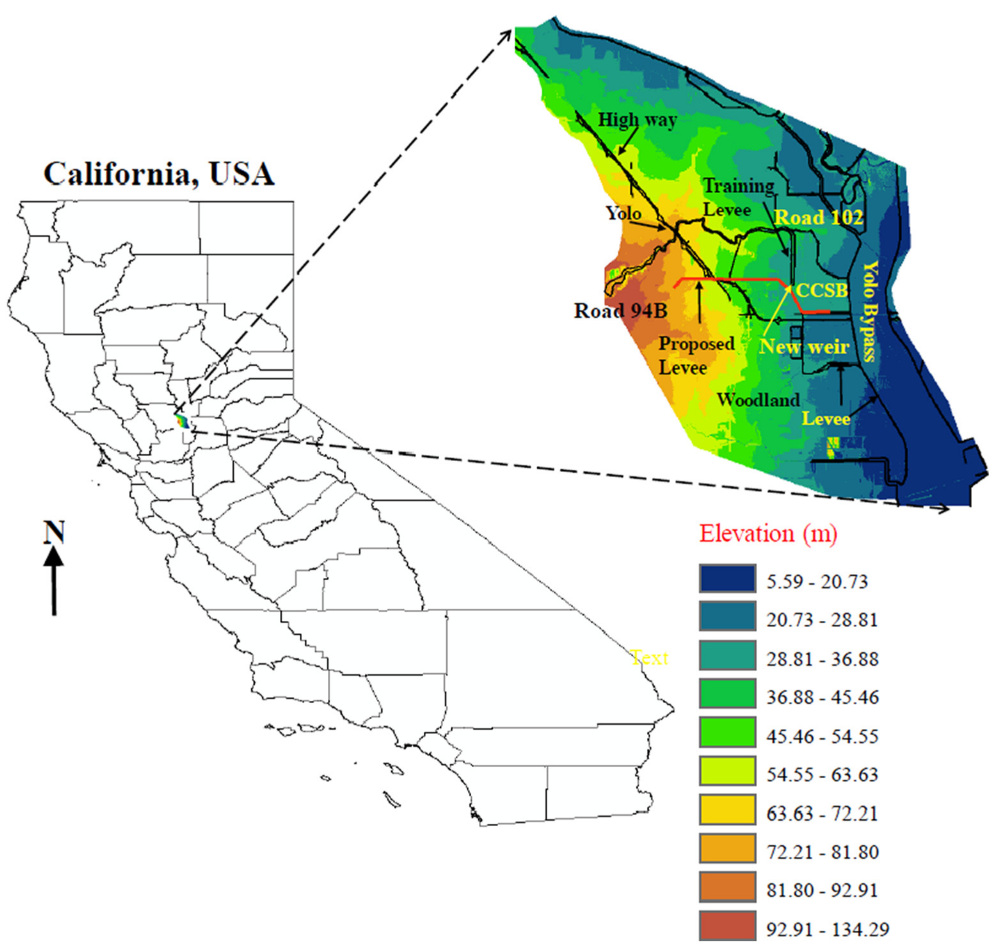

Fig. 1. Location of study area.

CCHE2D: the hydrodynamic module, the sediment transport module, and the morphological module.

3.1. Hydrodynamic module

The depth-integrated two-dimensional shallow water equations that neglect the effect of vertical motions are generally valid in the application of open channel flow. The governing equations for continuity and momentum equations of depth-integrated two-dimensional turbulent flows in a Cartesian coordinate system are given as (Jia et al., 2013):

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \tag{1}$$

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial huv}{\partial y}=-gh\frac{\partial z}{\partial x}+\frac{1}{\rho}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)+\frac{\partial D_{xx}}{\partial x}+\frac{\partial D_{xy}}{\partial y}+\frac{\tau_{sx}-\tau_{bx}}{\rho}+f_{Cor}hv \tag{2}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hv^2}{\partial y}=-gh\frac{\partial z}{\partial y}+\frac{1}{\rho}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)+\frac{\partial D_{yx}}{\partial x}+\frac{\partial D_{yy}}{\partial y}+\frac{\tau_{sy}-\tau_{bx}}{\rho}+f_{Cor}hu \tag{3}$$

where t is time; h is water depth; u and v are the depth-averaged velocity components in the x- and y-directions; g is the gravitational acceleration; z is the water surface elevation; ρ is water density; f_{Cor} is the Coriolis coefficient; $\tau_{xx},\tau_{xy},\tau_{yx}$ and τ_{yy} are the depth-averaged Reynolds stresses; D_{xx},D_{xy},D_{yx} and D_{yy}; τ_{bx} and τ_{by} are bed shear stresses; τ_{sx} and τ_{sy} indicate water surface shear stresses.

3.2. Sediment transport module

The sediment transport module in CCHE2D can model non-uniform, cohesive and non-cohesive sediment transport processes of suspended sediment and bedload. The sediment module also considers sediment movement under the influence of secondary flow in a curved channel. The total load sediment can be computed by separately calculating the bedload and suspended load transport. The depth-integrated governing equation for suspended sediment transport is given as (Jia et al., 2013):

$$\frac{\partial hc_k}{\partial t}+\frac{\partial huc_k}{\partial x}+\frac{\partial hvc_k}{\partial y}=\frac{\partial}{\partial x}\left(\frac{v_t}{\sigma_c}h\frac{\partial c_k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{v_t}{\sigma_c}h\frac{\partial c_k}{\partial y}\right)+\frac{\partial S_x}{\partial x}+\frac{\partial S_y}{\partial y}+\alpha\omega_{sk}(c_{*k}-c_k) \tag{4}$$

where $k=1,2,\ldots,N$ in which k denotes a sediment size class and N is total number of size classes; c_k is the depth-integrated suspended sediment concentration of size k; c_{*k} is the suspended sediment transport capacity at the equilibrium state of size k; v_t is the eddy viscosity; σ_c is the turbulent Schmidt number; $\omega_{sk}$is the sediment settling velocity of size k; $\alpha$is the non-equilibrium adaptation coefficient; and S_x and S_y are the dispersion terms due to the non-uniform flow velocity and sediment concentration distribution.

The depth-integrated bedload transport governing equation is (Jia et al., 2013):

$$\frac{\partial\delta\overline{c}_{bk}}{\partial t}+\frac{\partial\alpha_x q_{bk}}{\partial x}+\frac{\partial\alpha_y q_{bk}}{\partial y}+\frac{q_{bk}-q_{b*k}}{L}=0 \tag{5}$$

where δ is the bedload layer thickness; $\overline{c}_{bk}$ is the average bedload concentration of size k at the bedload zone; $q_{b*k}$is the bedload transport capacity or bedload transport rate at the equilibrium state of size k; L is the non-equilibrium sediment transport adaption length; α_x and α_y are the direction cosine components of bedload movement in the x- and y-directions. The formulae of suspended sediment transport capacity and bedload transport capacity can be found in Jia et al. (2013).

3.3. Morphological module

The bed deformation change for non-uniform sediment transport is determined by (Jia et al., 2013):

$$(1-p)\left(\frac{\partial z}{\partial t}\right)_k=\frac{q_{bk}-q_{b*k}}{L}+\alpha\omega_{sk}(c_{*k}-c_k) \tag{6}$$

where p is bed material porosity.

Governing equations in CCHE2D model are solved using the Efficient Element Method proposed by Wang and Hu (1992). Further description and applications of the CCHE2D model can be found in Jia et al. (2013).

3.4. Model application

To capture the high heterogeneity of the study area's bathymetry and roughness characteristics, the computational domain, which includes Cache Creek, a floodplain and the Cache Creek Settling Basin, is discretized and represented with a dense population of over 395,000 computational nodes. The same discretized computational domain is applied to the modeling of alternative modification of the study area. The elevation contour maps of the computational domain for the current and modified bathymetry are shown in Fig. 2.

Extreme floods with four different return periods, 10, 50, 100 and 200-year, were generated based on design storms prescribed by U.S. Army Corps of Engineers (USACE), and were used as inflow boundary conditions at the inlet as shown in Fig. 2. The four inflow hydrographs are provided in Fig. 3 (hydrographs were obtained through personal communication with USACE). Sediment loading conditions and size classes for the simulations were assigned as described by U.S. Army Corps of Engineers (1997). Simulations by CCHE2D model used representative grain size diameters of 0.003, 0.027, 0.797 and 15 mm for clay, silt, sand, and gravel respectively.

The hydrodynamic module of the two-dimensional model was calibrated using the inflow of a 4.5-day flow event with a peak flow of 450 m^3/s from March 18, 2011 through March 22, 2011, and validated with a 4.8-day flow event having a peak flow of 405 m^3/s from March 23, 2011 through March 27, 2011 at Yolo. The data used for calibration and validation was measured by United States Geological Survey (USGS). The water surface elevations at Road 102 (USGS gauge 11452600), Site C (within CCSB, USGS gauge 384041121402601) and the outflow weir (USGS gauge 11452800) were used in the calibration and validation of the model performance. Finally, a roughness formula based on Wu and Wang (1999) was found to provide good simulation results as Nash efficiencies were estimated above 0.85. Detailed information about the flow calibration and validation can be found in Carr et al. (2017). For relative comparison of the two modeling scenarios, current condition and alternative modification, the default model parameters, such as the sediment transport capacity, were used.

4. Results and discussion

4.1. Flood inundation

Flood inundation simulations of the two modeling scenarios, current condition and alternative modification, under 10, 50, 100 and 200-year flood events were performed by CCHE2D model. Modeling results showed that different extreme flood events generated very different flood inundation extents. In general, flow inundation depth increases under the alternative modification for each extreme flood event, compared with the depth under current condition. No overbank flow was found during the 10-year flood event in both modeling scenarios. Consequently, no flow entered the basin through the new inlet weir during a 10-year event under the alternative modification scenario. For the 50-year flood, out of channel flow existed in both scenarios, yet no flow passed the new inlet weir. Flood inundation results of 100-year and

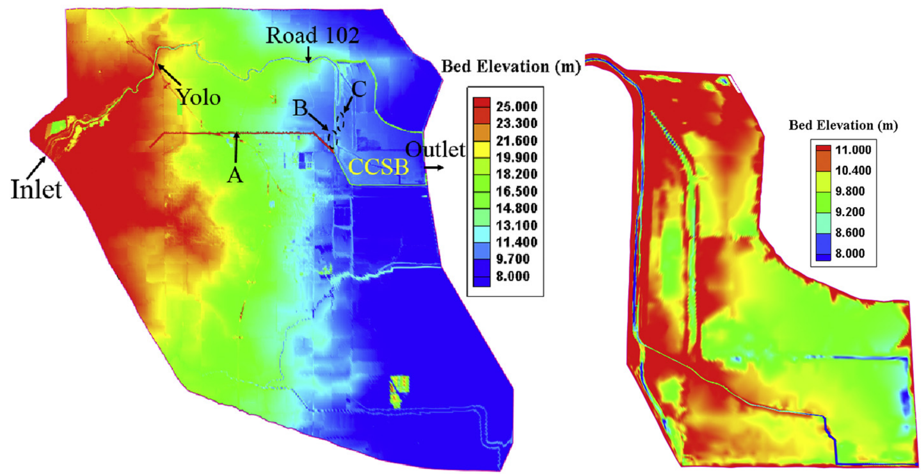

Fig. 2. Elevation contour maps of computational domain, the Lower Cache Creek systems: current condition with modification (left figure) and bed elevation within CCSB (right figure), where A, B and C are modifications. A: New levee approximately 10 km in length; B: New inflow weir to Cache Creek Settling Basin; C: Around 1600 m portion removal of the training levee in the basin.

200-year events included significant overbank flow, and, in the alternative modification, the new inlet weir functioned for both events. Therefore, only the flood inundation comparisons of these two extreme events are presented here due to their potential to cause major flood protection concerns to the surrounding community. Differences between simulated maximum water depth of the alternative modification scenario and the current condition for the 100 and 200-year events are depicted in the contour maps on Figs. 4 and 5 respectively. As shown on Fig. 5, under the 200-year flow event water depths within the CCSB are increased by between 0.1 and 0.5 m. Water depths along the west of CCSB increase between 2 and 2.5 m, with depth increases over 2.5 m in the alternative modification scenario along the east most portion of the new levee. A similar pattern of increase is seen on Fig. 4 for the 100-year flow event; however, water depth increases of between 0.1 and 0.5 m within the CCSB are localized to the region just downstream of the removed interior training levee section. As in the 200-year event, water depths for the 100-year event increase along the west of CCSB by 2 to 2.5 m. In the alternative modification scenario a small area of the southern portion of detention basin, along the east most portion of the new levee, is subject to increases over 2.5 m. Therefore, the alternative modification scenario can help protect the highly urbanized and industrialized area (below the new proposed levee) from extreme flood events, even with 200-year return period. It should be also be noted that the flood inundation of the area close to and above the new proposed levee would suffer from larger inundation depths compared with that under current condition.

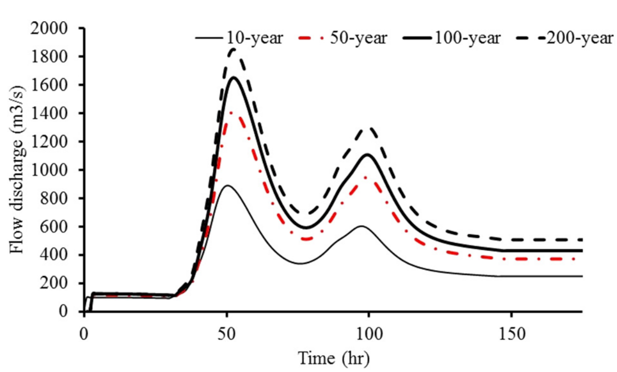

Fig. 3. Extreme flood hydrographs at the inlet.

4.2. Sediment transport dynamics

Sediment transport modeling results for the current condition and alternative modification scenario, under 10, 50, 100 and 200-year events are provided to make a relative comparison for sediment trapping performance under the two scenarios. The same flow and sediment boundary conditions described in the Model application section were used in both scenarios.

Analysis of the simulation results provided trap efficiencies for the entire simulation domain, as well as for the Cache Creek Settling Basin. The values provided from the simulation results can be used for relative comparison of the two scenarios. Trap efficiencies for the full domain are based on the total load (bed and suspended load) entering the system at the inlet, the upstream boundary at County Road 94B, and total load exiting the system at the outlet, the CCSB outflow weir, for the flow events of both current condition and alternative modification scenario. Trap efficiencies for the CCSB are based on total load entering the CCSB at Road 102, and exiting the system at the CCSB outflow weir for the flow events of the current condition. For the alternative modification scenario, trap efficiencies for the CCSB are based on total load entering the CCSB at Road 102 and the proposed inlet weir west of the CCSB, and exiting the system at the CCSB outflow weir. Trap efficiencies of each flow event for the current condition and alternative modification scenario are presented in Table 1.

As presented in Table 1, trap-efficiencies increase with extreme event magnitude for both the alternative modification scenario and the current condition, whether calculated for the full domain or the CCSB. Increase in trap efficiency of the full simulation domain with discharge magnitude may be attributed to outflow from the levees between Road 94B and Road 102 in higher flows and the resultant sediment deposition within the inundated areas outside of Cache Creek and the CCSB. Increase in trap efficiency of CCSB with discharge magnitude may be attributed to the increase in larger grain size particles transported by such flows into the settling basin. Under these high flows, larger particles are transported in channel, and are then deposited when flows overtop the channel levees, or reach the settling basin. Additionally, for each flow event simulated trap efficiencies are higher under the alternative modification scenario than under the current condition.

Four different sediment classes are used (i.e., to represent clay, silt, sand and gravel based on the representative mean diameter of each size class) in the sediment transport simulations. Rigorous grain size distribution analysis based on a robust sampling campaign in the

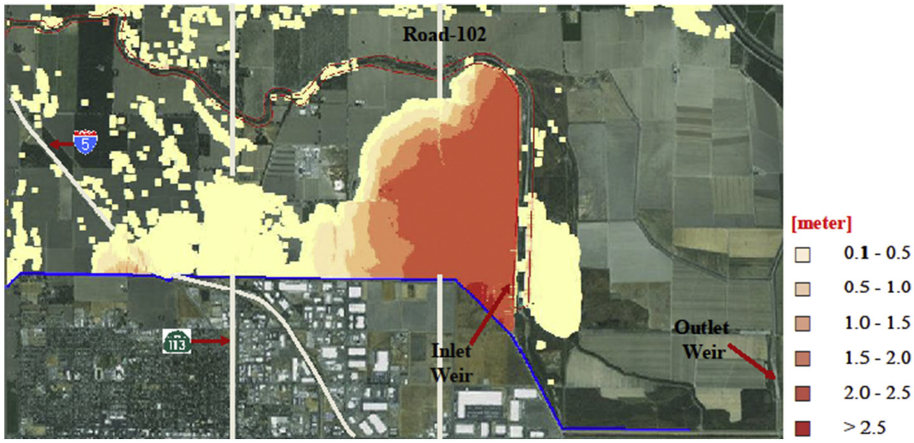

Fig. 4. Water depth differences, alternative modification scenario minus current condition, 100-year event.

study area was conducted to obtain the representative sediment size classes. According to the two-dimensional sediment transport simulations under the assumptions listed in the Model application section, which allow a relative comparison of current condition and alternative modification scenario, more than 99% of the gravel and sand particles and more than 95% of the silt particles were deposited upstream of the outlet weir for the 200, 100, 50 and 10-year events for both alternatives. Simulation analysis found that for all four flood events, under both the alternative modification scenario and the current condition, most of the sediment (more than 90%) leaving the simulation domain from the outlet weir into Yolo Bypass is clay. Sediment loads to the Yolo bypass for the alternative modification scenario for the 200, 100, 50 and 10-year events are respectively 103, 84, 96, and 87% of those found under the current condition.

4.3. Morphological change

The morphological responses to different extreme flood events, 10-year, 50-year, 100-year and 200-year, within the CCSB under the current condition and the alternative modification are presented in Figs. 6 and 7 respectively. Within the study domain, the sediment transport dynamics inside the CCSB are of most concern. Figs. 6 and 7 clearly show that deposition depth and area increases as the flood magnitude increases under both modeling scenarios. The deposition in the channel as shown in Figs. 6 and 7, especially within 100- and 200-year flood events, would greatly affect the channel conveyance capacity. Consequently, this may induce changes in the dynamics of flood hazards, such as the changes of overbank flow, flood inundation extent, and inundation time, in the river systems. The pronounced morphological changes in the channel during extreme floods also make the normally assumed unchanged river morphology for flood risk assessment questionable (Guan et al., 2016).

The corresponding bed change profile of extreme flood events of the same magnitude under the two modeling scenarios displayed noticeable difference. Differences in the bed change within the settling basin are shown on Fig. 8. It can be seen that the bed change differences (alternative modification minus current condition) are positive in the northern settling basin and negative in the southern settling basin mainly due to differences in the flow patterns after removal of 1600 m of levee from the terminus of the interior training levee in the alternative modification. Flow can more freely flood to the far tip of the northern CCSB and flow velocities decrease as flow passes through the removed portion of training levee. Decreased deposition is seen in the southern area of the CCSB under the alternative modification for all simulated flood events (Fig. 8). The decreased deposition is a result of the redistribution of flow resulting from the removal of a section from the terminus of training levee. For each flood event, less sediment is delivered to the southern CCSB, resulting in less sediment to be deposited. Additionally, it is noted that the northern positive change area in the CCSB tends to be larger as the flood increases from 10-year to 200-year and the southern negative difference area in the CCSB grows larger as the flood magnitude increases, which indicates that the alternative

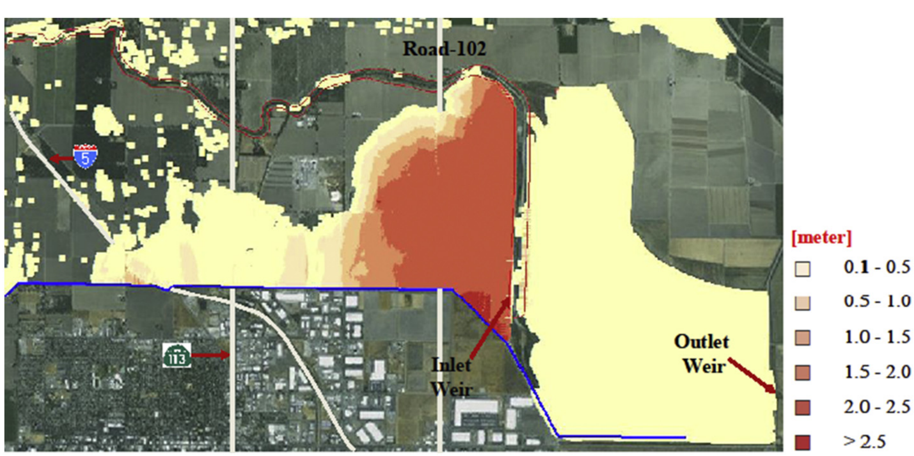

Fig. 5. Water depth differences, alternative modification scenario minus current condition, 200-year event.

Table 1
Trap efficiencies of 10, 50, 100 and 200-year flow events for the current condition, and alternative modification scenario, based on the entire simulation domain, as well as the CCSB.

Flow event	Full simulation domain		CCSB	
	Current condition	Alternative modification	Current condition	Alternative modification
10-year	80	83	31	41
50-year	86	86	56	58
100-year	88	90	57	63
200-year	93	92	66	71

modification can utilize the CCSB more fully to entrap more sediment in the domain compared with sediment trapping performance under current condition.

It should be noted that in this study movable bed is assumed in all the modeling scenarios to evaluate the flow inundation, sediment transport dynamics, and morphological changes. For flood inundation, the results of morphological changes clearly indicate that movable bed would be a more reasonable modeling choice during the assessment of flood hazards within extreme floods, compared with unchanging river geometry, since the modified morphology would greatly affect the channel conveyance capacity within the subsequent floods (Guan et al., 2016). Flood hazards assessment with the consideration of movable bed is more desirable for decision-makers allowing a more representative assessment of the flood risk.

In order to select the preferred management scenario to be implemented in practice, decision-makers should carefully evaluate the overall performance of every possible option. This is especially true in cases such as this one, in which when multiple agencies have different interests in the management strategy. In the described case, the local community is more concerned with overbank flood inundation while other management agencies are also concerned with sediment transport processes which in turn are directly related to environmental issues of the study area, such as mercury transport. The modeling results may serve as a reference for decision-makers on the selection of potential modifications in the Lower Cache Creek system and offer insights for policy-makers in developing informed management strategies that account for the interests of different agencies. For the two modeling scenarios in this study, the results illustrate that the alternative modification can protect the targeted area (south of the new proposed levee) from flooding even during 200-year flood and it can also entrap more sediment within the study area during all the extreme flood events under consideration. The sediment trapping performance of the alternative modification may make it more favored by the environmental protection agencies, as sediment transport is closely related to dynamics of mercury, methylmercury and other heavy metals in the study area (Marvin-DiPasquale et al., 2009; Springborn et al., 2011). In the study area, sediment mercury concentrations are

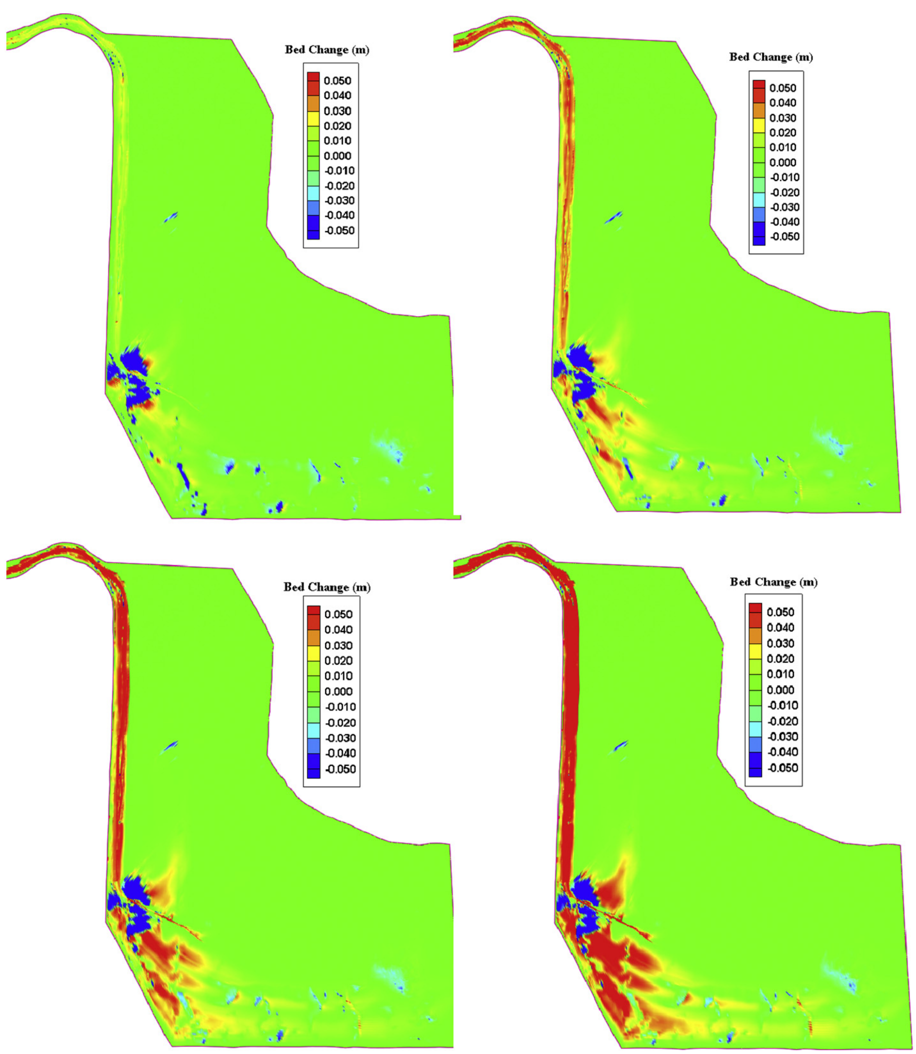

Fig. 6. Bed change within CCSB under current condition of different extreme flood events: 10-year (top left); 50-year (top right); 100-year (bottom left); 200-year (bottom right).

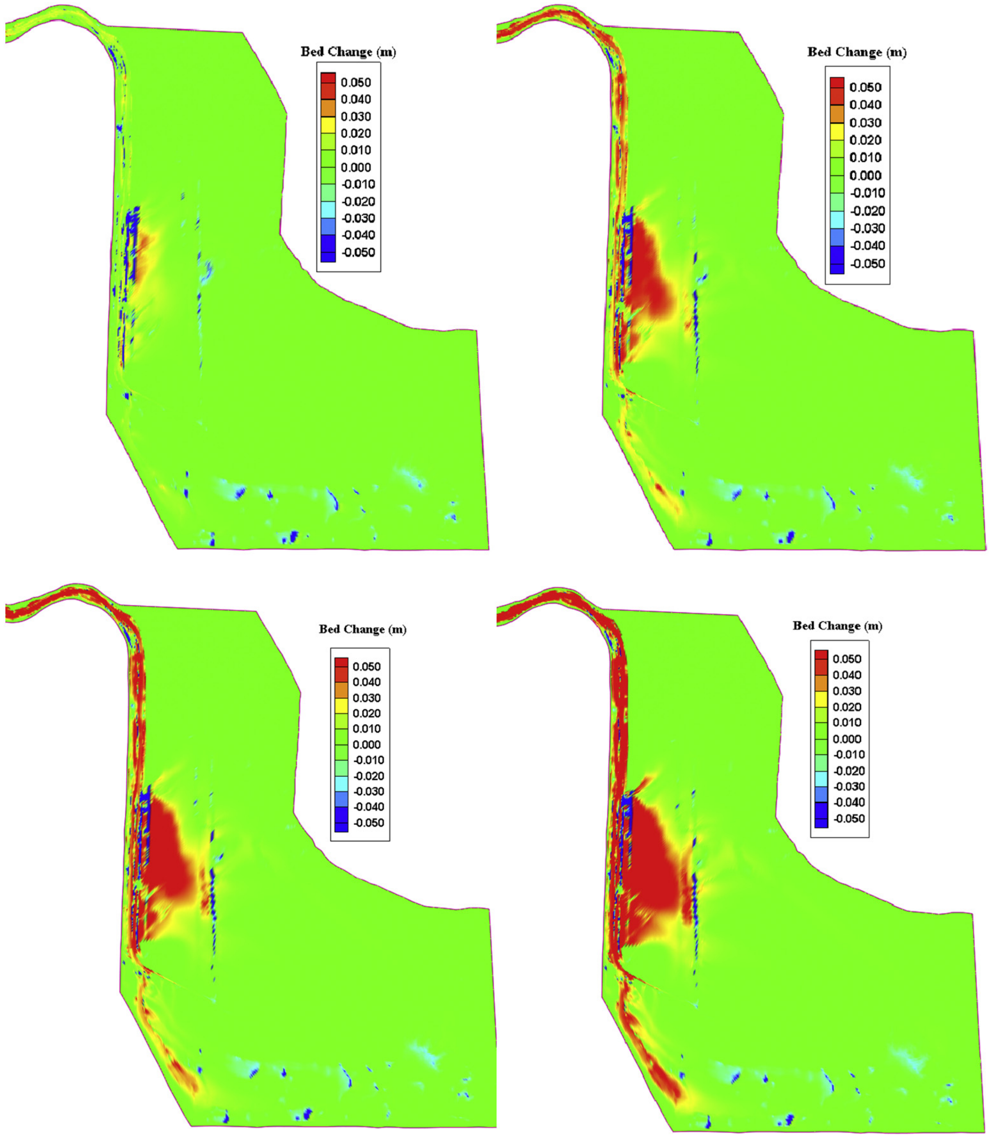

Fig. 7. Bed change within CCSB under alternative modification scenario of different extreme flood events: 10-year (top left); 50-year (top right); 100-year (bottom left); 200-year (bottom right).

positively correlated with sediment organic content and a positive correlation exists between suspended sediment concentration and mercury and methylmercury (Marvin-DiPasquale et al., 2009). Moreover, flood inundation duration can affect the sediment transport dynamics and consequently affect mercury and methylmercury transport (Marvin-DiPasquale et al., 2009). Larger sediment trapping capabilities of the alternative modification can potentially retain more pollutants within the CCSB and thereby provide more protection of the downstream area. However, compared with the current condition scenario, the implementation of the alternative modification, such as constructing a new levee, building a new inflow weir and removing a portion of the training levee, would carry a large economic cost. Moreover, the inundation depth of some areas (above the new levee) under the alternative modification scenario is significantly increased. Therefore, further evaluation of the choice of potential management strategies for the study area is needed in which the project budget, potential economic loss and environmental damages are considered. For example, the alternative modification scenario can be refined by investigating the optimal heights of the new levee and the inflow weir.

5. Conclusion

In this study, flood inundation, sediment dynamics and morphological changes of the landscape, which includes a flashy creek, a floodplain and a settling basin, within extreme flood events of different return periods, 10-year, 50-year, 100-year and 200-year, were evaluated by a coupled two-dimensional hydrodynamic and sediment transport model under two different basin management scenarios, i.e., the existing condition and a potential future modification scenario. The modeling results indicated that the future modification scenario can significantly affect the flood dynamics, sediment transport and morphological responses to the extreme events.

The modeling results showed that the assumption of movable river morphology for flood risk management in flood inundation modeling may be more reasonable and the results further indicated that flood inundation extent increases with flood magnitude. In general, the alternative modification scenario generated larger flood inundation depth in the west of CCSB during all the extreme events compared with the corresponding results under the current condition. Consequently, the potential economic losses, such as property damages and infrastructure

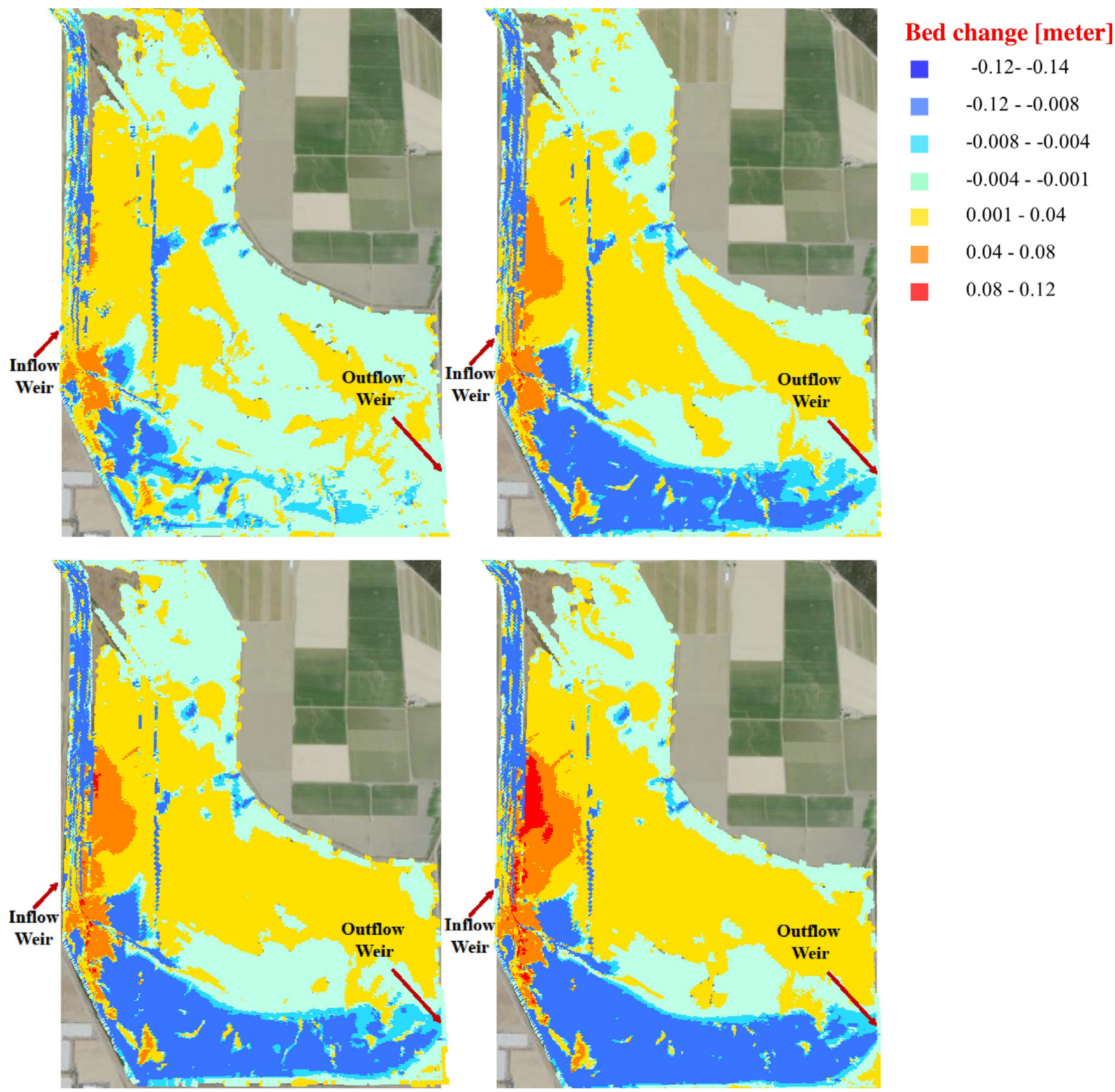

Fig. 8. Bed change differences within CCSB, alternative modification minus current condition, 10-year event (top left); 50-year event (top right); 100-year event (bottom left) and 200-year event (bottom right).

failure, would be entirely different under the two scenarios. Additionally, sediment trapping efficiency values increase as flood magnitude increases for both modeling scenarios. With the exception of the 200-year full domain calculation, trapping efficiencies under the alternative modification scenario are greater than the corresponding efficiencies under the current condition. These extreme event simulations clearly illustrate that each extreme flood event can result in significant morphological change by erosion and deposition processes and that human interventions can greatly alter sediment dynamics within these extreme flood events. For extreme flood events of the same magnitude, bed elevation changes west of the CCSB training levee show larger deposition area and sediment deposition depth under the modification scenario when compared with the corresponding results under the current condition. Bed change differences in the southern CCSB tend to be negative, i.e. the deposition depth under alternative modification scenario is generally smaller than that under current condition or the erosion depth under alternative modification scenario is larger than that under current condition. Additionally, in some areas the erosion depth is smaller than that under current condition. For the northern CCSB, bed change differences under different extreme events are positive, indicating that deposition dynamics are stronger in that region under the alternative modification scenario. Because the transport of mercury and other environmental pollutants in the study area is closely related to the sediment transport regimes, pollutant transport will be affected by the change in sediment transport dynamics under the alternative modification scenario.

The proposed coupled two dimensional flow and sediment transport modeling approach implemented with a variety of extreme inflow hydrographs (for 10, 50, 100, and 200 year return periods) and corresponding results can provide decision-makers with valuable information when considering the potential effects of modification plans, particularly with regard to flood inundation, sediment trapping performance and morphological evolution. The modification selection should be further evaluated and refined considering the potential economic and environmental consequences in order to best reconcile the interests of all parties.

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