Received: 21 April 2016 | Revised: 29 March 2017 | Accepted: 30 March 2017

DOI: 10.1002/rra.3159

WILEY

RESEARCH ARTICLE

Not all breaks are equal: Variable hydrologic and geomorphic responses to intentional levee breaches along the lower Cosumnes River, California

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Funding information
California Department of Fish and Wildlife (CDFW) Ecosystem Restoration Program (ERP), Grant/Award Number: E1120001; The Nature Concervancy (TNC); Consumnes River Preserve

Abstract

The transport of water and sediment from rivers to adjacent floodplains helps generate complex floodplain, wetland, and riparian ecosystems. However, riverside levees restrict lateral connectivity of water and sediment during flood pulses, making the re-introduction of floodplain hydrogeomorphic processes through intentional levee breaching and removal an emerging floodplain restoration practice. Repeated topographic observations from levee breach sites along the lower Cosumnes River (USA) indicated that breach architecture influences floodplain and channel hydrogeomorphic processes. Where narrow breaches (<75 m) open onto graded floodplains, archetypal crevasse splays developed along a single dominant flowpath, with floodplain erosion in near-bank areas and lobate splay deposition in distal floodplain regions. Narrow breaches opening into excavated floodplain channels promoted both transverse advection and turbulent diffusion of sediment into the floodplain channel, facilitating near-bank deposition and potential breach closure. Wide breaches (>250 m) enabled multiple modes of water and sediment transport onto graded floodplains. Advective sediment transport along multiple flow paths generated overlapping crevasse splays, while turbulent diffusion promoted the formation of lateral levees through large wood and sediment accumulation in near-bank areas. Channel incision (>2 m) upstream from a wide levee breach suggests that large flow diversions through such breaches can generate water surface drawdown during flooding, resulting in localized flow acceleration and upstream channel incision. Understanding variable hydrogeomorphic responses to levee breach architecture will help restoration managers design breaches that maximize desired floodplain topographic change while also minimizing potential undesirable consequences such as levee breach closure or channel incision.

KEYWORDS

avulsion, Cosumnes River, crevasse, floodplain restoration, levee breach, riparian, sand splay

1 | INTRODUCTION

Floodplains are semi-terrestrial areas inclusive of riparian and wetland ecological communities that provide some of the most dynamic and complex habitat mosaics found on Earth (Naiman & Décamps, 1997). The lateral connectivity of water and sediment during seasonal flood pulses is a key factor controlling the abiotic processes, biotic composition, and ecological dynamics that determine floodplain community structure (Junk, Bayley, & Sparks, 1989; Tockner, Malard, & Ward, 2000). However, riverside levees and dykes largely eliminate floodplain hydrologic connection in human-dominated riverscapes, making the re-establishment of hydrogeomorphic processes to lowland river floodplains through the breaching of riverside levees an emerging floodplain restoration practice (Swenson, Reiner, Reynolds, & Marty, 2012; Swenson, Whitener, & Eaton, 2003).

The hydraulic and sediment transport processes associated with flooding create floodplain topographic variability critical to the maintenance of heterogeneous floodplain ecological communities (Galat et al., 1998; Mount, Florsheim, & Trowbridge, 2002). In many modified floodplain landscapes, the partial diversion (intentional *or* accidental) of a river through breaks or breaches in riverside levees or dykes promotes dynamic hydrogeomorphic processes that modify the topography of adjacent floodplains (Arnaud-Fassetta, 2013; Florsheim & Mount, 2002). Analysis of ancient (e.g. Hajek & Edmonds, 2014) and modern (e.g. Bristow, Skelly, & Ethridge, 1999; Smith, Cross, Dufficy, & Clough, 1989) floodplain alluvial deposits identifies crevasse splays (Arnaud-Fassetta, 2013; North & Davidson, 2012) as a dominant geomorphic signature of floodplain development. Often, crevasse splay deposits are associated with progradational channel avulsions (Slingerland & Smith, 2004), where the flow of water and sediment through levee crevasse channels promotes the multi-stage generation of lobate sand bodies that prograde and extend into floodplain areas (Bristow et al., 1999; Mohrig, Heller, Paola, & Lyons, 2000; Smith et al., 1989). As the sand bodies grow, floodplain flows become progressively channelized, promoting down-floodplain extension of avulsion channels (Smith et al., 1989). Until recently, floodplains adjacent to large rivers were generally thought to form through the lateral accretion of point bars and repeated instances of spatially diffuse overbank flooding (e.g. Wolman & Leopold, 1957). However, numerous studies (e.g. Aslan & Autin, 1999; Slingerland & Smith, 2004) suggest that rapid and localized floodplain deposition associated with avulsion processes is a principal contributor to floodplain aggradation and growth. The long-term evolution of crevasse splays and avulsion channels creates highly complex floodplain topography and sedimentology (Smith & Perez-Arlucea, 1994) favorable to the ecological integrity of floodplain landscapes.

Intentional levee breaches often aim to replicate hydrogeomorphic processes introduced to floodplains following breaks in riverside levees and the routing of water and sediment onto floodplains during partial or full channel avulsion (e.g. Florsheim & Mount, 2002). This paper examines varying hydrogeomorphic responses to engineered levee breaches of differing sizes and geometries along a low-gradient river in northern California, USA, with the goal of understanding how levee breach architecture affects morphological responses in both the main channel of a river and the adjacent floodplain. We use hydrologic and geomorphic field observations to assess floodplain and channel morphology changes following levee removal in 2014 and seasonal flooding in 2015. Observations are used to extend the conceptual model of sand splay complex formation presented by Florsheim and Mount (2002) by including both narrow and wide levee breaches, as well as variation in initial floodplain topography. We ultimately conclude that while wide levee breaches appear to most effectively reduce river stage during flooding and produce the most heterogeneous floodplain topographic conditions, the cost of additional earthwork activities relative to narrow breaches, and the potential for both upstream channel incision and downstream channel aggradation must also be weighed in future hydrogeomorphic restoration actions on floodplains.

2 | STUDY AREA

2.1 | Cosumnes River watershed

The Cosumnes River of northern California, USA, drains a 2460 km^2 watershed located on the western slope of the Sierra Nevada. Basin headwaters are located at an elevation of approximately 2400 m ASL within a complex assemblage of granitic, andesitic, and metamorphic rocks that are part of the Sierra Nevada geomophic province. Flowing westward across the Sierran foothills, the lower Cosumnes River ultimately enters the Great Valley geomophic province, where the low-gradient river channel incises into Pleistocene alluvium and river terraces generated during multiple Plio-Pleistocene episodes of valley incision and filling (Shlemon, 1972). The Cosumnes River ultimately joins the Mokelumne River at the eastern edge of the Sacramento–San Joaquin River Delta, near sea level in California's Great Central Valley (Figure 1). The Mediterranean-montane climate of northern California produces strong seasonality in precipitation patterns, with the majority of precipitation in the Cosumnes River basin occurring as rain in the winter and spring months (Nov – Mar). Without any large regulating dams, the Cosumnes River exhibits a relatively unimpaired hydrograph that rapidly responds to precipitation events, although snowmelt peaks and recessions common to Sierran streams (Yarnell, Viers, & Mount, 2010) are also present. The 109-year-long record of streamflows in the Cosumnes River at Michigan Bar (USGS Site 11335000; see Figure 1) identifies highly variable peak annual discharges ranging from 6 m^3/s (1977) to 2634 m^3/s (1997). A flood regime typology for the Cosumnes River is explored thoroughly in Whipple, Viers, and Dahlke (2016). Only the loss of summer and fall baseflows in the lower reaches of the Cosumnes River due to regional surface and groundwater use deviates from a natural flow regime (Fleckenstein, Anderson, Fogg, & Mount, 2004).

2.2 | Floodplain restoration sites

The lower Cosumnes River (Figure 1) has long been used as a landscape-scale study area to assess floodplain ecosystem responses to intentional breaches in riverside levees (Swenson et al., 2012). Part of the Cosumnes River Preserve, the study area provides a unique laboratory within which to observe floodplain ecosystem responses following connection of unregulated seasonal flood pulses in the Cosumnes River—the largest undammed river draining the western flank of the Sierra Nevada—to proximal floodplain areas.

Prior to anthropogenic disturbance and conversion of floodplain areas to an agricultural landscape, the lower Cosumnes River was part of a flood basin known as the 'Cosumnes Sink' (Whipple, Grossinger, Rankin, Stanford, & Askevold, 2012). Throughout the flood basin, multiple shallow, low-gradient, and interconnected river channels created both anastomosing (Florsheim & Mount, 2003) and distributary (Whipple et al., 2012) channel patterns common to low-gradient river basins near base level (Makaske, 2001). Floodplain and terrace uplands adjacent to the once perennial Cosumnes River supported grasslands, valley oak woodlands, and riparian forests used extensively for foraging, hunting, and fishing opportunities by the aboriginal Plains Miwok (Levy, 1978). However, rapid anthropogenic changes to the river basin followed California's Gold Rush period (ca. 1850), with

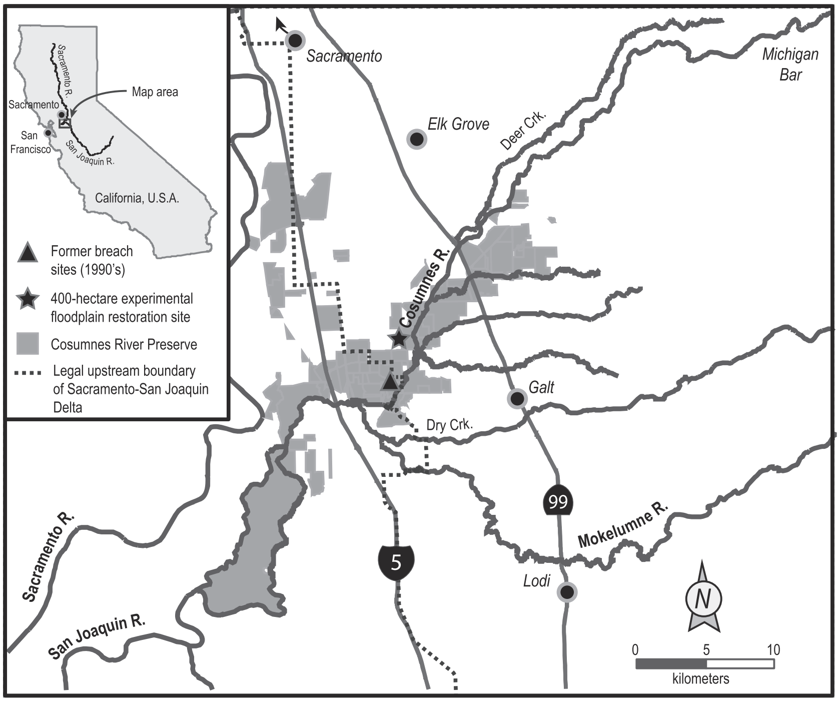

FIGURE 1 The lower Cosumnes River flows through the Cosumnes River Preserve study site in northern California, USA. [adapted from Florsheim and Mount (2002)]

extensive railroad and agricultural development. Throughout the past century, the construction of riverside levees and channel modifications have resulted in the presence of a single, incised river channel (Andrews, 1999; Constantine, Mount, & Florsheim, 2003) traversing the flood basin. The modern lower Cosumnes River is low-gradient (slope ~ 0.001), highly incised, and largely flanked by constructed levees protecting adjacent agricultural lands.

The conversion of the flood basin to support agriculture has resulted in a landscape where only small patches of natural areas remain, and hence the desire to restore and maintain native floodplain ecosystems (Reiner, 1996). Currently, natural vegetation covers 44% of the area around the Cosumnes River Preserve (Underwood et al., in press). However, many of these natural areas are currently experiencing conversion to urban land use from rapidly growing adjacent cities such as Galt and Elk Grove (Figure 1). The spatial extent of urban and developed areas has increased by 35% over the last decade (Underwood et al., in press), indicating urban expansion is reducing the amount agricultural and natural lands within the region.

Despite increasing urban pressures on the eco-agricultural matrix found in the Cosumnes River basin, the lack of flood control beyond riverside levees has resulted in comparatively low human population densities, which in turn has allowed for a unique approach to floodplain management. Throughout the 1990s, levee breaches along the lowest 3.5 km of the Cosumnes River immediately upstream from its confluence with the Mokelumne River were excavated to promote the development of sand splays and the establishment of riparian forests on former tomato fields (Mount et al., 2002; Swenson et al., 2003; Swenson et al., 2012). The depth of channel incision along the lower Cosumnes River has largely precluded the possibility of channel avulsion through the breaches. The periodic flow of water and sediment through uniformly narrow (<75 m) engineered levee breaches resulted in the generation of archetypal crevasse splays characterized by floodplain incision in areas closest to the levee breaches, and sand splay progradation into newly accessible floodplain areas (Florsheim & Mount, 2002). Resultant increases in floodplain topographic heterogeneity promoted the establishment of early stage successional riparian forests (Trowbridge, 2007; Viers et al., 2012). This hydrogeomorphic template is now the primary management method for floodplain restoration and flood risk reduction throughout the region.

Our work presents field observations of floodplain and channel topography changes following recent levee breaches along the lower Cosumnes River (Figure 1) and uses these observations to extend the conceptual model of sand splay complex formation initially presented by Florsheim and Mount (2002). These recent breaches allow floodwater to periodically inundate a 400-ha floodplain restoration site, which is bounded to the west by set-back levees that contain all but the largest of floods (>3-year recurrence interval) (Figures 2 and 3). Between 2002 and 2012, numerous 'accidental' levee breaches developed along the Cosumnes River adjacent to this floodplain restoration site. Expectedly, single crevasses developed proximal to the narrow (<25 m) breaches caused by limited levee failure, while lobate sand splays formed on the level floodplain (Figure 2). The crevasse splays exhibited landforms consistent with the previous observations of Florsheim and Mount (2002), including overlapping sand lobes dissected by primary and secondary flow paths flanked by lateral levees. Further, early stage successional floodplain forests have begun to develop on these evolving sand splays, as has deposition of large woody debris within and adjacent to the developing crevasses near the breach sites (sensu Arnaud-Fassetta, 2013).

In Fall 2014, two intentional breaches were excavated from existing levees along the Cosumnes River to further promote 'process-based' restoration of the 400-ha experimental floodplain site. However, the design of both levee breaches deviated from prior accidental and intentional breach sites, which were uniformly narrow and discharged water and sediment onto level floodplain areas (see Florsheim & Mount, 2002). At the upper breach site (Figure 3; Site U),

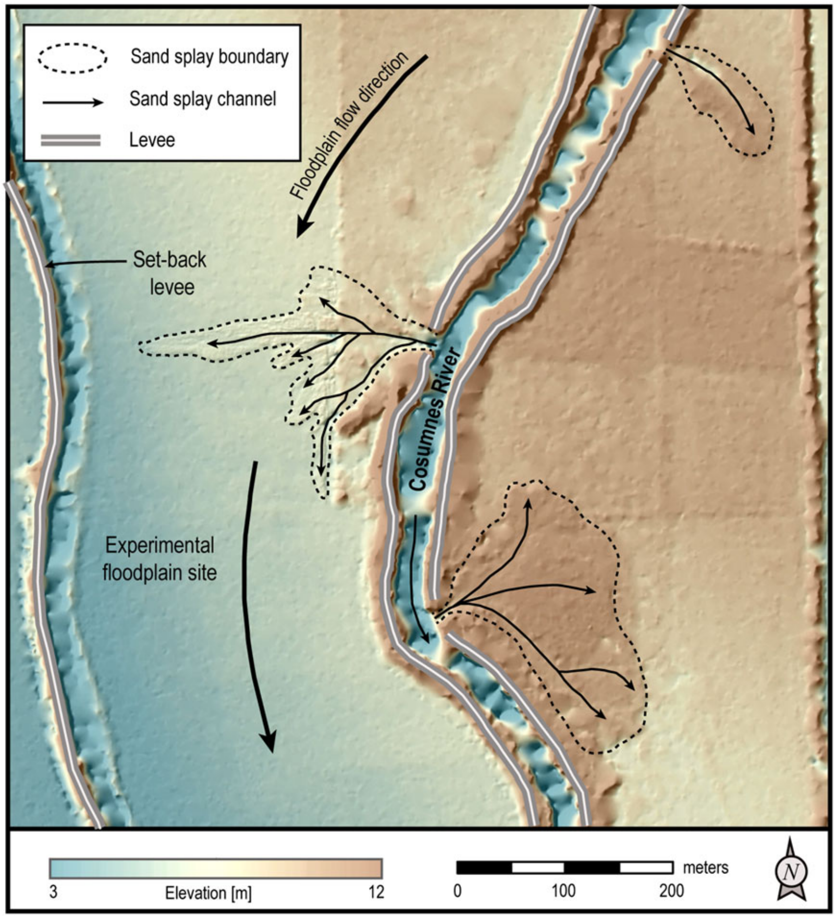

FIGURE 2 Archetypal crevasse splays developed following 'accidental' levee breaches adjacent to the Cosumnes River between 2002 and 2012. At each breach site, breach widths are narrow (<25 m). Crevasse splays exhibit floodplain scour proximal to the breach and sand splay deposition in distal floodplain areas [Colour figure can be viewed at wileyonlinelibrary.com]

more than 250 m of a riverside levee were removed, and the adjacent floodplain area was graded to the elevation of agricultural land inboard of the former levee. At Site U, the thalweg of the Cosumnes River is incised 2–3 m below the floodplain elevation to the west. At the lower breach site (Figure 3; Site L), a narrow (75 m) breach opens into a channel excavated approximately 2 m below the adjacent floodplain area to the west. The bottom of the floodplain channel at Site L is less than 1 m above the thalweg of the Cosumnes River. Field observations were used to characterize the in-channel and floodplain hydrogeomorphic responses to these unique levee breach designs.

2.3 | Floodplain connectivity thresholds

Increasing the frequency and duration of flow connectivity between the Cosumnes River and the adjacent experimental floodplain site was a primary goal of the levee breaching activities. Prior to intentional levee breaching, floodplain flow connectivity was achieved at Sites U and L (Figures 3 and 4) when the Cosumnes River at Michigan Bar exceeded ~225 m^3/s [approximate two year recurrence interval (RI) flood]. Discharge of 225 m^3/s is also the approximate bankfull channel capacity of the Cosumnes River upstream from Site U, which remained unchanged after levee breaching. Intentional levee breaching in Fall 2014 reduced flow connectivity thresholds to 57 m^3/s (1.25 RI) at Site U and 12 m^3/s (1.04 RI) at Site L (Figure 4). The connectivity threshold at Site L refers to the discharge magnitude required for water from the Cosumnes River to flow into the channel excavated into the floodplain. Due to persistent drought conditions throughout northern California, only two flood events exceeded connectivity thresholds at either breach site during water year 2015. Floodplain connectivity was achieved for a total of ~4 days at breach Site U, and ~13 days at Site L in water year 2015 (Figure 4). This connectivity was dominated by a single flood (206 m^3/s) in February 2015.

3 | METHODS

Repeat topographic surveys were used to characterize geomorphic changes to the Cosumnes River channel and floodplain areas following levee breaching in Fall 2014, and subsequent winter flooding in Winter 2015. Topographic data were gathered using multiple data collection platforms, including Topcon HiperLite + and HiperV realtime kinemetic Global Positioning System (rtkGPS) survey equipment and Structure from Motion (SfM) photogrammetry techniques using a Canon S100 digital camera mounted on a DJI Phantom 1 unmanned aerial vehicle (UAV). Images used in SfM photogrammetry were processed in Agisoft Photoscan Professional.

Floodplain topographic survey data were collected at Sites U and L (Figure 3) in Fall 2014, enabling the development of digital elevation models (DEMs) of each breach site prior to flooding in Winter 2015. At Site U, 9277 ground-based rtkGPS survey points were collected across the approximately 50 000 m^2 breach site, with sampling density greatest in floodplain areas exhibiting more pronounced topographic variability. Much of Site U was uniformly graded during levee breaching activities, allowing wide spacing of data collection points.

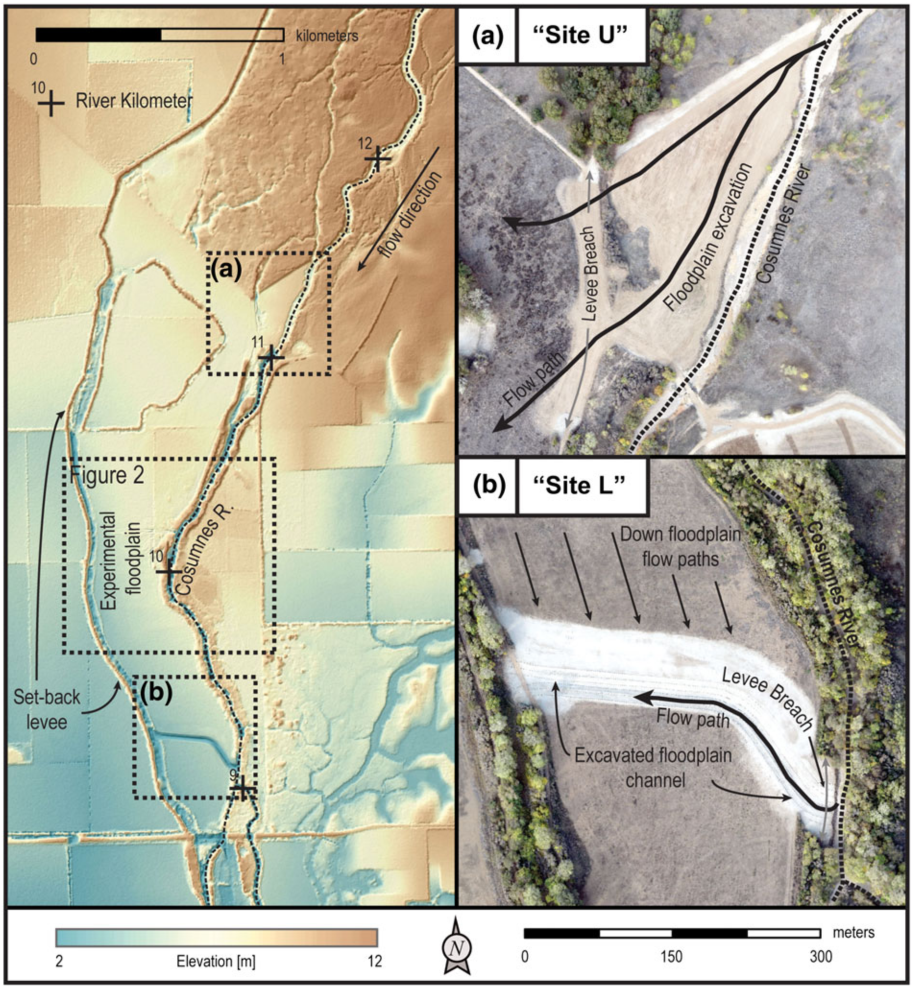

FIGURE 3 Configuration of experimental levee breach and floodplain grading designs adjacent to the Cosumnes River. At site U (panel a), more than 250 m of riverside levee was removed, and much of a floodplain terrace was excavated and graded to match elevations of adjacent agricultural fields. At site L (panel b), 75 m of riverside levee was removed, and a 2-m-deep channel was excavated across the entire experimental floodplain [Colour figure can be viewed at wileyonlinelibrary.com]

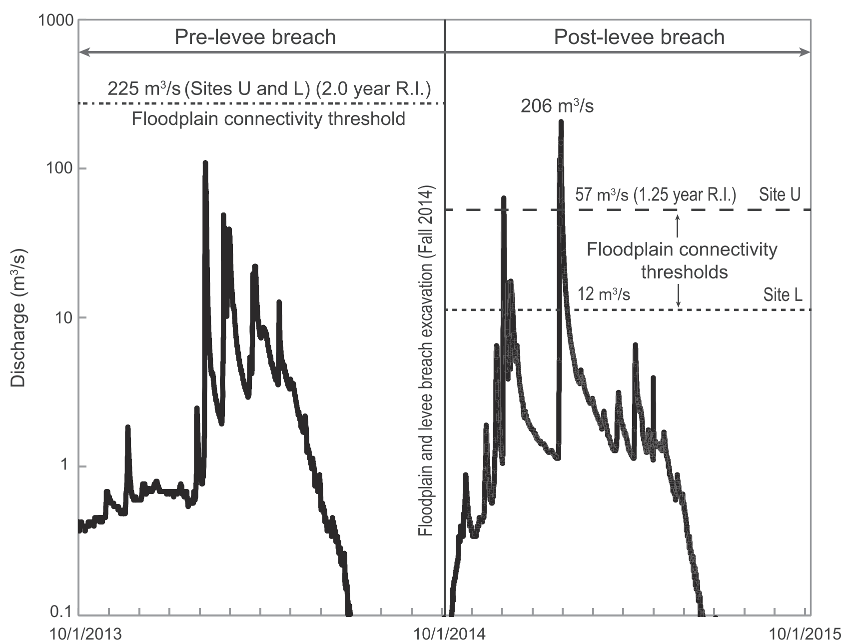

FIGURE 4 The Cosumnes River exhibits a largely unimpaired hydrograph. Levee breaching in Fall 2014 reduced flood connectivity thresholds at both levee breach sites from 225 to 57 m^3/s (site U) and 12 m^3/s (site L)

Using rtkGPS survey topographic data, a 1-m resolution DEM was generated in ArcGIS (v. 10.3. ESRI, Redlands, CA), following methods described in Wheaton, Brasington, Darby, and Sear (2010). At Site L, topographic data were generated using SfM photogrammetry techniques, from which a 0.1-m resolution DEM was generated for the approximately 40 000 m^2 breach site and floodplain channel excavation. Comparison of the SfM-generated DEM and 4152 ground control points (GCPs) collected during rtkGPS surveys produced residuals of ±0.03 m. The SfM DEM was used as a pre-flood topographic baseline because the higher resolution of DEM better characterized the sloping topography of the new floodplain channel. Following flooding in February 2015, repeat topographic surveys were performed. Ground-based rtkGPS survey points were collected at Sites U (n = 35 625) and L (n = 12 723). Survey point densities were greatest in areas where floodplain erosion or aggradation was observed. Post-flood, 1-m resolution DEMs were constructed for each site following methods outlined by Wheaton et al. (2010) (Figures 5 and 6).

Topographic changes at Sites U and L were mapped to identify and quantify spatial patterns in floodplain erosion and deposition. Digital elevation models (DEMs) of Difference (DoD) were created for each site by extracting elevations (m) from the pre-breach DEM (2014) using post-breach (2015) topographic ground survey points. Simple differencing quantified the elevation change, either positive or negative, at each 2015 ground survey point. Subsequently, a 1-m resolution DoD was generated from differenced point values for each breach site (see Figures 5 and 6). Net volumetric change of floodplain sediment was calculated by multiplying the elevation change at each DoD cell by the surface area of that cell (i.e. 1 m^2), and subsequently integrating those factors across the floodplain sites. To assess the level of detection for topographic change, a spatially uniform error of 0.02 m was assumed for all SfM and rtkGPS topographic measurements based on reported accuracy of the rtkGPS equipment. The propagated error across both measurement periods (following Brasington, Rumsby, & McVey, 2000) was 0.028 m.

To assess channel bed morphology changes following levee breaching, longitudinal profiles of the Cosumnes River channel thalweg were surveyed using rtkGPS between river kilometers (RK) 9 and 13 (see Figure 3) in the summers of 2013 and 2015. The 2013 profile identified pre-breach channel thalweg elevations adjacent to the experimental floodplain site, while the 2015 survey captured post-breach channel thalweg elevations.

4 | RESULTS

4.1 | Floodplain geomorphic change

Post-levee breach flooding produced varied patterns of floodplain topographic change. At both breach sites, February 2015 flood magnitudes (206 m^3/s; see Figure 4) exceeded sediment transport thresholds necessary to transport sand and small gravel from the Cosumnes River onto the adjacent floodplain areas. Herein, we describe the patterns of topographic change at Sites U (wide levee breach; graded floodplain)

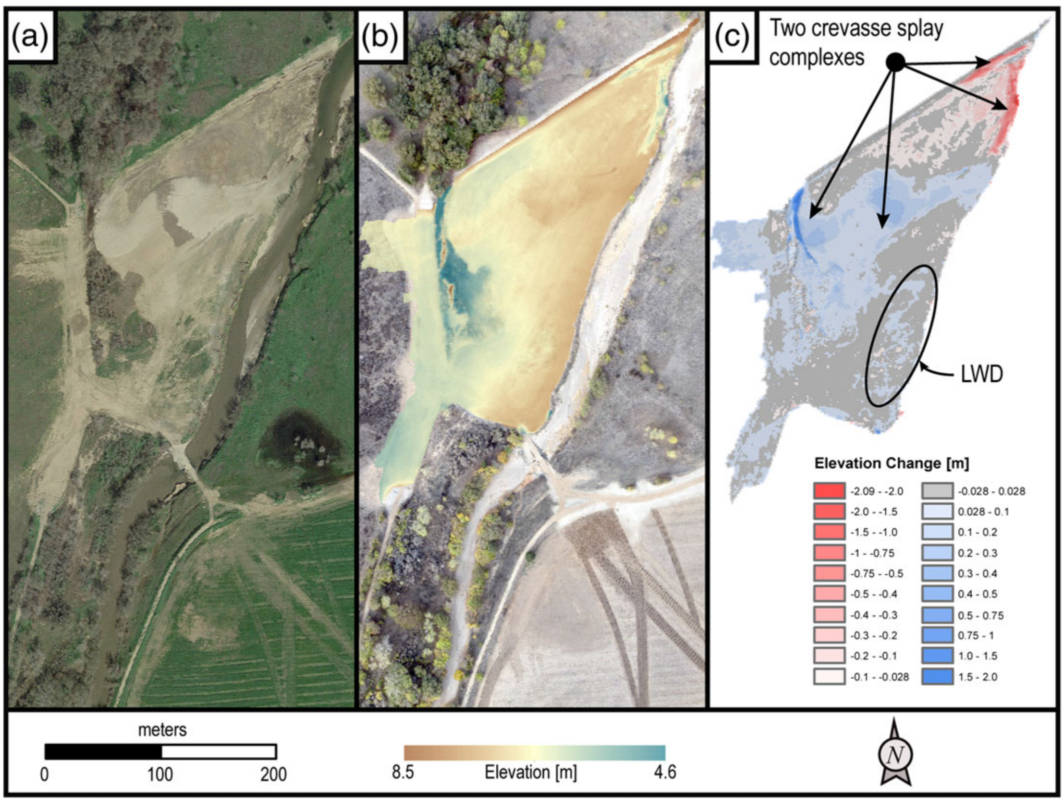

FIGURE 5 Levee breach site U along the lower Cosumnes River. (a) Aerial photograph following February 2015 flooding; (b) digital elevation model (DEM) of post-flood topography; (c) DEM of difference (DoD) identifying spatial patterns of floodplain deposition and erosion [Colour figure can be viewed at wileyonlinelibrary.com]

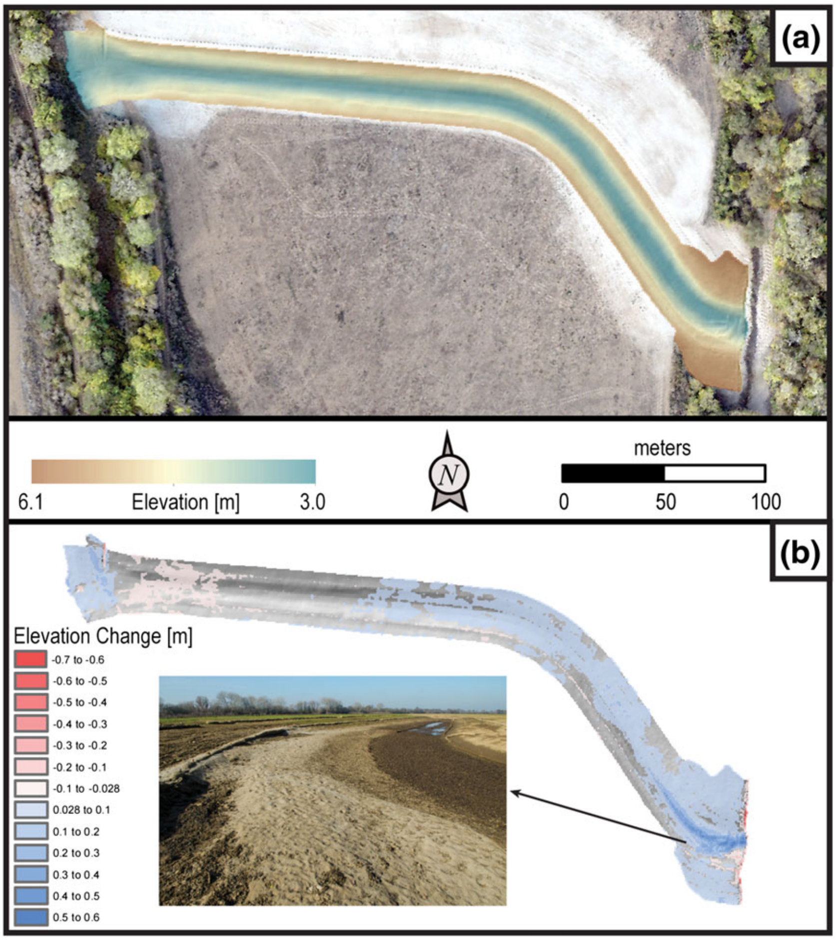

FIGURE 6 Levee breach site L along the lower Cosumnes River. (a) Digital elevation model (DEM) of post-flood topography; (b) DEM of difference (DoD) identifying spatial patterns of floodplain deposition and erosion [Colour figure can be viewed at wileyonlinelibrary.com]

and L (narrow levee breach; excavated floodplain channel) observed following the initial flood season in 2015.

4.2 | Site U (wide breach + floodplain grading)

Following 4 days of flooding in 2015, Site U exhibited multiple floodplain erosional and depositional features, resulting in complex spatial patterns of floodplain topographic relief dominated by the development of two crevasse splay complexes (Figure 5). Floodplain erosion characterized topographic change in the northeastern (upstream) corner of the floodplain excavation (Figure 5c). At this location, on the outer bank of a bend in the Cosumnes River, high-velocity transverse currents created two dominant flowpaths extending across the river bend and onto the graded floodplain. Two distinct erosional crevasses developed along these dominant floodplain flow paths, with depths of erosion exceeding 2 m in areas near the channel bank (Figure 5c). Both crevasses exhibited infilling with coarse sand, likely deposited during the falling limb of the flood hydrograph. In down-floodplain areas, overlapping, fan-shaped sand splays developed. The depositional splays exhibited a hummocky topography not incised by secondary channels. The overlapping splay bodies prograded more than 200 m from the bank of the Cosumnes River, with the largest amount of deposition (~ 1.75 m) observed where the toe of a prograding sand splay filled a pre-existing floodplain channel (Figures 5c and 7). Additionally, large woody debris (LWD) and diffuse patches of fine sediment accumulated in the southeast corner of the floodplain excavation, particularly along the channel bank. Net volumetric change at Site U in 2015 was 943 ± 63 m^3, identifying a general pattern of floodplain aggradation during the flood event.

4.3 | Site L (narrow breach + floodplain channel excavation)

Following 13 days of flooding in 2015, Site L exhibited floodplain topography changes dominated by bank erosion at the levee breach site and sediment deposition within the excavated floodplain channel (Figures 6 and 7). At the breach site, lateral bank erosion resulted in floodplain elevation losses that reached −0.64 m (Figure 6b). Floodplain erosion was also observed on the downstream edge of the channel excavated into the levee breach, where erosive helical flow paths developed as floodwaters from the Cosumnes River entered the excavated floodplain channel. Small amounts of erosion (−0.1 to −0.2 m) were also observed along the western portions of the floodplain channel (Figure 6b). This concentrated zone of floodplain erosion was located along the apparent pathway of highest velocity floodwater from upstream portions of the experimental floodplain site.

Sediment deposition dominated floodplain topography changes at Site L in 2015. Within the mouth of the floodplain channel, more than 0.48 m of sediment aggradation was observed (Figures 6b and 7). This zone of concentrated sediment aggradation (>0.2 m) prograded only 50 m into the excavated floodplain channel, with diffuse areas of fine sediment deposition observed more than 150 m from the levee breach

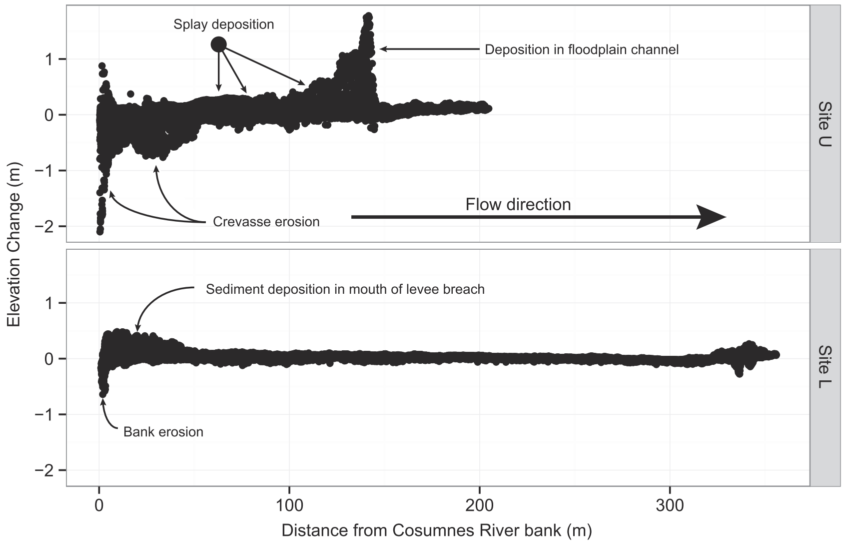

FIGURE 7 Longitudinal distribution of topographic changes at levee breach sites U and L. Distances are measured from the bank of the Cosumnes River

site (Figures 6b and 7). Additionally, a localized area of sediment aggradation was observed at the western edge of the excavated floodplain channel, where the channel enters a pre-existing borrow ditch at the base of the set-back levee bounding the western edge of the experimental floodplain restoration site. Net volumetric change in sediment at Site L in 2015 was 319 ± 21 m^3, identifying net floodplain aggradation. Sediment aggradation was predominantly located within the excavated floodplain channel. Minimal overbank sediment deposition was observed on floodplain areas adjacent to the excavated channel.

4.4 | Channel thalweg

The Cosumnes River near Site U developed distinct zones of channel incision and aggradation following flooding in 2015. Thalweg incision was observed throughout the channel reach extending ~0.5 km upstream from the floodplain excavation (Figure 8). In some localities, the channel incised more than 2 m, often extending through both sandy, alluvial bedforms and underlying, erosionally resistant duripan layers generally thought to limit channel bed incision throughout the lower Cosumnes River (Constantine et al., 2003). Adjacent to the floodplain excavation, at Site U, thalweg profile data identified a gradual downstream progression of channel aggradation. Downstream from the floodplain excavation, the Cosumnes River channel bed aggraded more than 0.75 m, likely in response to a localized reduction in sediment transport capacity due to the loss of stream power downstream from the breach site. Thalweg elevation change was not observed near Site L between 2013 and 2015.

5 | DISCUSSION

5.1 | Floodplain topography

Intentional breaching of riverside levees along the lower Cosumnes River has proven an effective method to generate hydrogeomorphic processes necessary to promote topographic variability critical for floodplain habitat restoration. Following levee-breach experiments in the late-1990s, Florsheim and Mount (2002) presented a conceptual model for the generation of floodplain topography at engineered levee breach sites, which has guided expectations of floodplain topography responses to intentional levee breaches elsewhere along the Cosumnes River. It has also highlighted the efficacy of using intentional

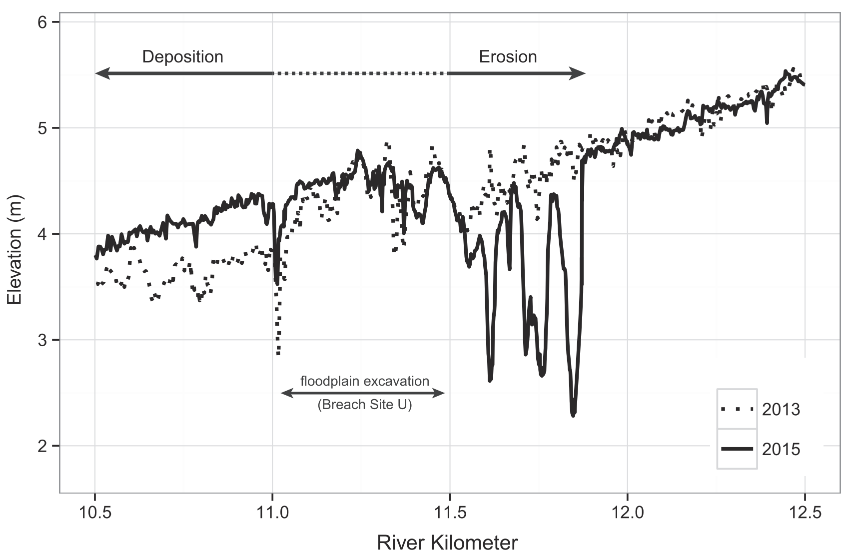

FIGURE 8 Cosumnes River channel thalweg elevation profiles surveyed with an rtkGPS in 2013 (pre-levee breach) and 2015 (post-levee breach). The profiles extend upstream and downstream of the levee breach site U floodplain excavation (see Figure 3)

levee breaches to initiate process-based restoration of floodplain riparian and wetland ecosystems (Mount et al., 2002), in concert with, or in lieu of, labor-intensive horticultural approaches (Reiner, 1996; Swenson et al., 2003; Swenson et al., 2012). However, this existing model of floodplain topography change in response to intentional levee breaching was derived from a largely uniform starting point: narrow levee breaches (<75 m) opening onto graded floodplain areas. Interestingly, breaches within both natural (e.g. Farrell, 2001) and engineered levees/dykes (e.g. Arnaud-Fassetta, 2013) along large alluvial rivers in North America and Europe are typically narrow (<100 m). Herein, we use new field observations to expand on Florsheim and Mount's (2002) conceptual model to include two different starting points for levee breach architecture: (i) narrow breaches (<75 m) opening into excavated floodplain channels; and (ii) wide breaches (>250 m) opening onto graded floodplains. All three models of engineered levee breaches are presented in Figure 9.

5.2 | Narrow breach opening onto a graded floodplain

As described by the conceptual model of Florsheim and Mount (2002), narrow engineered levee breaches adjacent to graded floodplain areas produce crevasse splay complexes similar to those described following unplanned breaches of both engineered levees/dykes (e.g. Arnaud-Fassetta, 2013; Bristow et al., 1999) and natural levees (Farrell, 2001; Smith et al., 1989). The confinement of flow through narrow breaches elevates hydraulic head. This, combined with the tendency for water flowing through the crevasse to be under capacity due to its sourcing from streamflow high in the water column that contains limited suspended sediment (Slingerland & Smith, 1998), promotes floodplain scour at the breach location (i.e. a 'crevasse') and the advective transport of both bedload from the main river channel and sediment scoured from the floodplain into distal floodplain areas. Floodplain flow expansion and consequent reduction in flow velocity promote the deposition of sediment in lobate sand bodies (i.e. 'splays') (Figure 9a). These depositional sand splays thin in the down-floodplain direction and typically exhibit down-gradient textural fining. Further, multiple channels develop on incipient splays, often flanked by lateral levees. Over multiple floods, numerous sand lobes and splay channels develop as sand splays aggrade vertically and prograde down the floodplain, producing the 'Stage I' crevasse splay complexes described by Smith et al. (1989). The principal characteristics of this model of floodplain topography change following levee breaching are a single crevasse at the breach location, and a single sand splay that is reworked during successive flood events.

Similar crevasse splay morphologies are observed at natural levee breaches along the lower Cosumnes River, where breach widths are typically quite narrow (<25 m) (see Figure 2). Observations from such narrow, natural breaches along the lower Cosumnes River suggest complex morphological evolution histories, where some breaches alluviate (i.e. 'heal'), and some maintain an equilibrium form where the sediment carrying capacity of the crevasse channel largely equals the incoming sediment flux. Slingerland and Smith (1998) suggest that the tendency of a breach to heal, maintain an equilibrium form, or continue to enlarge is controlled by the ratio of crevasse to main channel bed slopes, and the difference in elevation between the lip of the crevasse and the bottom of the main river channel. Along the lower Cosumnes River, the low slopes of crevasse channels relative to the slope of the main channel, and extensive main-channel incision, both promote crevasse (i.e. breach) healing and help to prevent channel avulsion and the development of anastomosing channel systems [e.g. Stage II and III splays described by Smith et al. (1989)] in floodplain breakout areas.

5.3 | Narrow breach opening into an excavated floodplain channel

The first new addition to Florsheim and Mount's (2002) conceptual model included variation in response to the excavation of a floodplain channel inboard from a narrow levee breach. Observations from Site L

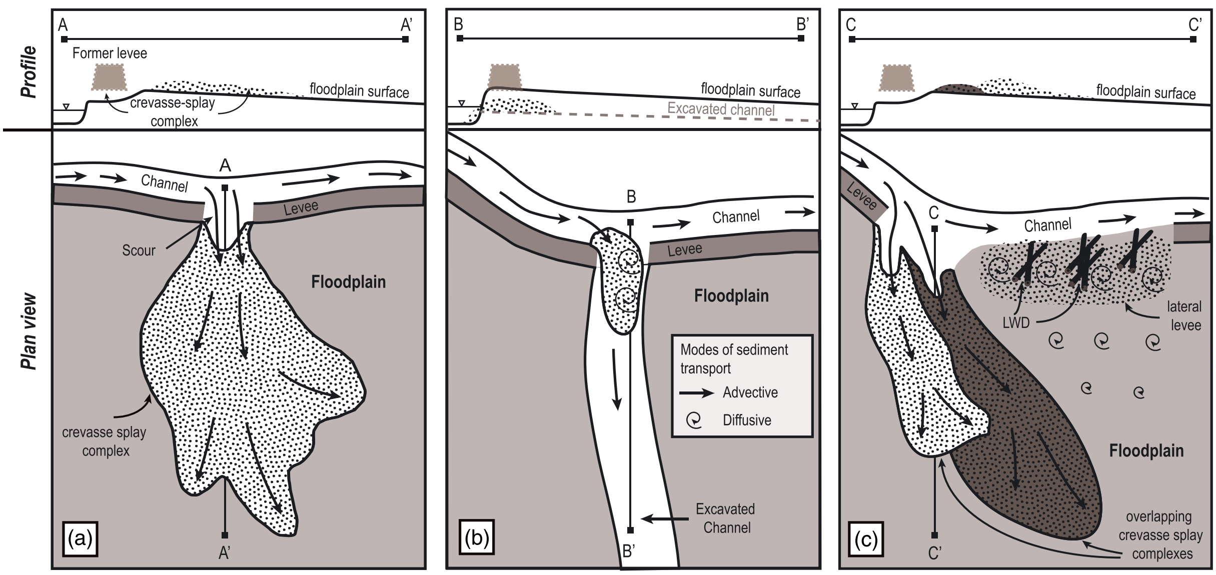

FIGURE 9 Conceptual models of floodplain topography changes to varying levee breach geometries [adapted from Florsheim and Mount (2002)]: (a) narrow breach (<75 m) opening onto a graded floodplain; (b) narrow breach (<75 m) opening into an excavated floodplain channel; (c) wide levee breach (>250 m) opening onto a graded floodplain [Colour figure can be viewed at wileyonlinelibrary.com]

indicate the concurrent excavation of a narrow levee breach and large floodplain channel promoted sediment deposition at the breach site and minimal advection of sediment to distal parts of the floodplain channel. At Site L, connectivity between the floodplain channel and the Cosumnes River was achieved at 12 m^3/s. This is due to the base of the floodplain channel being at an elevation less than 1 m higher than that of the Cosumnes River channel thalweg adjacent to the levee breach (Figure 9b). The entire excavated floodplain channel became submerged under floodwaters at discharges approaching 60 m^3/s, well below discharge thresholds (100 m^3/s) needed to transport sediment from the lower Cosumnes River onto adjacent floodplains (Florsheim, Mount, & Constantine, 2006). Thus, once bedload began to move within the main Cosumnes River channel, down river and down floodplain gradients were approximately equal, largely precluding advective sediment transport from the river into the floodplain channel. As such, diffusive sediment transport appeared to dominate, facilitating near bank depositional processes and aggradation in the mouth the excavated floodplain channel.

Hydrodynamic and sediment transport modeling work by Gaweesh and Meselhe (2016) can be used to explain how the engineered form of the breach at Site L promoted breach alluviation. An alignment angle of the floodplain channel >90° created helical velocity patterns at the breach, resulting in increased near-bed transverse velocities and subsequent transport of medium and coarse sand from the Cosumnes River into the floodplain channel. Additionally, the elevated ratio of floodplain channel depth versus main channel depth at Site L helped to maximize sediment capture by the floodplain channel. However, the filling of the floodplain channel and surrounding floodplain areas prior to the exceedance of sediment transport thresholds in the Cosumnes River largely equalized main channel and cross-floodplain water surface gradients, precluding gradient advantages needed to advect medium to coarse sand from the main Cosumnes River channel more than 50 m into the excavated floodplain channel.

Existing models of channel avulsion also provide insight into the dominantly aggradational sediment regime observed at breach Site L. Slingerland and Smith (2004) suggest comparing the ratio of water surface slopes in each trunk of a bifurcating channel [$S_c/S_{m;}$ c = crevasse (or breach) and m = main stem] to the ratio of the lip height of the crevasse (or breach) throat (l) and water depth in the main channel (H) (l/H) to predict whether a channel will avulse through a new crevasse/breach, or if the breach will 'heal' through infilling. During flooding at breach Site L in 2015 (~206 m^3/s), S_c/S_m approached 1, while l/H approached 0.15, suggesting the breach would likely 'heal' (Slingerland & Smith, 2004). The observed sediment aggradation at the breach site suggests that hydraulic conditions at the site are not favorable to channel avulsion, and that the breach will fill as sediment is transversely advected from the Cosumnes River into the floodplain channel. The breach will likely aggrade over time, increasing flow connectivity thresholds between the main channel of the Cosumnes River and the excavated floodplain channel.

5.4 | Wide breach opening onto a graded floodplain

The second new addition to Florsheim and Mount's (2002) conceptual model included the excavation of a wide levee breach adjacent to a graded floodplain that promoted complex floodplain hydraulic and sediment transport conditions. At the upstream edge of the floodplain excavation at levee breach Site U, near-bank crevasse development and distal sand splay deposition mimicked observations from narrow levee breaches along the lower Cosumnes River (Figure 9a). However, without flow confinement within a narrow levee breach (e.g. Florsheim & Mount, 2002), multiple preferential flow paths established. Dominant flow paths formed on the outer bank of a bend in the Cosumnes River (see Figure 3a). Thus, instead of the development of a single crevasse splay complex, multiple and overlapping crevasse splay complexes formed on the graded floodplain. Advective transport of water and sand dominated sediment transport conditions in this portion of the graded floodplain.

Diffusive transport of water, sediment, and debris appeared to dominate hydrogeomorphic conditions in downstream portions of the graded floodplain (Figure 9c), where neither near-bank crevasses or distal sand splays developed. Instead, LWD was deposited along the channel bank, with patches of sand found on the downstream side of the LWD piles. It is likely that this aggregation of LWD and sediment along the channel bank is the incipient stage of lateral levee development (sensu Adams, Slingerland, & Smith, 2004). This suggests the wide levee breach may narrow over time, with newly formed natural levees confining flow and sediment transport to the northern portion of the floodplain excavation.

5.5 | Channel thalweg incision

Width of levee openings have implications for in-channel processes. Pronounced channel incision upstream from Site U (see Figure 8) suggests the diversion of a large percentage of flow from the main Cosumnes River channel through the wide levee breach changed local hydraulic conditions in a way that promoted rapid channel bed erosion. Water surface elevation data from the breach site (RK 11; see Figure 8) prior to and following levee breaching indicates that the new diversion reduced the peak water surface elevation during the 206 m^3/s flow event by approximately 0.5 m. While a discharge of 206 m^3/s greatly exceeded the post-breach channel capacity at the breach site (57 m^3/s), it was less than the channel capacity (225 m^3/s) of the incised channel reach upstream from the levee breach site. We hypothesize that during this flood event, the diversion of water through the wide levee breach promoted the drawdown of the water surface immediately upstream (M2 water surface profile) (Brown et al., 2013), causing localized flow acceleration and channel bed erosion (Lamb, Nittrouer, Mohrig, & Shaw, 2012).

Simplified channel geometries and flow conditions can be used to illustrate how the diversion of water through the wide levee breach promoted water surface drawdown (Figure 10) and channel incision. Consider a channel of uniform width and constant bed slope. Upstream from the breach location, the 206 m^3/s flow was contained within the channel and normal flow conditions existed. Prior to levee breaching, these normal flow conditions extended across the entire channel reach depicted in Figure 10, largely creating a sediment bypass reach. However, the post-breach reduction of water surface elevations at the levee breach site caused water depths at the breach site (H_1 in Figure 10) to be less than the normal flow depth (H_n in

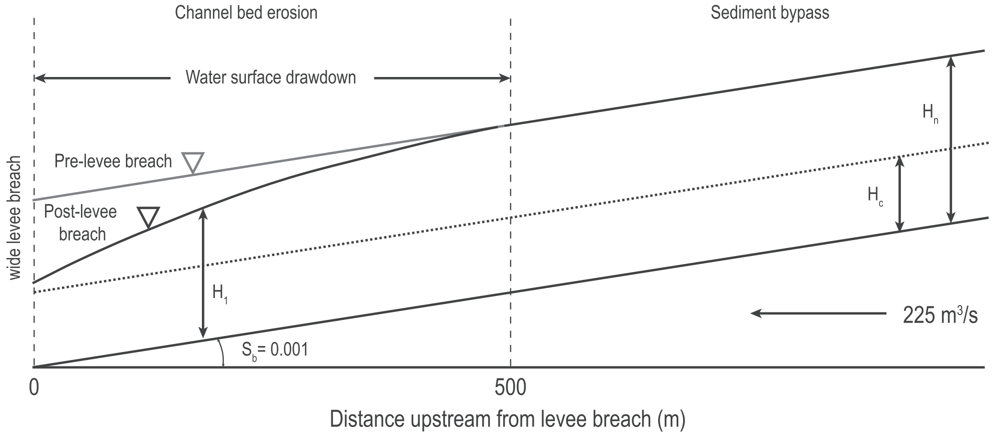

FIGURE 10 Conceptualized model of water surface drawdown conditions at site U during high flow conditions (modified from Lamb *et al.*, 2012). The diversion of flow from the main Cosumnes River channel moderates water surface elevations at the breach site relative to pre-breach conditions. During high flow events (e.g. 225 m^3/s), normal flow depths at the breach site (H_1) are less than normal flow depths in the channel upstream (H_n), promoting water surface drawdown, flow acceleration, and channel bed erosion across an approximately 0.5-km channel reach upstream from the levee breach site

Figure 10) upstream. The downstream reduction in flow depth created a water surface drawdown zone, forcing flow acceleration and concomitant channel bed incision. This observation is generally analogous to flow acceleration and channel bed scour observed at the mouth of the Mississippi River when water surface drawdown conditions establish during high flows (Lamb et al., 2012; Nittrouer, Shaw, Lamb, & Mohrig, 2012).

While minor channel bed erosion has been noted upstream from several levee breach sites along the lower Cosumnes River (Florsheim et al., 2006), such pronounced erosion as has occurred upstream from levee breach Site U has not been previously observed upstream from existing narrow levee breach sites (accidental or intentional). This suggests that by diverting volumetrically more flow from the Cosumnes River relative to narrow breach sites, the wide breach at Site U was able to dramatically alter local water surface profiles and promote channel incision upstream. This is a novel conclusion with important implications for floodplain management and went undetected in pre-project modeling simulations.

5.6 | Floodplain management implications

Intentional levee breaching and the reintroduction of hydrogeomorphic processes to formerly isolated floodplains along the lower Cosumnes River have proven effective strategies for restoring floodplain ecosystems (Swenson et al., 2003; Swenson et al., 2012). Principal responses to levee breaching along the Cosumnes River include increased floodplain topographic heterogeneity (e.g. Florsheim & Mount, 2002), riparian tree recruitment and growth (e.g. Trowbridge, 2007; Viers et al., 2012), groundwater recharge (pers. comm. G. Fogg, 2016), and potential reduction of flood hazards.

Observations from almost three decades of intentional levee breach experiments provide a foundation of knowledge that can help guide future levee breach efforts along the Cosumnes River and other low gradient waterways. First, each new levee breach helps to reduce water surface elevations during floods, with the magnitude of the reduction dependent on how much of the river's flow can be diverted through a levee breach. This study identified a more the 0.5-m reduction in peak flood stage for a 2.0-year RI flood following the excavation of a wide levee breach at Site U. Field observations suggest that routing of flood waters through the wide breach at Site U increased flooding thresholds at downstream levee breach locations (see Figure 2), indicating cumulative downstream effects from levee breaching and intentional floodplain reconnection. Our observations suggest that wider levee breaches have a greater capacity to mitigate flood hazards.

While wide levee breaches appear to most effectively reduce river stage during flooding, the cost of additional earthwork activities relative to narrow breaches and potential for upstream channel incision and downstream channel aggradation must be weighed against desired outcomes of hydrogeomorphic restoration activities. Furthermore, observations from the Cosumnes River Preserve suggest that the areal extent of sand splay deposition (a proxy for riparian tree recruitment) does not correlate with breach width. An explicit statement of desired outcomes from levee removal can help in the design of breach geometry and location. For example, wide levee breaches opening onto large floodplain areas that fill slowly may be appropriate for projects with explicit downstream flood protection goals. However, such designs must recognize the potential for dynamic channel morphology responses, and possible reduced riparian tree recruitment per unit dollar, relative to narrower and less expensive breach alternatives. It should also be noted that downstream flood attenuation implies that breach activities along a given river should begin in downstream locations, to maximize the depth and velocity of water flowing through the breach and potential for geomorphic work such as sand splay deposition. Following desired floodplain ecosystem responses at a downstream site, upstream breaches can be sequentially excavated, providing additive flood hazard mitigation, without compromising water depths and velocities through the newly excavated breaches during flood events.

6 | CONCLUSIONS

Hydrogeomorphic observations following several decades of levee breaches along the lower Cosumnes River suggest that levee breach architecture influences hydrologic and geomorphic process on newly accessible floodplain areas and adjacent channel reaches. Narrow levee breaches (<75 m wide) opening onto a graded floodplain produce a single crevasse splay complex that progrades down the floodplain through advective sediment transport processes. Decades of observations suggest that these breaches remain open and splay complexes continue to build over time, helping to promote the growth of complex floodplain and riparian ecosystems. Conversely, recent observations suggest that at a narrow breach site opening into an excavated floodplain channel, the filling of the floodplain channel and surrounding floodplain areas with water prior to the exceedance of sediment transport thresholds precluded gradient advantages needed to preferentially and directly advect water and sediment into the floodplain channel. Consequently, both transverse advection and turbulent diffusion appeared to transport sediment into the breach mouth, promoting sediment deposition and possibly breach closure over time.

A wide breach (>250-m width) opening onto a graded floodplain promoted unique hydrogeomorphic responses on the newly accessible floodplain and within the adjacent channel. Multiple floodplain flow paths advectively transported water and sediment onto the graded floodplain, helping to form multiple and overlapping crevasse splay complexes oriented along these flow paths. Additionally, turbulent diffusion processes also transported sediment and large wood onto the floodplain, helping to form incipient lateral levees. Because of the large volume of water diverted from the main channel through the wide levee breach during high flow events, water surface drawdown conditions developed upstream from the breach site, promoting flow acceleration and channel incision. We conclude that wide levee breach architecture promoted unique floodplain hydrogeomorphic changes not previously observed at narrow breach locations along the Cosumnes River and other locations globally, extending the generalized crevasse splay conceptual model first proposed by Florsheim and Mount (2002).

Levee breach architecture clearly affects floodplain and channel hydrogeomorphic processes. This evolving understanding of hydrologic and geomorphic responses to varying levee breach architectures can help floodplain restoration managers worldwide better predict physical responses to levee breach experiments and avoid unintended, and possibly undesirable, consequences of well-intentioned restoration actions.

ACKNOWLEDGEMENTS

We would like to thank The Nature Conservancy and other partners at the Cosumnes River Preserve for logistical assistance, support, and site access. We greatly appreciate the work of many field assistants, including Eric Holmes, Devon Lambert, Kyle Phillips, Jeff Laird, and Jenny Ta. We would also like to thank the anonymous reviewer whose feedback improved the manuscript. This work was funded under the California Department of Fish and Wildlife (CDFW) Ecosystem Restoration Program (ERP) Grant # E1120001, in cooperation with The Nature Conservancy (TNC) and Cosumnes River Preserve affiliates. Finally, we wish to state that there is no conflict of interest associated with this research and manuscript.

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How to cite this article: Nichols AL, Viers JH. Not All Breaks are Equal: Variable Hydrologic and Geomorphic Responses to Intentional Levee Breaches along the Lower Cosumnes River, California. *River Res Applic*. 2017;0:1–13. https://doi.org/10.1002/rra.3159