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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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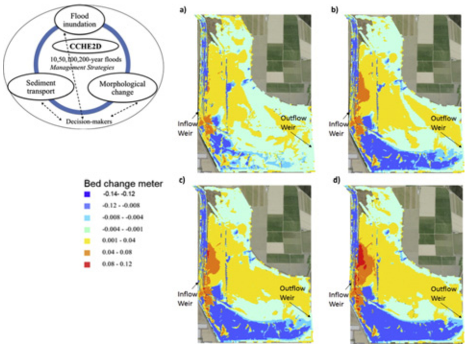
HIGHLIGHTS

- 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