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Authors

Gervasi, Arielle A
Pasternack, Gregory B
East, Amy E

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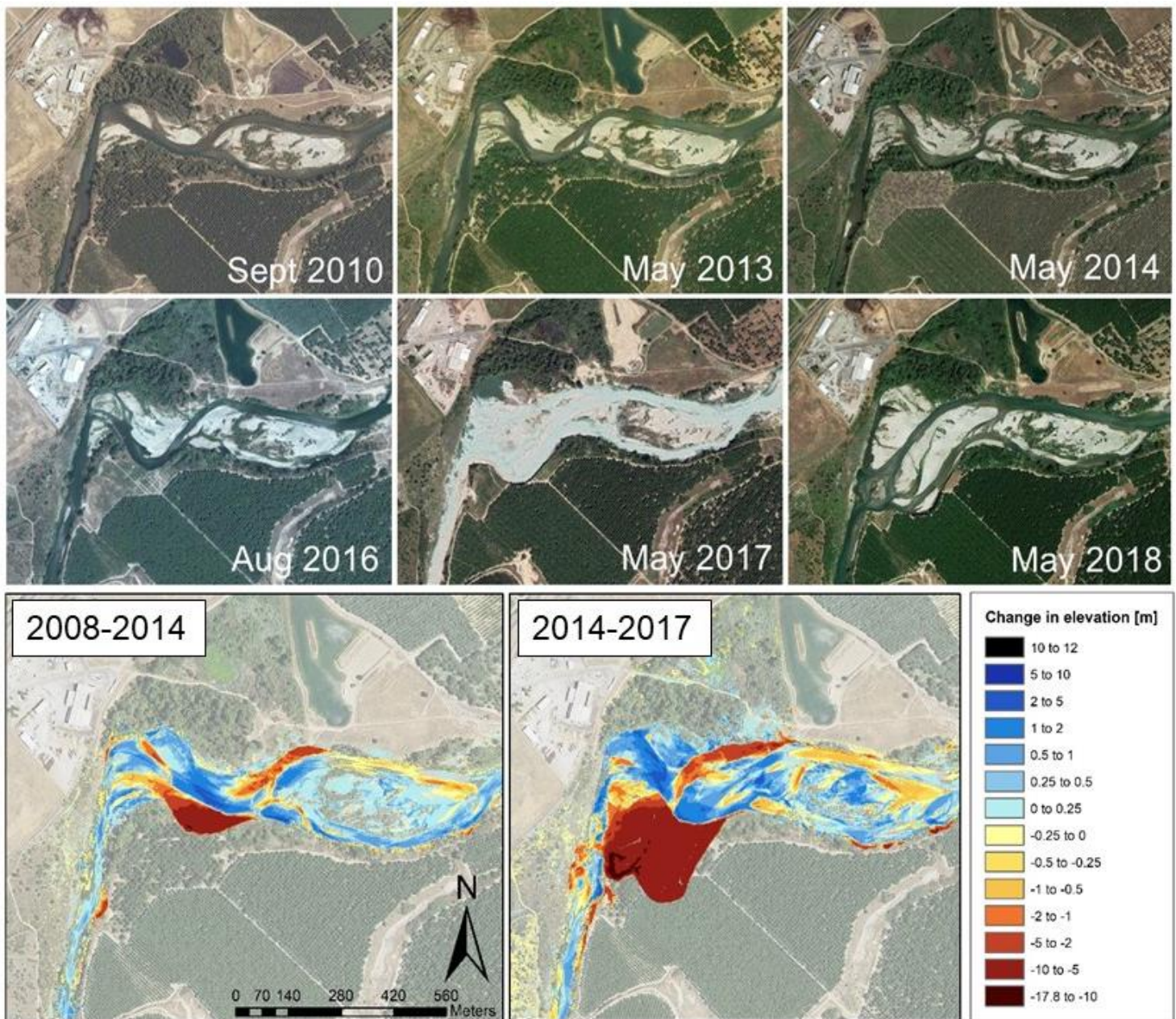
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The data associated with this publication are available upon request.

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**Flooding duration and volume more important than peak discharge in explaining
18 years of gravel-cobble river change**

Arielle A. Gervasi^{a*}, Gregory B. Pasternack^a, Amy E. East^b

^aUniversity of California, Davis, One Shields Avenue, Davis, CA 95616, USA

^bU.S. Geological Survey, Pacific Coastal and Marine Science Center, 2885 Mission St.,
Santa Cruz, CA 95060, USA

* Corresponding author. Tel.: +1 (253) 468-6097

E-mail: arielle.gervasi@gmail.com

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Abstract

Floods play a critical role in geomorphic change, but whether peak magnitude, duration, volume, or frequency determines the resulting magnitude of erosion and deposition is a question often proposed in geomorphic effectiveness studies. This study investigated that question using digital elevation model differencing to compare and contrast three hydrologically distinct epochs of topographic change spanning 18 years in the 37-km gravel-cobble lower Yuba River (LYR) in northern California, USA. Scour and fill were analyzed by volume at segment and geomorphic reach scales. Each epoch's hydrology was characterized using 15-minute and daily averaged flow to obtain distinct peak and recurrence, duration, and volume metrics. Epochs 1 (1999-2008) and 3 (2014-2017) were wetter than average with large floods reaching 3,206 and 2,466 m³/s, respectively, though of different flood durations. Epoch 2 (2008-2014) was a drought period with only four brief moderate floods (peak of 1,245 m³/s). Total volumetric changes showed that major geomorphic response occurred primarily during large flood events; however, total scour and net export of sediment varied greatly, with 20 times more export in epoch 3 compared to epoch 1. The key finding was that greater peak discharge was not correlated with greater net and total erosion; differences were better explained by duration and volume above floodway-filling stage. This finding highlights the importance of considering flood duration and volume, along with peak, to assess flood magnitude in the context of flood management, frequency analysis, and resulting geomorphic changes.

I. Introduction

What controls topographic change in a river? Fundamentally, change is measured as any positive or negative change in elevation (deposition and erosion, respectively) that occurs within the maximum boundaries of wetted extent over a designated period of time. Some broad physical controls on topographic change in fluvial systems include catchment-scale valley and channel topography (Montgomery, 1997; Peckham, 2003), sediment supply and bedload grain size (Carling 1988; Dietrich *et al.*, 1989), vegetation roughness/distribution and woody debris (Lancaster *et al.*, 2003; Abu-Aly *et al.*, 2014), and hydrologic regime (Poff *et al.*, 1997). Beyond these natural drivers, nearly all modern rivers change in response to human development including dams, channelization, mining, agriculture, or water extraction (e.g., Brown *et al.*, 2017). Typical effects downstream of damming, for example, include channel narrowing, coarsening of bed substrate material, and channel incision, as well as altered hydrologic regime due to flow regulation (Williams & Wolman, 1984; Grant *et al.*, 2003; Schmidt & Wilcock, 2008). Lane (1955) identified the balance between discharge characteristics and sediment supply as the key in determining channel incision or aggradation trajectory. More recently, East *et al.* (2018a) asserted that understanding channel response to sediment-supply disturbance is still one of the longest-standing problems in geomorphic process studies and is critical to understanding anthropogenic effects on watersheds.

Fluvial geomorphologists link 'cause' and 'effect' by quantifying the ability of hydrologic discharge to do work on a landscape through metrics such as shear stress

(DuBoys, 1879), unit stream power (Bagnold, 1977), and geomorphic effectiveness (Wolman & Miller, 1960). Holding grain size and density constant, uniform channel dynamics equations dictate that higher peak flow leads to more erosion, as shear stress and total bed load transport scale proportionally with discharge. Conversely, geomorphic effectiveness studies have implicated flooding duration and energy as the primary metrics that determine the magnitude of resulting topographic changes (Lisenby *et al.*, 2016). The relative roles and importance of different discharge metrics are unclear. The overall goal of this study is to evaluate whether flooding peak flow, duration, or volume drives more topographic change in a gravel-cobble river setting, while accounting for other non-hydrologic and topographic influences within the study setting.

Topographic change processes in rivers

By measuring spatial patterns and temporal dynamics of erosion and deposition, fluvial geomorphologists infer topographic change mechanisms. Studies in fluvial geomorphology and morphodynamic theory have historically proposed, defined, and quantified mechanisms controlling change in response to topographic forcing or hydrologic events to explain why rivers change the way they do, with the ultimate prospect of predicting how rivers will change using morphodynamic models (e.g., Costa & O'Connor, 1995; Dean *et al.*, 2016; East *et al.*, 2018b; Hooke, 2015; Kleinhans, 2010; Magilligan *et al.*, 2015; Pasternack & Wyrick, 2016). Overall, fluvial topographic change processes (e.g., knickpoint migration, lateral channel migration, channel downcutting,

floodplain aggradation) are governed by the interplay of hydrodynamic processes (e.g., particle trapping, eddying, backwatering) and the topographic structure controlling the river at various stages, as well as by sediment supply input (e.g., Figure 1). Predictive morphodynamic models for unsteady, non-uniform flow conditions (such as those encountered in most rivers, in contrast with flume experiments) are progressing but exclude important processes and produce results with large uncertainties. Model advancements require more observational understanding to guide their progress (Kleinhans, 2010; Weber & Pasternack, 2017).

The differencing of sequential digital elevation models (DEMs) with an accounting of uncertainty achieves the gold-standard of characterizing spatially explicit river changes to evaluate geomorphic processes from point scale to cross-section scale up to segment (entire river) scale and quantify volumetric changes (Montgomery, 2003; Wheaton *et al.*, 2010; James *et al.*, 2012; Cavalli *et al.*, 2017; Calle *et al.*, 2020). Studies employing DEM of Difference (DoD) rasters have highlighted the importance of nested valley topology, topographic steering at variable depths and widths, and explored how unique hydraulics activate at different discharges (Sawyer *et al.*, 2010; Mandlbürger *et al.*, 2015; Pasternack *et al.*, 2018). DEM differencing is also becoming a more widely used means to estimate sediment budgets (Ritchie *et al.*, 2018; Anderson & Jaeger, 2020; Guilingner *et al.*, 2020). Through repeat topographic surveys, the processes governing change and self-maintenance of landforms in a river may be determined.

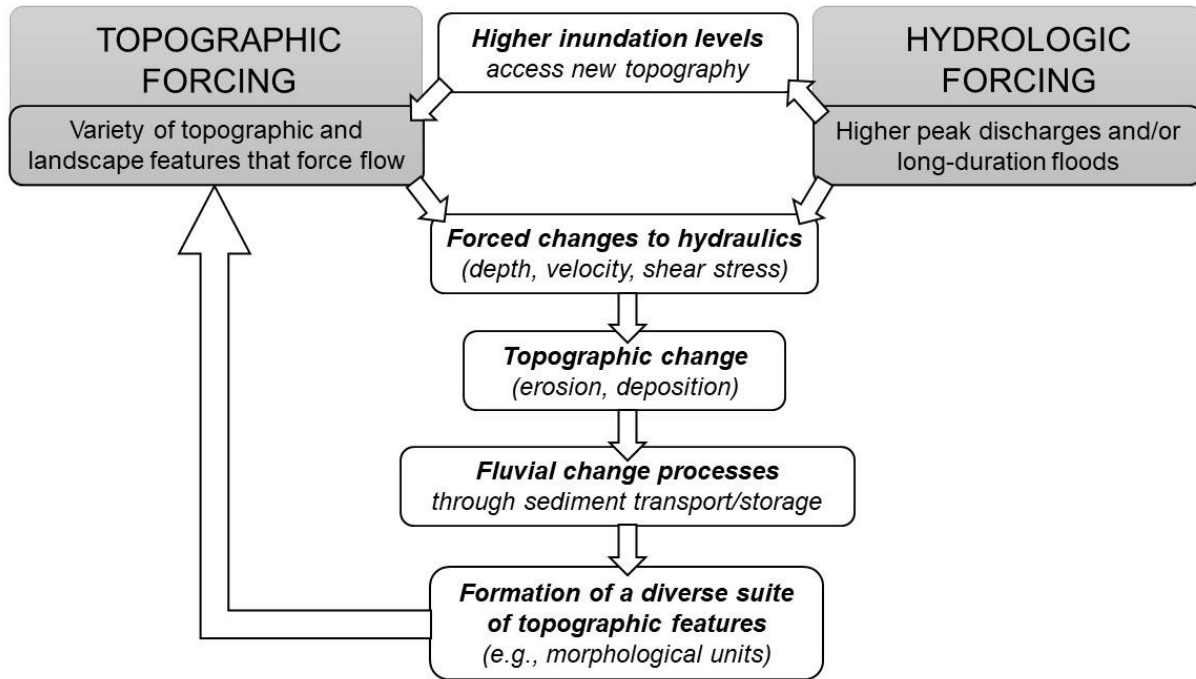


Figure 1. Conceptual diagram illustrating the interplay between topographic and hydrologic forcing in fluvial change processes. It should be noted that this diagram is focused on internal dynamics and excludes sediment supply input, which can further drive river form and topography.

Hydrologic regime significance

The concept of the hydrologic regime acknowledges the significance of timing; how flow is distributed and its variability through time can drastically alter the effect of a particular discharge (Costa & O'Connor, 1995; Lisenby *et al.*, 2016). Hydrologic regime metrics – timing, magnitude, frequency, duration, and rate of change – may all affect geomorphic dynamics (Pickup, 1976). Antecedent hydrologic conditions and climatic shifts can create conditions that alter the effect of subsequent discharge events in complex fluvial systems (Gray *et al.*, 2015a). Flood frequency analysis relies upon characterization of flow variation. This method uses the statistical distribution of flows from the historical record to predict the recurrence of particular discharges, which is

critical for effective floodplain and reservoir management (Bačová-Mitková & Onderka, 2010). For example, flood peak magnitudes corresponding to chosen flooding risks or failure of a structure are frequently estimated as part of water engineering and management practice (Bezák *et al.*, 2014).

Geomorphic effectiveness

Fluvial geomorphologists quantify the ability of hydrology to do work on and change landscape topography through the concept of geomorphic effectiveness (Wolman & Miller, 1960). Typical hydrologic metrics implicated and quantified in the literature include discharge and recurrence interval, rainfall duration and intensity, shear stress, unit stream power, and total flood energy (Lisenby *et al.*, 2016). Threshold discharges above which sediment may be entrained and erosional processes will occur are often determined on a site-scale basis with consideration for mean grain size, with significant thresholds including a river's dominant, effective, bankfull, and channel-forming discharges (Carling, 1988; Lenzi *et al.*, 2006; Yochum *et al.*, 2017; East *et al.*, 2018a).

In uniform flow conditions, shear stress and total bedload transport scale proportionally with discharge and dictate that a greater peak discharge will transport and erode more sediment. However, a review of geomorphic effectiveness studies by Lisenby *et al.* (2016) concluded that flood energy is the best metric by which to quantify hydrologic 'cause' of geomorphic response. Under the geomorphic effectiveness model, flood archetypes have been defined using the flood energy metric (**Figure 2**). Floods

that are long-lived, but with a low peak, as well as floods of high peak, but short duration, may cause little geomorphic change due to lack of energy generated above the alluvial erosion threshold. Floods that have both high peak and long duration are predicted to be the most geomorphically effective floods, transporting large volumes of sediment (Costa and O'Connor, 1995). Other geomorphic studies have similarly emphasized the importance of flooding duration in controlling channel geometry (e.g., Grams *et al.*, 2020).

Magilligan (1992) and Magilligan *et al.* (2015) explored using threshold unit stream power, rather than discharge, to characterize the onset of major geomorphic change. However, recent analyses have shown threshold stream power to be an elusive concept (East *et al.*, 2018a), as the stream power signifying geomorphic change varies locally with flood magnitude and duration, valley confinement, slope, local obstacles, and bank resistance (Miller, 1990; Buraas *et al.*, 2014; Yochum *et al.*, 2017). Threshold stream power for sediment entrainment or geomorphic change also varies with bed-sediment packing geometry (Kirchner *et al.*, 1990; Yager *et al.*, 2012; Masteller & Finnegan, 2017) and perhaps most importantly by how recently the channel has been reconfigured by floods large enough to move the largest particles (East *et al.*, 2018b; Eaton *et al.*, 2020). Therefore, in this study we focus on discharge as the most readily measurable metric to associate with geomorphic change and have not emphasized the role of any threshold stream power in the study area.

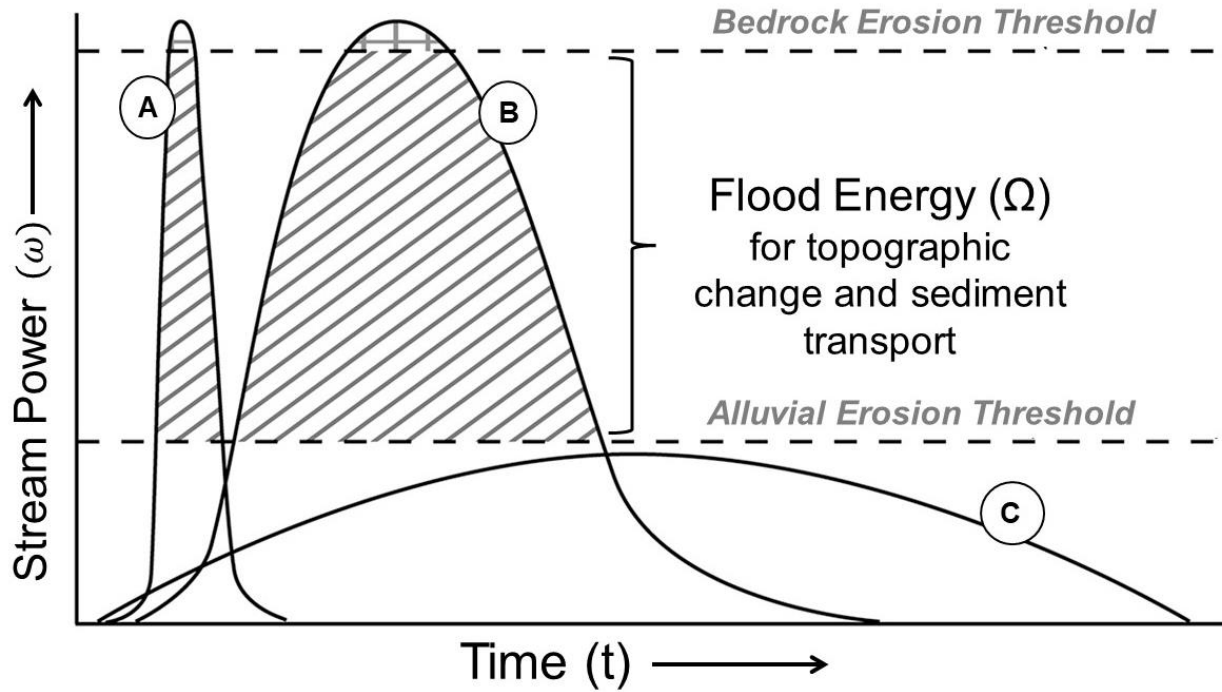


Figure 2. Relationship between stream power (ω in unit such as Watts/m²) and flood energy (Ω in unit such as Joules) for sediment transport for three different flood archetypes. A) High peak, short duration flood. B) High peak, long duration flood. C) Low peak, long duration flood [reproduced from Lisenby *et al.* (2016), with permission from Wiley].

II. Study objectives

Clearly, flood peak is an important component of the hydrologic regime, but just how significant is it in regard to geomorphic effect and topographic change when compared to flooding duration and energy, and the interplay of these hydrologic components? This study used digital elevation model (DEM) differencing with uncertainty analysis to quantify topographic changes at two spatial scales (segment and geomorphic reach) and then quantified specific hydrologic metrics to evaluate how topographic changes are driven by hydrologic and topographic controls independently, and in tandem. The study begins by employing the multi-scalar, object-oriented framework from Pasternack and Wyrick (2016), delineating the river into segment,

geomorphic reach, and morphological unit scales to address questions related to where topographic changes are occurring over time (**Table 1**, Objective 1). Then, to address hydrologic controls (**Table 1**, Objective 2), a novel framework was implemented to characterize the hydrologic regimes for each study period beyond “drought” or “flood” designation; peak, volume, and duration metrics were chosen for their relevance to geomorphic effectiveness. Five significant discharges and their inundation zones were chosen to represent potentially significant geomorphic thresholds (e.g., **Figure 2**). After collecting and analyzing both topographic and hydrologic data, relationships between the topographic changes (scour, fill, and net) and the hydrologic metrics were explored to determine which hydrologic periods were more geomorphically effective, and answer the following overarching study questions, one for each objective:

Objective 1. What are the topographic features and non-hydrologic local influences that explain observed topographic changes?

Objective 2. Does greater peak flow lead to more erosion? If not, what other hydrologic metrics explain erosion and topographic changes at the segment scale?

Table 1. Study design.

Objective	Scale	Questions	Metric	Method
1-Compare topographic change scales and metrics across epochs 1-3	A Segment	- Is the LYR net scour or net fill? - How was scour and fill distributed between in-channel and overbank regions?	Volume sediment (m ³)	- Measure total volume of scour and fill in the LYR. Scour – fill = net. - Stratify into in-channel ($\leq 113.26 \text{ m}^3/\text{s}$) and overbank ($> 113.26 \text{ m}^3/\text{s}$) regions and repeat.
	B Reach	- What was the profile of fill/scour from upstream to downstream? - Which reaches were net sources or sinks of sediment?	Volume sediment (m ³ , m ³ /year)	- Stratify scour, fill, and net by geomorphic reach to create sediment budgets. - Net scour = source. Net fill = sink.
2-Characterize the hydrologic regimes through hydrologic metrics	A 15-minute	- What were the peak flows (year/epoch)? - What are the recurrence intervals for these peak events?	Peak (m ³ /sec)	- Compile gage flow readings between 1999 and 2017 water years and find annual peaks. - Use Bulletin 17-B method in HEC-SSP to calculate recurrence intervals.
	B 15-minute, Daily	- What was the total discharge (year/epoch)? - What were the volumes of water discharged above significant inundation zones?	Volume water (m ³)	- Convert flow to volume and sum for each year using daily flow. - From the 15-minute gage flows, integrate the volume released above each inundation zone.
	C 15-minute	What was the duration in days above the inundation zones?	Duration (days)	Calculate the amount of time spent at or above each inundation zone discharge.

III. Study site

The lower Yuba River (LYR) of north central California was selected as the test river, because its topographic changes have been monitored systematically during the period 1999-2017. The 37-km lower Yuba River (LYR) segment (**Figure 3**) is a single-thread channel (~ 20 emergent bars/islands at bankfull) with low sinuosity, high width-to-depth ratio, slight to no entrenchment, and eight distinct geomorphic reaches (Wyrick & Pasternack, 2012). Englebright Dam (**Figure 3**, panel 2) initiates the segment and is a 79-m high dam with a small water storage capacity that effectively blocks all sediment supply. The regulated river segment has a mean bed slope of 0.185% and a mean surface substrate diameter of 97 mm (i.e., small cobble). Daguerre Point Dam (DPD) is an 8-m high sediment barrier/irrigation diversion dam located at river kilometer (RKM)

17.8 upstream from the Feather River confluence. Its sediment storage capacity is full. Dry and Deer Creeks are gaged LYR tributaries upstream of DPD that are both dammed. Using the LYR 2006/2008 DEM, Wyrick and Pasternack (2012) delineated four lateral inundation zones (**Table 2**). The bankfull channel and floodway are delineated by discharges of 141.6 and 597.5 m³/s, respectively (**Figure 3**, panel 3).

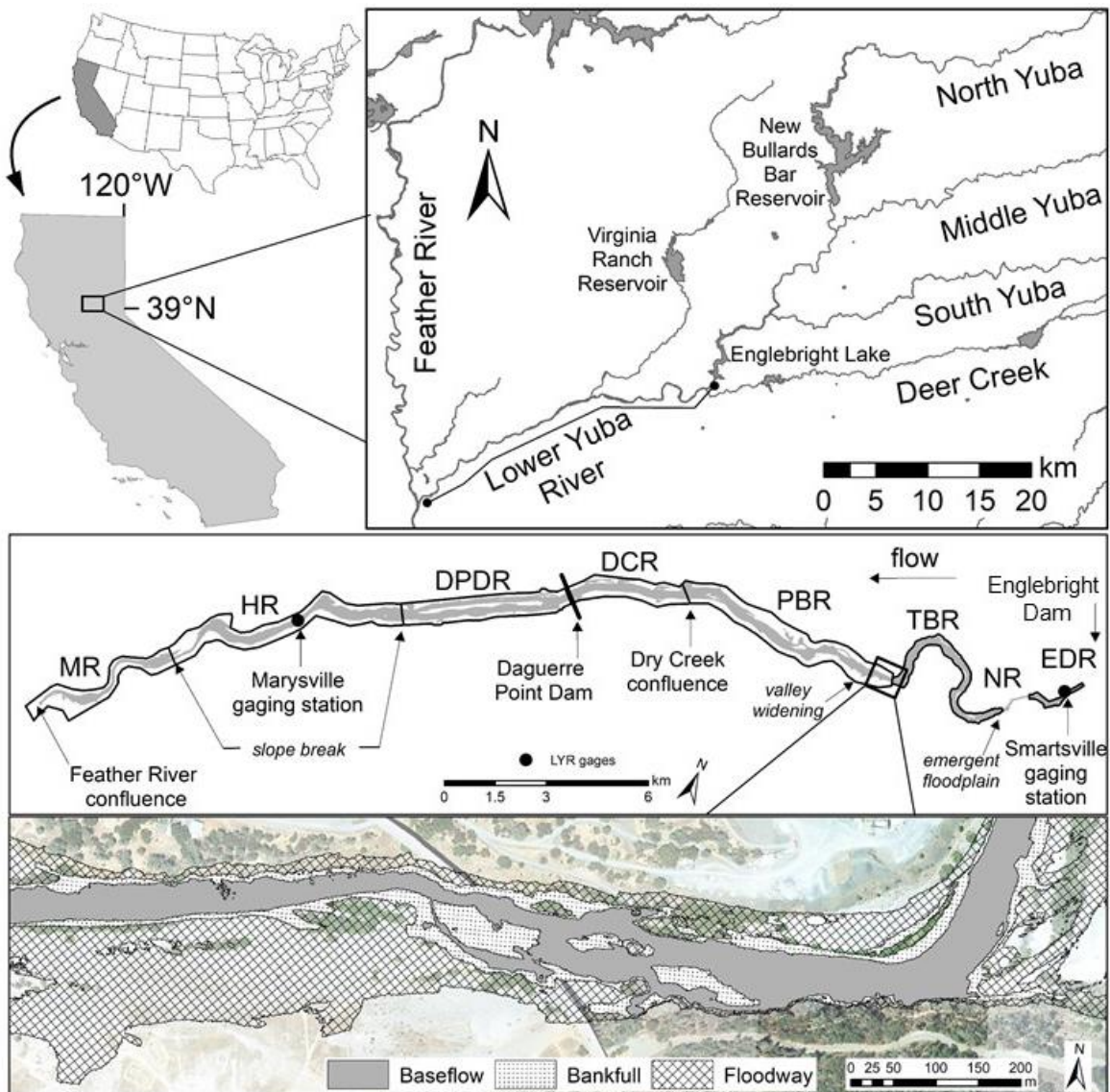


Figure 3. Location map showing the LYR and its eight geomorphic reaches, including key reach break factors and USGS gaging stations, Marysville and Smartsville. Reach acronyms: Marysville Reach (MR), Hallwood Reach (HR), Daguerre Point Dam Reach (DPDR), Dry Creek Reach (DCR), Parks Bar Reach (PBR), Timbuctoo Bend Reach (TBR), Narrows Reach (NR), and Englebright Dam Reach (EDR). Bottom panel: LYR inundation zones at baseflow (~ 18.5 m³/s), bankfull (141.6 m³/s), and floodway (597.5 m³/s).

Table 2. Inundation zones delineated for the LYR with definitions and their corresponding discharge thresholds, from Wyrick and Pasternack (2012).

Inundation Zone	Discharge range	Description
In-channel bed zone	$\leq 15 - 25 \text{ m}^3/\text{s}$	The region whose upper limit was defined by the wetted area polygon for an unvegetated 2D model flow of $25 \text{ m}^3/\text{s}$ above DPD and $15 \text{ m}^3/\text{s}$ below DPD. These were average baseflow discharge values that reflect the effect of interdecadal irrigation withdrawals. It was never assessed whether this zone is just a hydro-ecologically significant inundation area for its frequency and duration or whether it goes further to literally represent a geomorphically carved inset channel.
In-channel bar zone	$\leq 141.6 \text{ m}^3/\text{s}$	The region whose upper limit was defined by the wetted area polygon for an unvegetated 2D model flow of $141.6 \text{ m}^3/\text{s}$. This was selected primarily on the basis of field examination of the water's edge during flows of $85 - 198 \text{ m}^3/\text{s}$, including visual and photographic evidence of medial bars and banks inundating at $\sim 141.6 \text{ m}^3/\text{s}$. The statistical bankfull discharge computed using flood frequency analysis methods (i.e., 1.5-year return interval) using the post-1970 data is higher than this, but the suitability of the 1.5-year return interval is highly questionable in this Mediterranean setting.
In-channel	$\leq 141.6 \text{ m}^3/\text{s}$	Refers to all of the terrain that is inundated at a discharge of $\leq 141.6 \text{ m}^3/\text{s}$ (same as bankfull discharge).
Overbank	$\geq 141.6 \text{ m}^3/\text{s}$	Refers to all of the terrain that requires $> 141.6 \text{ m}^3/\text{s}$ (bankfull) to inundate.
Floodway	$\leq 597.5 \text{ m}^3/\text{s}$	The region whose upper limit was defined by the wetted area polygon for an unvegetated 2D model flow of $597.5 \text{ m}^3/\text{s}$. This is admittedly the most questionable of all zone boundaries. It was based on visual field indicators that a slope break existed somewhere in the $500\text{-}700 \text{ m}^3/\text{s}$ range. The discharge of $597.5 \text{ m}^3/\text{s}$ was the maximum discharge whose stage was recorded using an automated water level sensor at the confluence with the Feather River, so that is why this value was used.
Valley	$\geq 597.5 \text{ m}^3/\text{s}$	The region outside the floodway.
Floodprone area	$\leq 1,195 \text{ m}^3/\text{s}$	The region inundated by a discharge of $1,195 \text{ m}^3/\text{s}$. Rosgen (1996) defined the floodprone area as the lateral extent inundated when water depth is twice the bankfull depth. There is no previously published morphological feature associated with the floodprone area, but it is used to help assess whether a river channel is entrenched or not. On the lower Yuba River, it was discovered that a discharge of $1,195 \text{ m}^3/\text{s}$ (twice the selected floodway discharge) yielded a near-census average water depth very close to double bankfull depth.

Topographic change history

Since the California Gold Rush there has been a 170-year history of dramatic geomorphic river changes in the Yuba River catchment and a subsequent need for monitoring these changes. Like many Sierra Nevada rivers, this one has historical and modern anthropogenic impacts, notably hydraulic and dredge-based gold mining, deforestation, agriculture, river training, and flow regulation. The Yuba River experienced extreme sedimentation and sediment transport after hydraulic mining operations ended—the California Debris Commission estimated that the valley accumulated ~ 200 million m^3 of mining sediment in the late 19th century (Gilbert, 1917; Adler, 1980). During the early 20th century, high sediment loads overwhelmed the transport capacity of valley channels and caused major geomorphic adjustments such

as channel aggradation and avulsions (Adler, 1980; James *et al.*, 2009). Englebright Dam was installed in 1940 to block all bedload and most suspended load from entering the LYR, thereby promoting some downstream geomorphic recovery—even after 80 years, recovery continues (James, 2005).

Hydrology

The Yuba River watershed's climate involves little to no precipitation June through September and then a wet season late November to May with precipitation of ~ 500-2000 mm depending on elevation and aspect. Wet-season floods are often generated by narrow-banded atmospheric rivers that deliver localized, intense, high-magnitude precipitation (Ralph *et al.*, 2006; Dettinger, 2011). Extreme precipitation events that occur remarkably regularly with a periodicity of ~ 10 years (Guinn, 1890) deliver large quantities of warm rainfall onto snow-packed mountain slopes. Flow analysis statistics on the western coast of the U.S. reveal that these interannual to decadal cycles between dry and wet periods are caused by El Niño Southern Oscillation (ENSO) cycles (Gray *et al.*, 2015b).

The LYR's flow regime is highly dynamic. Two of the major tributaries contributing to the LYR (Dry and Deer Creeks) do not have large water supply dams and cannot abate floods. Although the river is partially regulated through New Bullards Bar on the North Yuba River and Englebright Dam on the main stem, the latter is kept nearly full. Flows greater than bankfull discharge overtop the ogee-crested dam or pass through two smaller (12,000 kW and 50 mW) powerhouses located immediately

downstream and are rapidly delivered to the lower Yuba River segment with only mild attenuation.

The key hydrological point for this study is that the 1999-2017 period encompasses two extreme, wet period flood events, creating the unique ability to not only contrast large versus small flood regimes, but also two large flood regimes. Conditions were average to dry 1999-2005, because the previous large flood event happened in 1997 before systemic topographic surveying got underway. A large flood (peak of 3,207 m³/s; 23-year recurrence) occurred in the 2006 water year (**Figure 4**), but then from 2012-2016 California experienced a severe drought (East *et al.*, 2018b; Swain *et al.*, 2018). The next large flood event occurred during the 2017 winter (peak of 2,466 m³/s; 13-year recurrence), which became one of the wettest on record for the western US, with integrated vapor transport estimated at three standard deviations above the mean quantity for the California coast (Gershunov *et al.*, 2017; East *et al.*, 2018b).

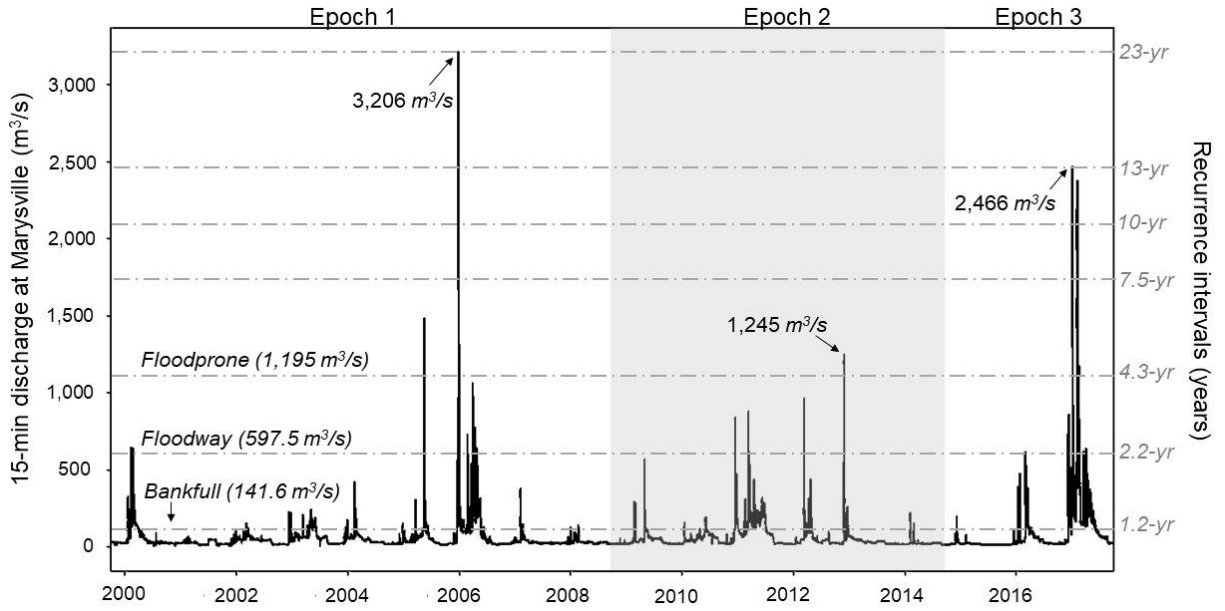


Figure 4. Hydrograph of 15-minute discharge across survey epoch 1 (Oct 1st 1999–Sept 30th 2008), epoch 2 (shaded, Oct 1st 2008–Sept 30th 2014), and epoch 3 (Oct 1st 2014–Sept 30th 2017). Recurrence intervals listed on right axis.

IV. Methods

Temporal scale and topographic surveys

The LYR's topography has been closely monitored over the 18-year period between 1999 and 2017. Four high-resolution DEMs of the river bed and valley bottom provided topographic snapshots from the following years: (i) 1999, collected using aerial photogrammetry and single beam echosounding; (ii) 2006/2008, collected using airborne near-infrared LiDAR, single beam echosounding tied to RTK GPS, and ground surveys; (iii) 2014, collected using primarily airborne LiDAR with both near-infrared and green lasers, as well as multibeam and single beam echosounding tied to RTK GPS, and ground surveys; (iv) 2017, collected with the same methods as in 2014. The date

for the second DEM is combined as 2006/2008 because Timbuctoo Bend was mapped in 2006 and then the rest of the river (excluding the Narrows Reach) was predominantly surveyed in 2008.

An epoch is the time period between two topo-bathymetric surveys. In this study there are three epochs: (i) epoch 1 is the 7-9 year period between 1999 and 2006/2008 (Pasternack & Wyrick, 2016); (ii) epoch 2 spans 6-8 years between 2006/2008 and 2014 (Weber & Pasternack, 2017); (iii) epoch 3 is the 3-year period between 2014 and 2017, with this study introducing this latest set of topographic change results. Epoch 3 is short because a large flood in 2017 warranted new mapping.

DEM differencing and topographic change detection

The differencing of sequential DEMs with an accounting of uncertainty creates three DEMs of Difference (DoDs) for the three change epochs from the four input DEMs for the LYR (**Figure 5**). Pre-existing peer-reviewed DoD rasters were used from Carley *et al.* (2012) for epoch 1 and Weber and Pasternack (2017) for epoch 2. Epoch 3 is the latest period. Its DoD raster was produced using the same data collection and topographic change detection (TCD) procedure methods as in Weber and Pasternack (2017). The TCD procedure used herein for the 2014-2017 data provided a spatially explicit uncertainty raster to account for and combine error from multiple sources including land cover type (vegetation, water, or bare earth), topographic variability due to slope, DEM interpolation, and sampling point density. Vertical error ranged from 0.02 to 6.02 meters across the entire study site and was log-normally distributed, with error

concentrated at the lower end of the values. The mean error was 0.16 m, with a median of 0.10 m, skewness of 1.97, and a standard deviation of 0.17 meters. The level of detection raster containing the estimated vertical error in elevation values was subtracted from the raw difference between 2014 and 2017 DEMs prior to topographic change analysis, so that the reported elevational change in the resultant DoDs is within a 95% confidence interval. The final resolution for all DoD rasters is 1.524 x 1.524-m² pixels. This dimension was chosen because larger pixels caused too much uncertainty in locations with steep side slopes while smaller pixels lacked enough survey points to enable robust statistical results.

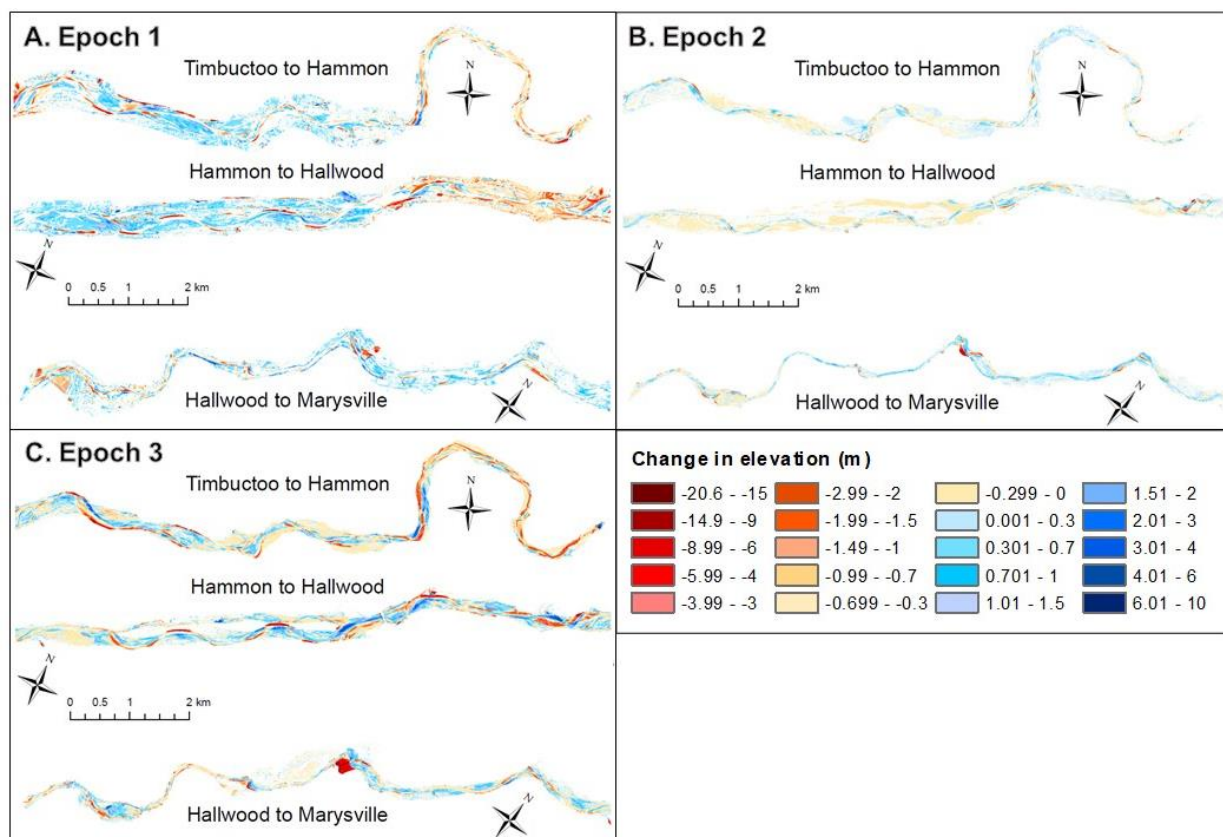


Figure 5. DEM of Difference (DoD₉₅) on the entire LYR for A) Epoch 1: 1999-2006/2008, B) Epoch 2: 2006/2008-2014, and C) Epoch 3: 2014-2017.

Topographic change framework

Topographic changes were analyzed at segment (entire LYR), geomorphic reach, and morphological unit scales to isolate patterns of change to address different scientific questions (Pasternack & Wyrick, 2016). The questions raised in this study only involve the first two spatial scales, because these were the only scales that could be applied uniformly across all three study periods. In-channel versus overbank lateral inundation zonation is a stratification of the segment-scale data. Ideally a boundary for the estimated bankfull discharge ($141.6 \text{ m}^3/\text{s}$) would be available for all survey dates, but the only available wetted extent for 1999 was $109 \text{ m}^3/\text{s}$, so the closest available extent to that for the other epochs (from two-dimensional hydrodynamic modeling of a steady $113.26 \text{ m}^3/\text{s}$) was used to delineate the channel regions for all epochs instead, as was done in previous work (Pasternack & Wyrick, 2016). Areas outside this near-bankfull boundary are referred to as overbank regions (**Table 2**).

This study analyzed topographic change by scale using area (m^2 , %), volume (m^3 , m^3/year), and sediment depth (cm/year) metrics, with extra area, volume, and depth results reported in supplementary materials. Volumetric changes reflect not only differences in driving process, but also how long there was for change to occur, which varied from 3 to 9 years in this study depending on the reach and epoch. Total volumetric flux (m^3) represents overall geomorphic effectiveness (Lisenby *et al.*, 2016) over the entire epoch. Due to different durations and survey timing in epochs 1, 2, and 3, scour and fill volumetric results can be normalized by year (m^3/year) for direct comparison on a time-free basis. This normalization provides a second viewpoint to

consider processes between epochs given the inevitable differences in duration between re-surveys. Annualization is a long-standing, standard approach in morphodynamic analysis (e.g. lateral migration rates in meander bends and volumetric budgeting), but it neglects the variety of processes that vary in time, yielding differential rates of change at a finer time resolution than can be accommodated with expensive repeat surveys. Possible effects of studying epochs of different durations and start/end time positions relative to when a flood occurs are addressed at the end of the discussion section below.

To calculate volumetric sediment budgets of scour and fill using DoD rasters, the areal distributions of scour and fill were multiplied by the mean change in elevation that occurred within the spatial scale of interest using the Zonal Statistics tool in ArcGIS 10.5. Because uncertainty was already accounted for in producing DoD rasters, no further steps were taken to assess and report volumetric uncertainty (e.g., Pasternack & Wyrick, 2016; Weber & Pasternack, 2017). The LYR sediment budget is greatly simplified due to the presence of upstream dams on the main stem and tributaries, which block nearly all sediment load. As a result, net influx of sediment into the LYR is assumed to be zero.

Hydrologic metric framework

For each epoch, the following metrics were collected: peak discharge and duration and volume above significant discharge thresholds in the river. Discharge (Q) in m^3/s is used in place of unit stream power (ω in $Watts/m^2$) from the geomorphic

effectiveness metrics (**Figure 2**), because these terms are equivalent when controlling for fluid density (ρ), gravitational acceleration (g), slope (S), and channel width (w), by considering the entire river as one unit at the segment scale (**Equation [1]**). Volume (V), in m^3 , can then be substituted for flood energy (Ω in Joules) because it is simply the integration of the stream power, or discharge (Q) in this study, over a period of time (dt) (**Equation [2]**).

Although there is strong support from the literature to use stream power to estimate a major control of geomorphic response with some significant assumptions (e.g., Baker & Costa, 1987; Magilligan, 1992; Thompson & Croke, 2013; Magilligan *et al.*, 2015), stream power is a cross-sectional analysis of local conditions, not a reach or segment scale analysis tool for understanding the aggregate role of the input flow regime. This study does not address the diversity of local topographic change conditions and drivers, and given the nonuniform river condition in the LYR, two-dimensional numerical modeling of velocity and bed shear stress would perform better for that task than stream power anyway, as illustrated by Brown and Pasternack (2014) and Strom *et al.* (2017). While stream power can be averaged to reach or segment scales, use of discharge provides an appropriate alternate to stream power for Objective 2 of the study because this objective is primarily focused on linking hydrologic metrics to geomorphic response at the segment scale to help inform scientists and managers lacking detailed topographic data to compute stream power or run numerical simulations.

The major lateral inundation zones of the river previously delineated using the LYR 2006/2008 DEM by Wyrick and Pasternack (2012) were employed to represent

discharge thresholds (**Table 2**). These thresholds set time intervals over which volume was integrated. These discharges for the LYR include: bankfull (141.6 m³/s), 2x bankfull (283.2 m³/s), floodway (597.5 m³/s, also termed the “floodplain-filling flow”), 6x bankfull (849.5 m³/s), and flood-prone area (1,195 m³/s). To produce the most precise metrics, 15-minute flow data were used to calculate peak, duration, and volume above thresholds, while daily averaged flow was used only to calculate annual volumes. Because 2008 is the survey year for the majority of the LYR in the second DEM (the lower 5 reaches below Timbuctoo Bend Reach (TBR)), the hydrologic analysis uses the 2008 water year as end year for epoch 1 (1999-2008) and start year for epoch 2 (2008-2014).

$$\omega = \frac{\rho g Q S}{w} \rightarrow Q \quad [1]$$

$$\Omega = \int \omega \, dt \rightarrow V = \int Q \, dt \quad [2]$$

Annual water year statistics and metrics were obtained from two USGS flow gages: Smartsville #11418000 (USGS, 2021a) and Marysville #11421000 (USGS, 2021b) (locations indicated in Figure 3). Recurrence intervals for key peak discharges were calculated from the Smartsville flow data on a water year basis (October to September) using the Bulletin 17-B method (USGS, 1981), implemented in HEC-SSP. All other hydrologic metrics were derived from flow readings from the Marysville gage, which includes discharge contributions from the Dry and Deer Creek tributaries but excludes seasonal diversions for irrigation and other uses.

V. Results

Objective 1: Topographic changes - segment scale

In epoch 1, a small net of $0.06 \times 10^6 \text{ m}^3$ of sediment was exported out of the LYR as large volumes of scour material ($-2.52 \times 10^6 \text{ m}^3$) (all scour values reported with a negative symbol) mostly re-deposited downstream within the river ($2.46 \times 10^6 \text{ m}^3$) (**Figure 6**). Net export volume increased to $0.14 \times 10^6 \text{ m}^3$ in the drought period of epoch 2, resulting from $-0.64 \times 10^6 \text{ m}^3$ of scour and only $0.50 \times 10^6 \text{ m}^3$ of deposition. Over three years in epoch 3, the LYR experienced more scour than epoch 1 and simultaneously experienced less re-deposition ($-3.39 \times 10^6 \text{ m}^3$ and $2.03 \times 10^6 \text{ m}^3$ respectively). This combination of responses resulted in a net erosional export of $1.37 \times 10^6 \text{ m}^3$, more than 20 times greater than the export over the 9 years of epoch 1.

A comparison of channel change between the channel and overbank areas found that they experienced net fill and net scour of sediment, respectively, for all epochs (**Figure 7**). This is an opposite outcome from the expectation for regulated rivers. However, the distribution of scour and fill within and between in-channel and overbank regions was unique in each epoch. Epoch 1 showed the most balance between scour and fill volumes between regions and the most re-deposition of sediment in the overbank ($1.84 \times 10^6 \text{ m}^3$) of any epoch. In epoch 2, the overbank was less active, with a greater percentage of scour and re-deposition occurring in the in-channel regions; it experienced the lowest net fill in the channel region ($0.12 \times 10^6 \text{ m}^3$) and lowest percent overbank fill of any epoch. Epoch 3 had the greatest in-channel fill ($1.25 \times 10^6 \text{ m}^3$) and

overbank scour ($-2.67 \times 10^6 \text{ m}^3$) of any epoch. In all cases, the majority of segment scale scour came from the overbank region, but in both epochs 1 and 3, the overbank contributed a majority, about 80%, of the total scour volume.

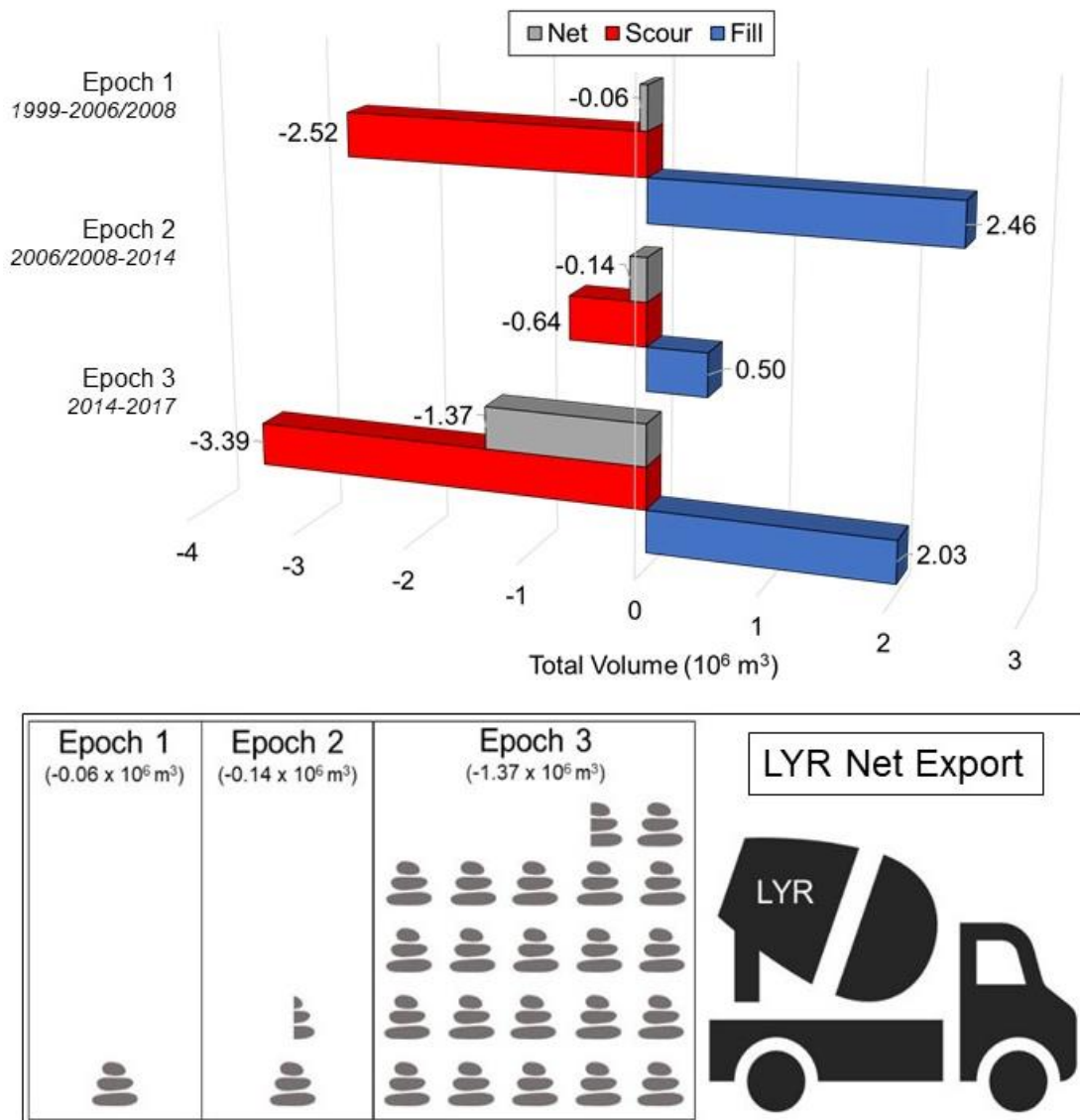


Figure 6. Total volume of scour, fill, and net in 10^6 m^3 .

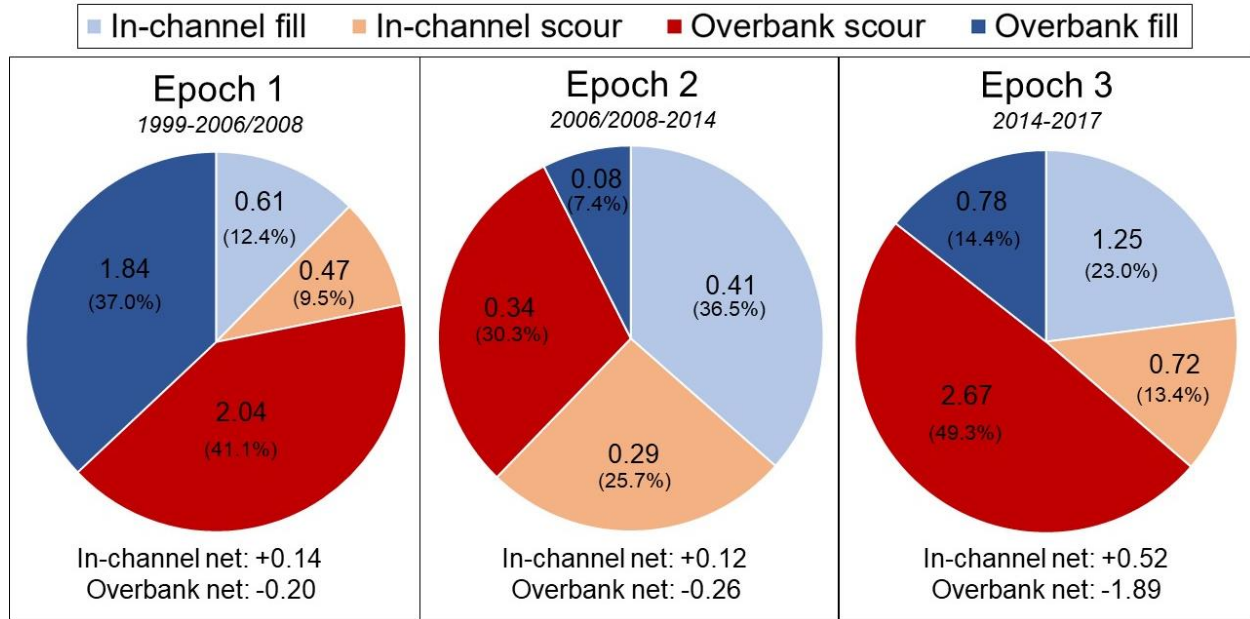


Figure 7. Total volumetric changes in 10^6 m^3 , stratified into in-channel ($\leq 113.26 \text{ m}^3/\text{s}$) and overbank regions.

Objective 1: Topographic changes - reach scale

TBR, at the top of the LYR segment, remained in a state of net scour in all epochs (**Figure 8**). Parks Bar Reach (PBR) varied between net deposition in epoch 1 and net erosion in epochs 2 and 3, due to relatively balanced scour and re-depositional processes. Despite being upstream of a dam and downstream of a tributary confluence supplying some sediment, Dry Creek Reach (DCR) was consistently net erosional across epochs and was the only reach that experienced greater scour volume in epoch 1 ($-62.7 \times 10^4 \text{ m}^3$) than in epoch 3 ($-49.7 \times 10^4 \text{ m}^3$). Below DPD, Daguerre Point Dam Reach (DPDR) exhibited an interesting pattern in that it was the most net depositional reach in epoch 1, the most net erosional reach in epoch 2, and the only net depositional reach in epoch 3. Next downstream, Hallwood Reach (HR) shifted from strongly net depositional in epoch 1, to nearly net neutral in epoch 2, and then experienced the

greatest scour volume of any reach over all epochs at $-76.1 \times 10^4 \text{ m}^3$ of scour in epoch 3, making it the most net erosional reach in that epoch. Lastly, Marysville Reach (MR), which connects to the Feather River confluence, experienced scour and fill patterns similar to PBR, shifting gradually from a net depositional reach in epoch 1 to net erosional in epochs 2 and 3.

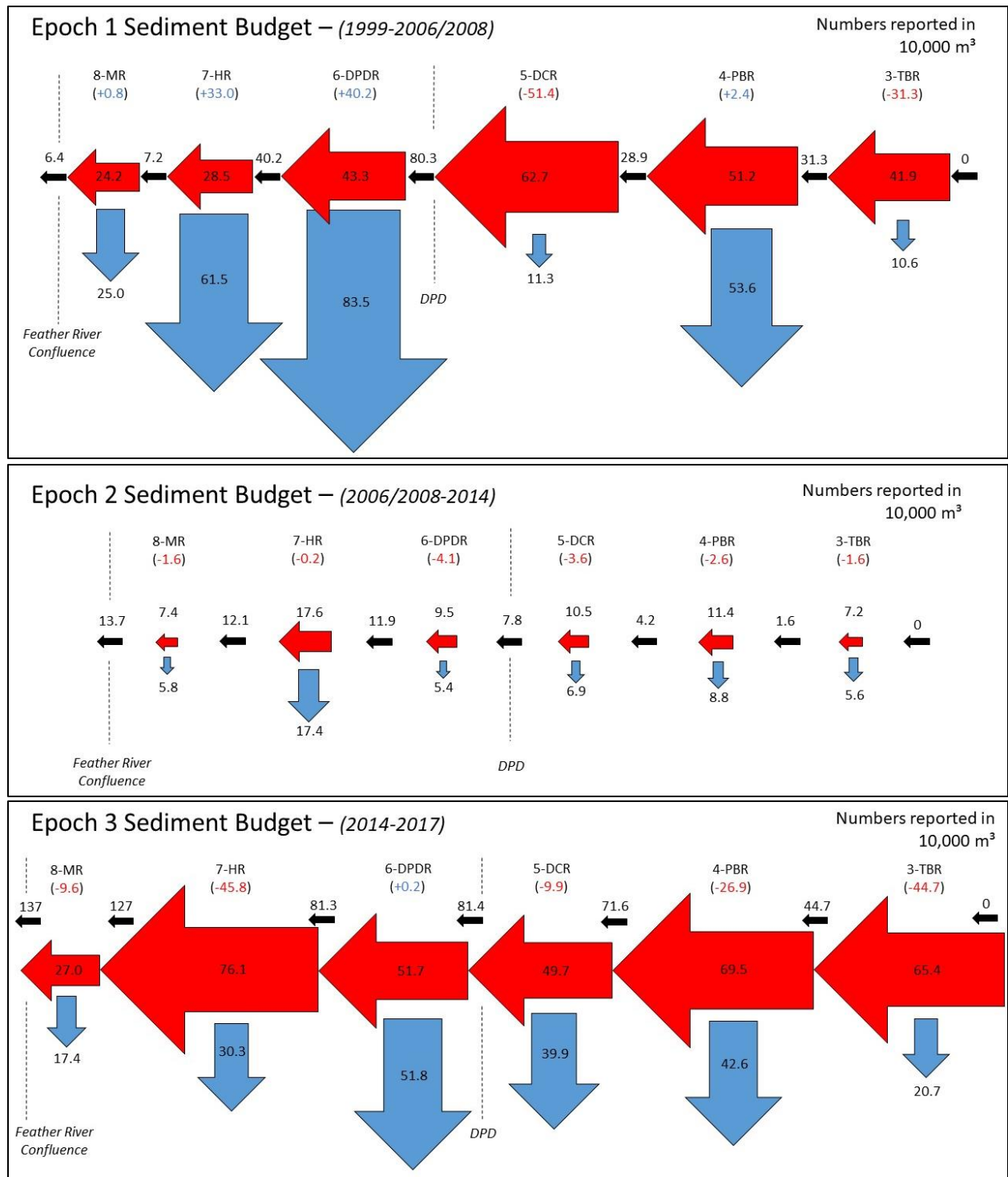


Figure 8. Reach scale sediment budget with total volume of sediment scoured (red horizontal arrows) or re-deposited (blue vertical arrows) in each reach, in 10⁴ m³. Sizes scaled proportionally to volume. Horizontal arrows point in direction of flow. Numbers in parentheses indicate net for each reach. Black arrows indicate net transport between reaches.

Annualized results represent the total volumes divided by the number of years between DEM surveys, in order to standardize the results and compare the relative intensities of scour and re-deposition in each epoch (**Figure 9**). In epoch 3, HR experienced the greatest scour rate of any reach at $25.4 \times 10^4 \text{ m}^3/\text{year}$ of scour. After net changes were taken into account at each reach moving from upstream to downstream, the annualized rate of sediment export out of the LYR indicated an increase in export rate between the flood and drought periods of epochs 1 and 2, from 1.70×10^4 to $2.22 \times 10^4 \text{ m}^3/\text{year}$, an increase of only 30%. The next epoch, epoch 3, saw a net export rate of $45.6 \times 10^4 \text{ m}^3/\text{year}$, 20 times greater than the export rate of epoch 2 and 25.8 times the export rate of epoch 1.

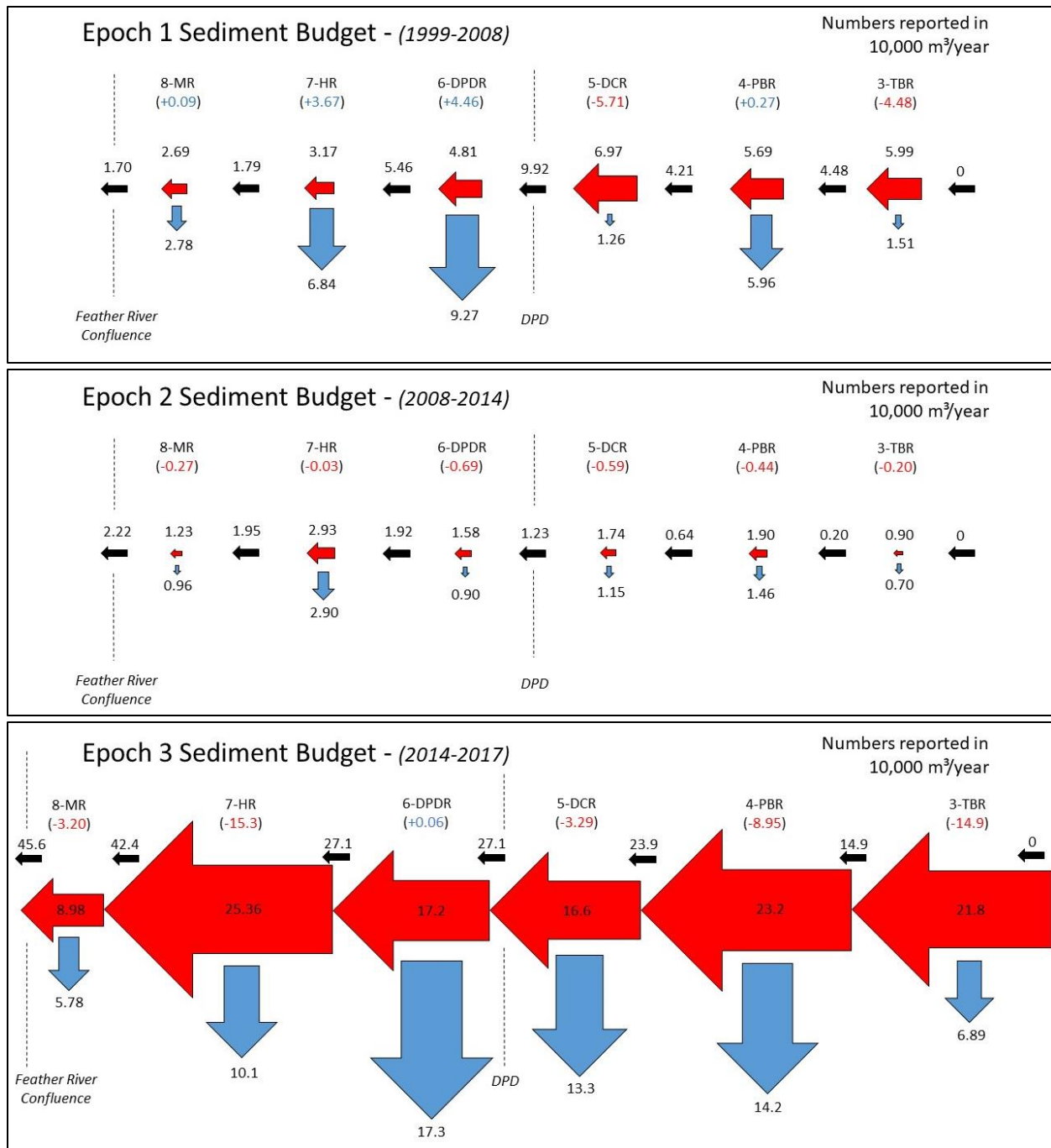


Figure 9. Reach scale sediment budget with annualized volumetric rates of sediment scoured (red horizontal arrows) or re-deposited (blue vertical arrows) in each reach, in 10⁴ m³. Sizes scaled proportionally to volume. Horizontal arrows point in direction of flow. Numbers in parentheses indicate net for each reach. Black arrows indicate net transport between reaches.

Objective 2: Hydrologic metrics - peak

Epoch 1, the longest epoch in the study, experienced the highest intensity flood (instantaneous discharge of 3,207 m³/s in the 2006 water year), with a moderate flood the previous year and again in the following spring (**Figure 4, Table 3**). That peak event corresponded to a 23-year event and 22.6 times bankfull discharge. Epoch 2 had four floods filling the floodway (597.5 m³/s), ranging from 875 to a peak of 1,245 m³/s instantaneous flow in 2013, although these floods were the exception to the trend as flows were generally below normal during this drought period. Those peak flows corresponded to ~ 3–5-year recurrence interval events and 6–9 times bankfull discharge. The maximum instantaneous discharge for epoch 3 was 2,466 m³/s (January 2017), corresponding to a 13-year recurrence interval. This peak was ~ 25% less than that in epoch 1.

Table 3. Summary of water year statistics (epoch 2 shaded). Discharge data from daily average and 15-minute flow data from Marysville gage. Water year begins October 1st of the year prior to year indicated.

Water year	Instant. peak (m³/s)	Daily avg peak (m³/s)	Annual avg. volume (10⁶ m³/y)
2000	642.0	608.8	1,779
2001	63.5	55.8	697
2002	149.3	142.7	1,241
2003	236.3	231.1	1,829
2004	418.9	345.5	1,355
2005	1,480	1,229	1,830
2006	3,207	2,384	4,794
2007	375.0	283.2	901
2008	138.2	130.3	819
2009	566.3	356.8	1,242
2010	189.6	181.2	1,419
2011	875.0	761.7	3,838
2012	961.1	603.2	1,366
2013	1,246	628.6	1,272
2014	217.8	178.1	614
2015	195.0	147.5	527
2016	612.0	877.8	1,748
2017	2,466	2,217	6,288
Epoch 1	3,207	2,384	1,694
Epoch 2	1,246	761.7	1,625
Epoch 3	2,466	2,217	2,854

Objective 2: Hydrologic metrics - volume

To calculate annual discharge volumes released, daily average flows were summed for each water year (**Table 3**, last column). The 2017 water year resulted in the greatest annual volume at 6.29×10^9 m³ of water. The 2006 water year in epoch 1 experienced the second highest volume at 4.79×10^9 m³ and the third highest volume year was in 2011, during epoch 2.

For each epoch, the 15-minute flow data were used to calculate the volume of water that was released above five significant inundation zones (**Figure 10**, top panel). Epoch 1 experienced greater volumes of water above all thresholds relative to epoch 2. The volume of discharge above all thresholds was consistently higher in epoch 3 compared to the first two epochs. Notably, the discharge released above the three highest inundation zones (floodway, 6x bankfull, and flood-prone) in epoch 3 was typically twice the volume released over the same threshold during epoch 1.

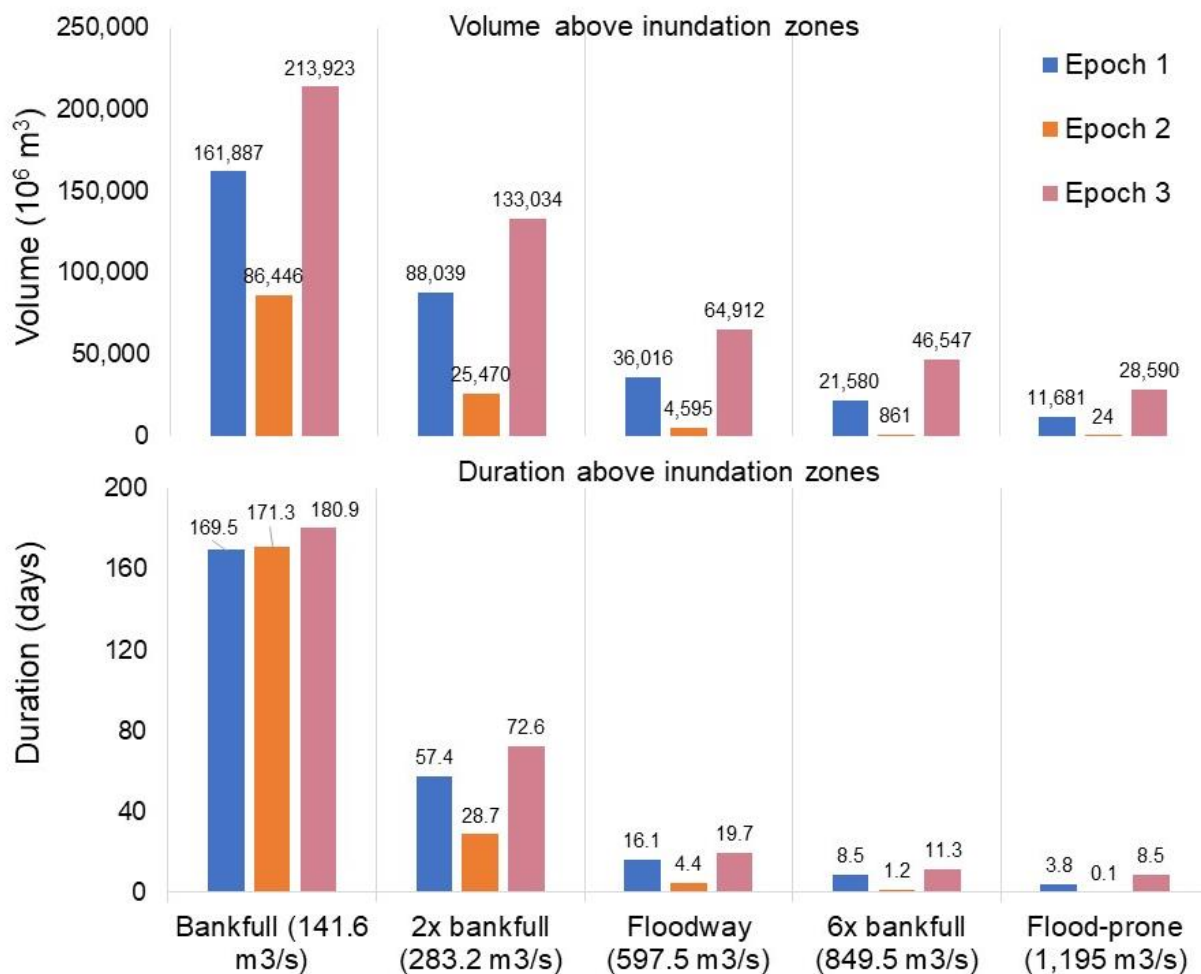


Figure 10. Volume and duration analysis in the LYR using 15-minute flow data from Marysville gage.

Objective 2: Hydrologic metrics - duration

Duration analysis revealed that each epoch experienced nearly the same amount of time at or above the bankfull stage (**Figure 10**, bottom panel), although in epoch 2 this pattern did not correspond with a significant increase in volume (**Figure 10**, top panel). Epoch 1 had 169.5 days above bankfull, epoch 2 had 171.3 days above bankfull, while epoch 3 experienced the most time above bankfull at 180.9 days. Beyond this threshold, differences in duration at 2x bankfull and above are more distinct across epochs. As with volume, epoch 3 experienced the longest duration above all key inundation zones despite being the shortest period, and had more than twice as many days above flood-prone stage relative to epoch 1.

Comparing the hydrographs for flood epochs 1 and 3 (**Figure 11**) highlights why epoch 3 experienced greater discharge volumes and durations, especially at the higher flood stages, relative to epoch 1. Epoch 3 experienced two nearly equivalent flood peaks in January and February of the 2017 water year, with sustained flood discharge through the month of February, whereas epoch 1 experienced only one peak flood event in the 2006 water year.

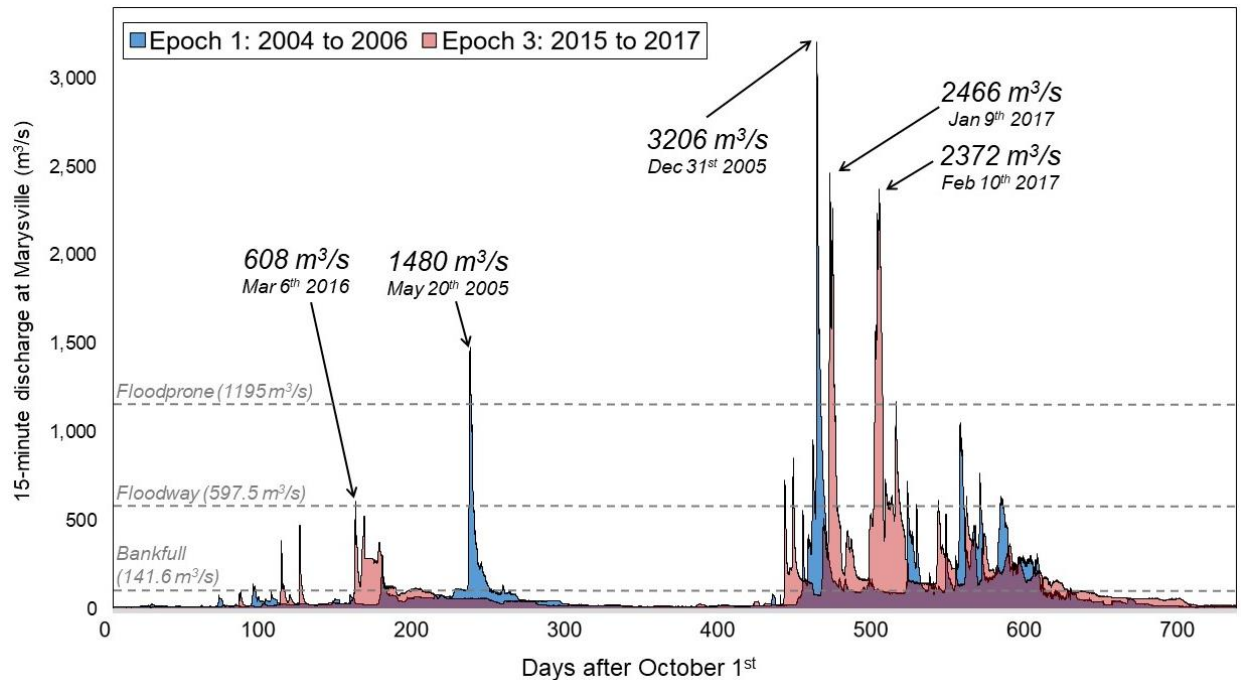


Figure 11. Hydrograph with two example years from epochs 1 (blue) and 3 (red), with overlap in purple.

VI. Discussion

In answering study question 1, the first two discussion sections explore patterns in topographic change across the study epochs, with a focus on topographic drivers, historical impacts, and local reach scale behavior. The LYR is strongly influenced not only by stage-dependent topography, creating naturally variable channel depth and width, but its topography is also influenced by dams, historical hydraulic mining, levees, training berms, and natural terraces. Downstream of DPD, the valley has a wide floodplain and low slope gradient (**Figure S1**) but exhibits stage-dependent expansions and constrictions (Pasternack *et al.*, 2018) creating a highly variable environment in regard to geomorphic response. By using the scale-based approach to analyzing topographic changes, patterns emerged in scour and re-deposition at the segment and

geomorphic reach scales with implications for the topographic drivers controlling the underlying processes.

Upon acknowledging the local topographic drivers at the reach scale and internal dynamism inherent in the LYR system due to historical and current impacts and influences, the final three discussion sections address study question 2 regarding which hydrologic metrics are correlated with greater geomorphic effectiveness at the segment scale. The hydrologic metrics yielded compelling evidence that a long duration flood, releasing sustained volumes of water above high inundation thresholds causes more scour and net export, especially in a system such as the LYR where the channel is well-connected to its expansive floodplain, allowing access to erode those sediments.

A non-incising channel and net scour river corridor

Typically for a regulated river, one expects to see that dams cause in-channel incision, entrenchment, and disconnection between channel and floodplain (Williams & Wolman, 1984; Grant *et al.*, 2003; Schmidt & Wilcock, 2008). However, the opposite appears to be the case for the LYR. As the channel migrates or avulses from its initial location to its final location at the end of the epoch, it tends to fill in its old channel while scouring through the banks and cutting new pathways over floodplains. There are several topographically driven explanations for lack of in-channel incision. First, the bed of the LYR is armored and consists of coarse gravel-cobble, but the steep (often unconsolidated) banks, levees, and mining tailings along the lateral edges are composed of fine gravels and sands (Wyrick & Pasternack, 2015). These finer

sediments would be preferentially scoured over coarser sediments along the bed (Dietrich *et al.*, 1989; James, 2005). Mining tailings indeed exhibited the third highest scour volume epoch 3 within morphological unit analysis (see Supplemental Materials). However, this sediment size factor alone does not explain the erosive nature of the epoch 3 flood event. While steep surfaces like tailings and banks may only be erosional given their shape, flat surfaces like floodplains and terraces may be both erosional and depositional. The epoch 3 event yielded more balance between net erosion of flat surfaces (whether by lateral or vertical dynamics) and net erosion of tailings, with highest preference towards flat terrace and floodplain surfaces. Therefore, the coarse gravel-cobble bed load is often not the subject of transport. Furthermore, the valley floor stores ~200 million cubic meters of hydraulic-mining alluvium (Gilbert, 1917; James *et al.*, 2005), but between 1999 and 2017, $1.57 \times 10^6 \text{ m}^3$ of sediment was exported from the LYR, which is only 0.78% of that amount. An excess of remnant mining sediments in the LYR may provide an internal accessible sediment load in the absence of external supply. Sediment supply has been found to be equally or more important than flow dynamism and hydraulic controls in determining geomorphic response in rivers with high sediment loads (e.g., Dean *et al.*, 2016).

The LYR overbank experienced net scour in all epochs regardless of hydrologic regime. Englebright Dam was specifically designed to block sediment and both gaged tributaries (Dry and Deer Creek) downstream of the dam are themselves dammed. Therefore, this net scour result is feasible under the assumption that the channel receives no significant external sediment supply input. But again, the immense internal supply from long-term storage as well as observed re-mobilization of tailings sediment

(James, 2005) also makes it unsurprising to observe that these areas are consistently sediment exporting. The LYR's unique history and topographic influences must be taken into consideration when applying existing concepts of geomorphic response to explain the channel and overbank dynamics.

Reach scale influences

DPDR was the only reach to remain net fill in both flood regimes, but was net erosional in a drought period. Review of validated 2D hydrodynamic model results used for river management (**Figure 12**) confirmed that flood-stage flows initiate channel expansion; at lower discharge, erosive forces are focused in the channel and on banks but after water spills onto the floodplain, channel velocity declines as patches of peak velocity shift onto the floodplain (Abu-Aly *et al.*, 2014). This pattern may rely upon DPDR's ability to access the large Daguerre alley side channel (**Figure 12**) as the key topographic component that allows it to remain a sediment sink during flood regimes.

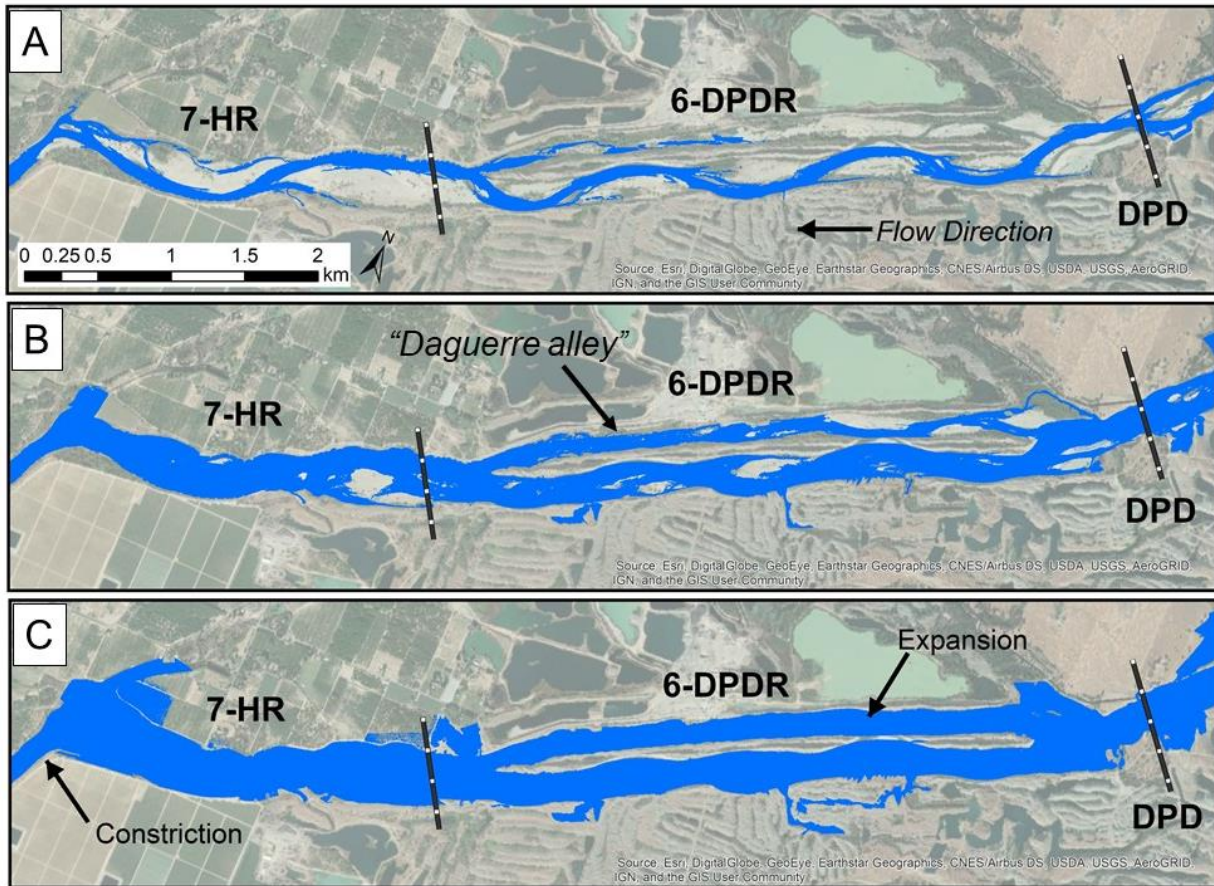


Figure 12. Wetted extents generated using a 2D hydrodynamic model with the 2014 topography. A) Bankfull ($141.6 \text{ m}^3/\text{s}$). B) Floodway ($597.5 \text{ m}^3/\text{s}$). C) Epoch 1 peak daily averaged flow ($2,389 \text{ m}^3/\text{s}$).

TBR and DCR were the only two reaches to remain the same (net scour) in all epochs regardless of hydrologic regime. Therefore, they may be driven more by topographic features than hydrology. Likely their proximity to dams “fixes” their roles, with TBR beginning with little sediment supply and DCR ending at a dam imposing a base level. TBR, in addition, is in a constricted valley within the Sierra Nevada foothills above the start of the alluvial fan (**Figure 3**) and may experience increased erosion as an effect of two processes. First, it receives sediment-starved “hungry water” (Kondolf, 1997), so it can scour from upstream to downstream to pick up sediment supply. However, there is no indication of a reduced slope at the head of TBR, so this would

have a limited distance of downstream effect. Second, upstream migratory waves of channel adjustments are thought to have occurred (Carley *et al.*, 2012) in response to an over-steep longitudinal bed-elevation profile (associated with hydraulic mining valley fill and evacuation history) relative to the equilibrium slope sustainable in light of the base level imposed by Daguerre Point Dam.

PBR, HR, and MR were all reaches that changed over time, from sediment sinks in epoch 1 to sediment sources in epochs 2 and 3, indicating factors that changed over time related to topographic dynamics as well as hydrology. Interestingly, these are also the reaches that are separated from a dam by at least one reach indicating lack of dam influence. The clearest example of a sequence of events where topographic and hydrologic forcing interacted to produce a new topographic change outcome is illustrated in HR, where a terrace collapsed in epoch 3. While the valley and floodplains are generally wider downstream of DPD, constrictions exist at bends and the onset of levees. Topographic features are highly stage-dependent and constrictions are exacerbated at higher flows. As areas upstream collect more water and expand into the floodplain, nozzles form downstream as large volumes of water are forced to quickly flow through the constriction creating concentrated areas of high velocity and shear stress that easily mobilize sediment and promote erosion (Pasternack *et al.*, 2018) (e.g., **Figure 12**). The major terrace erosion in HR was exactly at one such abrupt constriction downstream of DPDR. Aerial imagery revealed that the river began scouring into the sharp, constricting bend during epoch 2, setting the stage for the flood-driven collapse in epoch 3 (**Figure 13**). The terrace collapse accounted for 9.8% of the entire volume of sediment eroded downstream of DPD in epoch 3.

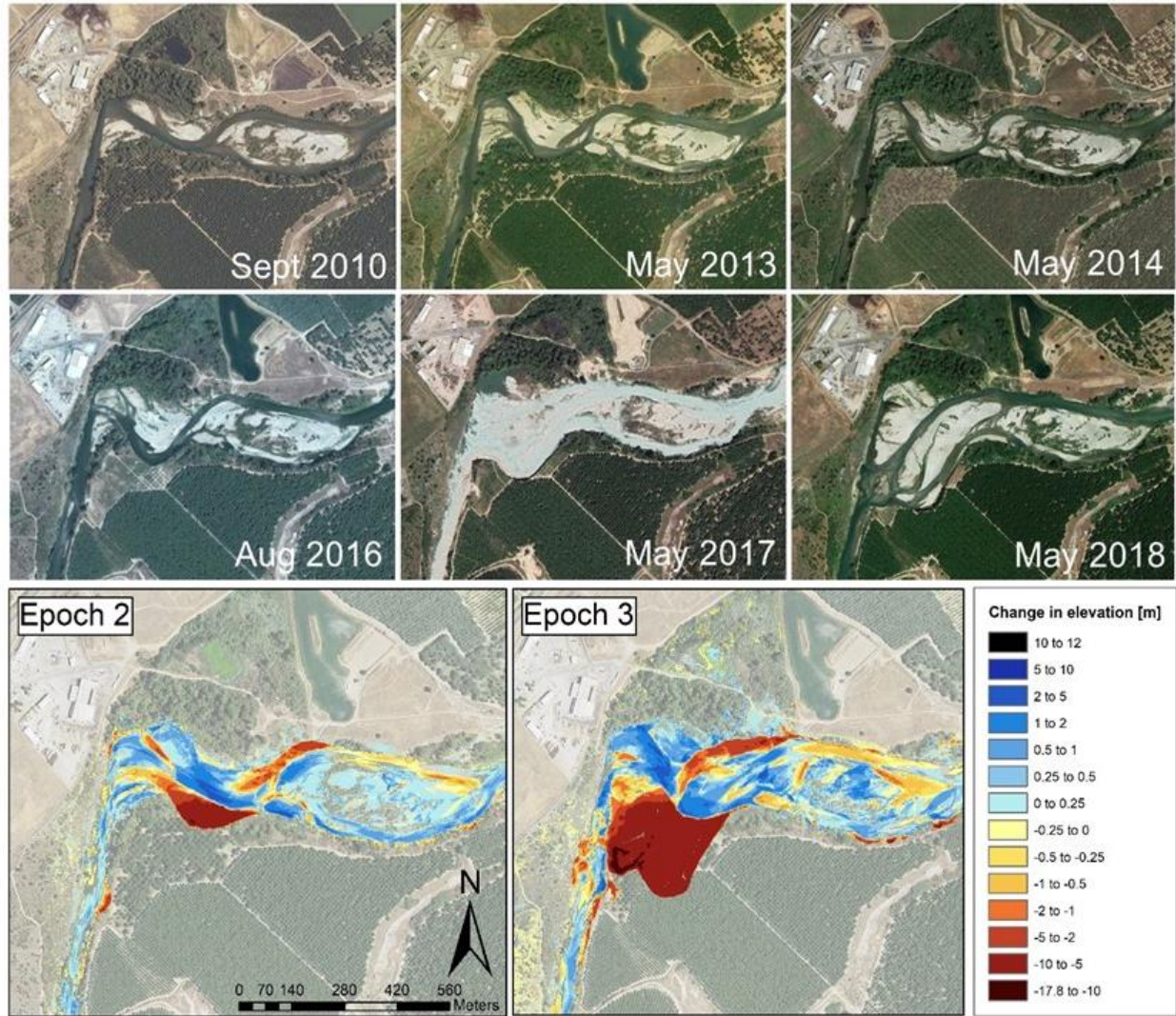


Figure 13. Top: HR terrace September 2010 – May 2018 (Google Earth Pro, 2020). Bottom: Epoch 2 and 3 DoD rasters.

Flood peak magnitude not correlated with erosion and export

The main finding of this study was that peak discharge was not correlated with total scour nor net export of sediment across epochs, and the contradictions were stark. Despite a flood peak during epoch 1 that was 1.5x greater than the peak of epoch 2, not only was there not 150% more sediment export—or any greater sediment export in

epoch 1, but instead there was 33% more sediment exported during drought epoch 2 (**Figure 6**). Net export then increased to $1.37 \times 10^6 \text{ m}^3$ over flood epoch 3, a 21.8x increase in export from the first flood epoch 1, even though epoch 3 had a 25% lower peak flood. Of the $1.57 \times 10^6 \text{ m}^3$ net volume of sediment exported out of the LYR over the 18-year period, 87.2% occurred over 3 years during epoch 3 (**Figure 6**).

It is important to differentiate the statement “more erosion” as it relates to net scour/export versus total scour. The first indicates how well re-deposition balanced erosion, while the second captures the magnitude of scour events alone. Epoch 1 actually did experience much more total scour than epoch 2 (-2.52×10^6 and $-0.64 \times 10^6 \text{ m}^3$ respectively) (**Figure 7**). The key difference was that re-deposition in epoch 1 was great enough to nearly negate scour. Segment scale re-deposition was positively related to peak discharge which explains the small net export of epoch 1. In epoch 3, scour volume was greater than in epoch 1 by 34.7% while re-deposition decreased by 17%, causing a large overall increase in net export. A stronger relationship exists between total scour and the hydrologic duration and volume metrics, rather than the peak metric. Comparing total scour between the two flood epochs shows a connection between scour and volume discharged, especially above floodway stage (**Figure 10**, **Figure 14**).

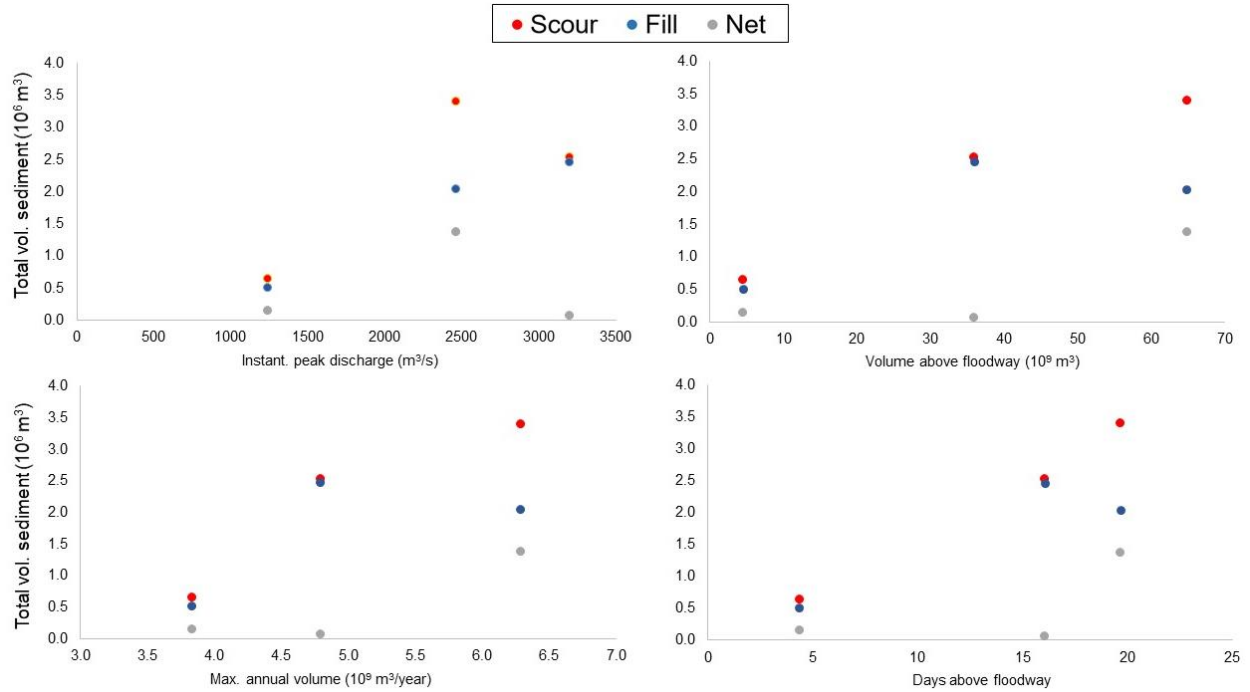


Figure 14. Example relationships between scour, fill, and net topographic change at the segment scale (y-axis) against various hydrologic metrics (x-axis).

These results contrast with uniform channel dynamics in which higher peak discharge leads to more erosion as dictated by total bed load transport. However, the Yuba River's hydro-geomorphic dynamism fits well within the geomorphic effectiveness framework and flood archetypes from the literature. The epoch 3 period experienced long duration flooding and high release volumes, especially above floodway, with the peak flood year (2017) experiencing the greatest annual volume of discharge, analogous to flood energy, relative to any year within the previous two epochs (**Table 3, Figure 10**). While the epoch 1 flood best matches the type A flood curve, with a high peak and short duration, epoch 3's flood fits the profile for the type B high peak, long duration flood type as described by the geomorphic effectiveness model (e.g., **Figure 2**). Type B flood types are predicted to be the most geomorphically effective fluvial

events in any landscape and include exceptional floods like the Rubicon River, California (1964) and Teton River, Idaho (1976) dam-failure floods, and colossal paleofloods like the Missoula Flood, Columbia River Gorge (~13,000 years before present) and the Bonneville Flood, Idaho (~14,500 years before present) (Costa and O'Connor, 1995; Baker & Costa, 1987).

These findings highlight why annual peak discharge, one of the most common hydrologic metrics used in flood frequency analysis, can be an oversimplified indicator of the true magnitude of a flood period in regard to fluvial geomorphic response. Although the traditional annual maximum method is still one of the most commonly used at U.S. stream gaging sites and internationally, defining samples using only this method results in a loss of information, and improvements to flood frequency analysis techniques to capture the behavior of extreme hydrological events are still sought after for this reason (Lang *et al.*, 1999; Bačová-Mitková & Onderka, 2010). Ideally, methods account for temporal complexities of the regime—one example is the peaks-over-threshold (partial duration series) method (Lang *et al.*, 1999) which accounts for years with multiple flood events. However, this flood frequency analysis method still fails to capture both water volume and its temporal distribution; further, this must be translated into metrics at a scale significant to water management. This finding regarding the disconnect between flood peak magnitude and geomorphic response is significant because years with multiple flood peaks and sustained flooding (creating high annual discharge volume) can also stress reservoir infrastructure. Indeed, these two characteristics were defining features of the 2017 water year which exacerbated

conditions during the Oroville emergency spillway failure (White *et al.*, 2019; Vano *et al.*, 2019) ~45 km north of the LYR on the Feather River.

In-channel vs overbank dynamics

In-channel versus overbank dynamics help explain how topographic changes varied at two distinct inundation levels. Because overbank regions were always net scour, they explain the majority of the LYR's net export patterns across the study epochs. In epochs 1 and 3, 80% of scour was overbank scour (**Figure 7**) from terrain above an inundation level of 113.26 m³/s. In epoch 1 the LYR experienced one high peak, short duration winter flood pulse in the 2006 water year; the geomorphic response that allowed the LYR to remain nearly neutral in terms of net export was that sediment eroded upstream was then re-deposited in the overbank (as 1.84 x 10⁶ m³ of overbank fill), especially in reaches below DPD (**Figure 8**). Due to the nature of the multi-flood epoch 3 period, it is possible that the same overbank re-deposition process may have initially resulted following the first flood pulse, with the subsequent sustained flood leading to evacuation of that re-deposited sediment. Interestingly, the in-channel region also experienced the most fill in epoch 3 (**Figure 7**) displaying how this geomorphically impactful flood period drastically changed the channel geometry. Indeed, areas that were initially overbank in 2014 but became in-channel in 2017 accounted for 62% of overbank scour, confirming lateral migration was a dominant scour process in epoch 3. Combined with the bank collapse observed in this epoch, these findings align with

previous evidence supporting flood flow duration as a primary determinant in channel change and widening (Magilligan *et al.*, 2015).

Effects of flow variability and antecedent conditions

Topographic change outcomes result from the interaction of topographic drivers and hydrology, but observed effects are dependent on time as a second-order variable. What is measured is a product of the time span of observation (e.g., **Figure 13**).

Uniform channel dynamics equations dictate that higher flow leads to more erosion; Recking *et al.* (2012), however, noted that in field experiments, the predictive accuracy of erosional behavior using channel bed load transport equations increases over longer timescales of measurement. Further, caution is advised against the notion of expecting geomorphic response to scale linearly with energy input, given the often non-linear behavior of complex river systems with diversity of topography, processes, and non-uniform flow patterns (e.g., Hooke, 2015; Lisenby *et al.*, 2016).

Mediterranean climates, like this study area, are particularly prone to ‘whiplash’ events involving rapid shifts from extreme drought to extreme flood conditions, such as the 2016-2017 flood period following the dry 2012-2016 period in California (Swain *et al.*, 2018). El Niño years experience above-normal precipitation concentrated in winter, generally resulting in landsliding and greater fluvial sediment flux (Mertes & Warrick, 2001; Gray *et al.*, 2015b; East *et al.*, 2018b). Drought periods can lead to decreased soil moisture, low runoff efficiency (Davenport *et al.*, 2020), and a build-up of flood-transportable sediments. Therefore, the large sediment evacuation event observed in

epoch 3 may also be a product of the extremely dry conditions leading up to the event. The LYR's flow regime is quite dynamic, and flow heterogeneity is known to promote process diversity (Parker *et al.*, 2003). Indeed, many of Australia's coastal rivers, which are similarly dominated by alternating flood and drought regimes, change cyclically in response to flood cycles and therefore exhibit continuous changes rather than becoming statically adjusted to mean annual or bankfull discharge (Erskine & Warner, 1988). It is pertinent, therefore, to also account for antecedent conditions, regime variability, and concentration of flow volume in time when predicting geomorphic response.

While this study captured broad differences between dry and wet periods, it did not have enough temporal resolution to isolate different processes and rates of change in different stages of hydrograph rise and fall on an event basis, nor compare dynamics between periods of small floods right after a large flood versus long floods after a large flood. Temporal positioning of a topographic change study relative to antecedent conditions has not been addressed in the literature and remains one of the most important topics future studies could address. It is especially difficult, because the weather cannot be controlled to obtain particular sequences of events in nature, whereas flume studies capable of such control cannot yield the morphodynamic diversity of a river like the LYR. For the LYR, past work sheds some light to help constrain what might be missed in this instance and why this topic would be interesting to investigate more.

Pasternack (2008) carried out repeat surveys of one pool-riffle-run site on the LYR in 1999, 2004, 2005, and 2006 to evaluate how rates and patterns of

morphodynamics vary locally for different kinds of flow regimes, but without the rigorous hydrological analysis herein. The period 1999-2004 was a normal period (**Figure 4**) with several smaller events (maximum instantaneous peak ~ 5 times bankfull discharge) shortly after one of the largest rain-on-snow events in recorded history (January 1997). Meanwhile, the period 2004-2005 had a moderate flood (Sawyer *et al.*, 2010), and then 2005-2006 had the large flood discussed earlier (**Figure 4**). Although the study did not use sophisticated uncertainty analysis as it exists now, it found that the 1997 large flood ripped up the armor layer and left behind over-steepened, unconsolidated riverbanks. As a result, the smaller floods 1999-2004 were able to create locally intense scour at these weak points, and then, given sufficient duration (5 years), the material could be predominantly transported out of the site (though it was not known how far downstream it went). These results are very similar to the subsequent findings of Weber & Pasternack (2017), but the later study spanned the whole river and was able to confirm that in fact most of this type of local scour does not travel far downstream. Field observations of riffles as part of redd surveys found that riffles re-established bed armor over time from 1999-2005, but the moderate May 2005 flood (Sawyer *et al.*, 2010) was enough to remove that again and trigger knickpoint migration at riffles (Wyrick & Pasternack, 2007). The New Years' flood of 2006, just seven months later, catalyzed dramatic changes as bed and banks were destabilized. Interestingly, that flood ended up filling in the channel significantly and creating new channels via avulsions. From 1999-2006, ~ 2/3 of change occurred in the New Years' flood period, while 23% occurred over the long 5-year period 1999-2004. While these results were never formally peer reviewed, they provide insights into the finer details of antecedent

conditions and motivate future research to not only perform repeat surveys immediately after large floods, but ideally at multiple moments during normal conditions to isolate effects during different stages of recovery between disturbances.

VII. Conclusions

Morphodynamic processes in rivers are comprised of complex interactions between topography and hydrology. However, hydrographic forcing is independent in that hydrologic input is a driver external to the river system itself (e.g., Figure 1). Therefore, characterization and differentiation of hydrologic metrics is important in order to distinguish different flood period ‘types’ (e.g., types A, B, C of the geomorphic effectiveness flood energy model), and their effects. While the ‘cause’ and ‘effect’ aspect of fluvial geomorphology is hardly straightforward, it is nonetheless the goal of geomorphic effectiveness studies and fluvial morphodynamics models to link geomorphic patterns to hydrologic metrics. This study presents a novel approach to distinguish flood periods at a scale significant to geomorphic river response, using threshold-based volume and duration analysis. In the lower Yuba River, California, peak discharge was found to be less effective than duration and volume of flood events in initiating high volumes of scour and net export of sediment. This finding highlights the need for including these hydrologic metrics in considerations for river infrastructure design, erosion control, and flood planning.

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Flooding duration and volume more important than peak discharge in explaining 18 years of gravel-cobble river change

SUPPLEMENTARY MATERIALS

This file is organized in the same structure that parallels the sections in the article, with further information on any topic discussed or background on the study.

I. Introduction supplements

Topographic change processes in rivers

Defining fluvial change mechanisms and processes is still a burgeoning field. Keller (1971) introduced the velocity reversal mechanism in riffles and pools as one of the first fluvial change mechanisms. MacWilliams, et al (2006) later generalized this assertion, providing measurements to show that velocity reversal depends on channel width and valley-scale topology, introducing the flow convergence routing mechanism, a morphodynamic process that relies on stage-dependent topographic steering. There is a lack of detailed studies that analyze the joint roles of dynamic hydrology and hierarchically structured topography in controlling mechanisms of channel change in rivers (Brown & Pasternack, 2013); this motivated the original emphasis of this study (**Table S1**, Objective 1) on scale-dependent changes.

Describing, quantifying, and understanding how rivers follow measurable patterns of geomorphic change enables study of river processes and rivers as functional systems. Process-based restoration (Beechie et al., 2010) is a developing field that employs an understanding of river dynamics in river modification. Conceptually, implementing designs that restore or enhance the “mechanistic chain” (sensu

Pasternack, 2020) creates functional, self-sustaining ecosystems rather than unnaturally static habitats with particular features designed solely to satisfy a management checklist. Thus, topographic change studies provide the essential baseline upon which to quantify geomorphic mechanisms for use in predictive models, and are important aides when modifying a river (Schwindt et al., 2020).

Hydrologic regime significance

None.

Geomorphic effectiveness

Additionally, a river may experience multiple significant inundation zones evident in the topography, soils, and vegetation that play different but important roles in geomorphic processes and ecosystem functions (Brown, 1997). While defining static discharge thresholds and their associated inundation zones aid in characterization and understanding of a particular river system, these often do not account for the complexity and non-linearity of geomorphic response and recovery in fluvial systems (Hack, 1960; Lisenby et al., 2018).

Topographic change detection

Topographic change detection has evolved in sophistication over the past century with cartometry (Hooke & Perry, 1976), cross-section averaging (Langbein, 1964; Stewardson, 2005), and contour-mapping giving way to high resolution digital point clouds using RTK-GPS (Brasington et al., 2000), total stations (Milne & Sear, 1997), aerial photogrammetry (Winterbottom & Gilvear, 1997; Lane, 2000), multi-beam echo-sounding (Calder & Mayer, 2003) and airborne LiDAR (Cavalli et al., 2008). Often,

multiple techniques are combined (Williams et al., 2014). Meter-resolution mapping is now advancing the understanding of non-uniform gravel-cobble rivers (Passalacqua et al., 2015). Instead of taking a small number of subjectively located cross-sections in the field to characterize a river, fluvial geomorphologists can quickly generate meter-resolution digital elevation models (DEMs) of tens-of-kilometer river segments to identify changes and processes in a river with ‘near-census’ accuracy (Gonzalez & Pasternack, 2015).

Topographic change detection (TCD) is the method for producing a DoD raster with > 95% statistical confidence. Quantifying topographic change starts by mapping the landscape at two times and then observing how it changed by subtracting the older DEM from the more recent one to create a DEM of difference (DoD) raster. The procedure must also include a thorough, spatially explicit uncertainty analysis to account for numerous complications, such as survey and interpolation errors (DeVries and Goold, 1999; Brasington et al., 2000; Heritage et al., 2009) presence of vegetation and water, and mathematical propagation uncertainty (Wheaton et al., 2010; Carley et al., 2012). Additionally, these uncertainties are not spatially uniform but change with data collection methods and sampling point density and configuration (DeVries and Goold, 1999; Brasington et al., 2000).

II. Study objectives supplements

Classic topographic change analysis using cross-sections enabled a simple one-to-one testing framework in which one change (either at one cross-section or averaged at the reach scale) could be related to one hydrologic variable (e.g., peak discharge) via

one hydrodynamic inference (e.g., stream power). Modern topographic change detection is significantly more spatio-temporally detailed, accurate, and geomorphically meaningful. Modern topographic change studies show that change patterns reflect multiple processes over-printed on top of each other and/or laterally adjacent such that they cannot be isolated, let alone easily isolate distal controls (Wheaton et al., 2013; Mandlbürger et al., 2015; Pasternack & Wyrick, 2016). As a result, it is significantly more difficult to relate complex map products to simple distal controls of hydrology, sediment supply, topography, etc. Pasternack and Wyrick (2016) proposed that the solution to this conundrum is to analyze topographic change datasets within a multi-scalar framework using object-oriented data stratification. By mindfully stratifying data with different kinds of objects, one can isolate specific patterns of topographic change data to answer specific scientific questions about distal, local geomorphic controls (Pasternack & Wyrick, 2016).

The supplementary file offers additional spatial scales, with topographic changes analyzed longitudinally as well as within morphological units, which offered additional insight to how topographic changes varied in each epoch, highlighting topographic controls and influences such as dams and mining tailings (**Table S1**, Objective 1). Within hydrologic metric objectives, additional analysis was done to compare the daily averaged and 15-minute flow results for each metric, in order to highlight the difference between using coarse and fine scale (temporal) data (**Table S1**, Objective 2).

Table S1. Full study design table.

Objective		Scale	Questions	Metric	Method
1- Topographic change scales and metrics	A	Segment	- Is the LYR net scour or net fill? - How was scour and fill distributed between in-channel and overbank regions? - Do the results change in areas above and below DPD? - What was the longitudinal profile of fill/scour from upstream to downstream? Are there distinct areas dominated by scour or fill near the dams?	Volume sediment (m ³ , m ³ /yr), Area (%)	- Measure total volume of scour and fill in the LYR. Scour - fill = net. - Stratify into in-channel (≤ 113.26 m³/s) and overbank (> 113.26 m³/s) regions and repeat. - Separate into regions above and below DPD and repeat. - Stratify the LYR into 6.096-m spaced longitudinal station boxes along the thalweg, clip to DoD extent.
	B	Reach	Which reaches were net sources or sinks of sediment?	Volume sediment (m ³ , m ³ /yr)	- Stratify scour, fill, and net by geomorphic reach to create sediment budgets. - Net scour = source. Net fill = sink.
	C	Morpho-logical unit	Controlling for areal size, which MUs are scouring or filling at the fastest rates?	Depth (mm/yr)	Using the MUs delineated at the start of the survey period (available for epochs 2 and 3 only), measure the mean rate of net change of depth.
2- Characterize the hydrologic regimes through hydrologic metrics	A	Daily, 15-minute	- What were the peak flows (year/epoch)? - What are the recurrence intervals for these peak events?	Peak (m ³ /sec)	- Compile gage flow readings between 1999 and 2017 water years and find annual peaks. - Use Bulletin 17-B method in HEC-SSP to calculate recurrence intervals.
	B	Daily, 15-minute	- What was the total discharge (year/epoch)? - What were the volumes of water discharged above significant inundation zones?	Volume water (m ³)	- Convert flow to volume and sum for each year using daily flow. - From the 15-minute gage flows, integrate the volume released above each inundation zone.
	C	Daily, 15-minute	- What is the duration in days above the inundation zones? - Does this duration change significantly using daily averaged vs 15-minute flow data?	Duration (days)	Calculate the amount of time spent at or above each inundation zone discharge.

III. Study site supplements

A reach is a section of river with a characteristic set of attributes controlled by the balance of sediment transport capacity, sediment supply, and topography. Wyrick and Pasternack (2012) delineated eight distinct reaches within the LYR segment based on

the longitudinal profile and associated geomorphic variables (**Figure S1**). Delineation factors included confluences with two major tributaries contributing significant water and some sediment supplies during channel-altering flows, presence and impacts of two dams, degree of lateral confinement of the river-corridor by natural valley slopes and artificial berms, and aspects of the longitudinal profile, including bed slope, slope breaks, and bed undulation pattern. Tributary junctions form the upstream boundary of two reaches (NR and DCR) and dams form the upstream boundary for two more reaches (EDR and DPDR). The other reach boundaries are identified by hydro-geomorphic variables: onset of emergent floodplain gravel (TBR); transition from confined bedrock valley to wider, meandering system (PBR); and a decrease in bed channel slope (HR and MR).

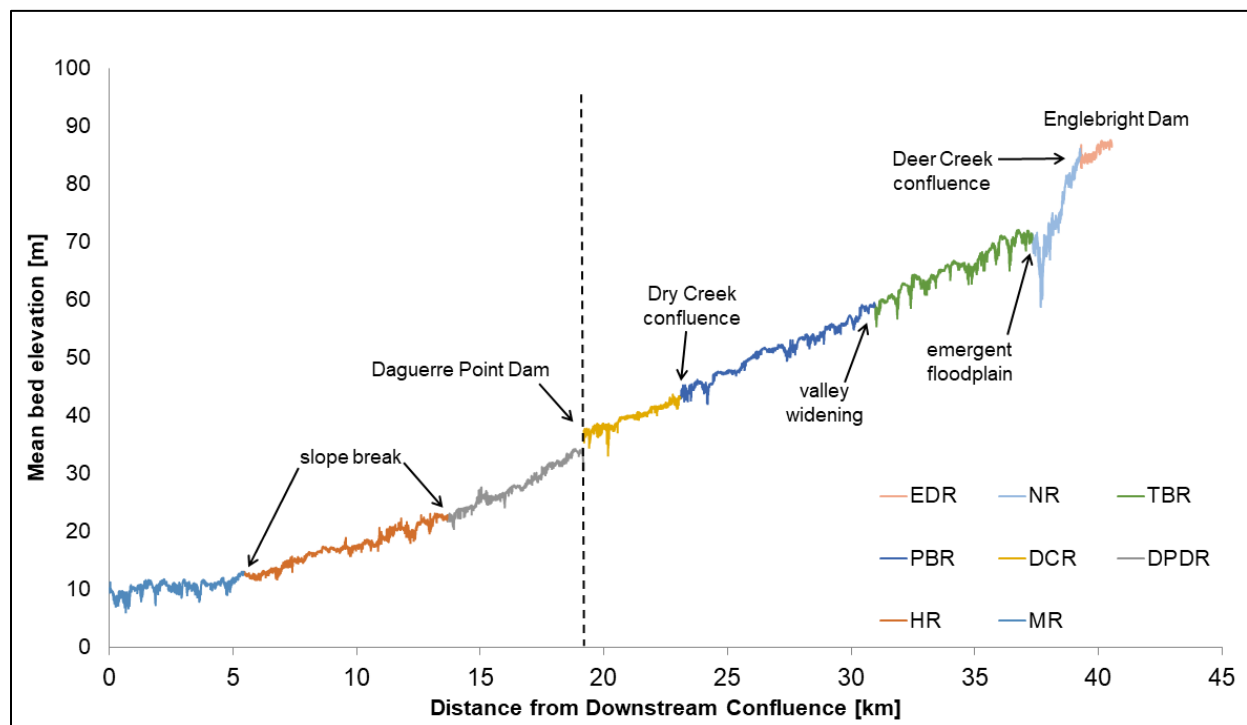


Figure S1. Longitudinal profile of the LYR using mean cross-sectional elevation values from the 2017 DEM, describing the mean elevation of the bed at a discharge of 530 cfs. Geomorphic reach break features are labelled and indicated with arrows.

River corridors also exhibit a cross-sectional pattern with distinct landform features zoned along a gradient that is evident in the topography, soils, and vegetation (Brown, 1997). Each zone plays different but important roles in geomorphic processes and ecosystem functions (Brown, 1997), primarily by setting a river corridor's topographic template within which finer scale dynamics occur. For example, inundation frequency and duration, nutrient availability, and vegetation composition and structure are all demonstrated to vary between lateral zones. Therefore, it is an important step in river assessment to characterize the lateral zonation of a river corridor as part of a modern, hierarchical approach to river ecology (Frissell et al., 1986). Depending on different scientific and engineering needs as well different regional contexts, there exist different lateral zonation schemes. Using the LYR 2006/2008 DEM, Wyrick and Pasternack (2012) applied expert-based methods to delineate the lateral zonation of the LYR, which they termed the “channel regions” (Table 2 in main text). This was a misnomer, as the regions go beyond the channel and span the whole river corridor. They also estimated discharge values to inundate them, and thus used the hydrological term “inundation zone” as synonymous with channel region.

Topographic change history

The California Debris Commission estimated that the LYR valley accumulated ~ 200 million m³ of mining sediment in the late 19th century; nearly 90% remained in 1980 (Adler, 1980). During the late 19th to mid-20th century, gravel and gold miners dredged and re-arranged the topography of the LYR, creating high and wide berms of dredger mine tailings that separate the modern river from the ~ 40-km² of extremely disturbed

landscape (Yuba Goldfields), which is still actively mined. Yuba Goldfields is a labyrinthian, heavily mined, wide valley area isolated from the modern river by high coarse-sediment training berms. Downstream of DPD, river corridor width is constrained by agriculture and engineered levees.

As comprehensive, high-quality datasets became available through remote sensing surveys of the entire LYR, it was detected that between 1999 and 2006/2008 the LYR experienced scour on the order of 2.5 million m³. This was counterbalanced by a nearly equal amount of internal re-deposition (Carley et al., 2012; Pasternack & Wyrick, 2016). Between 2006/2008 and 2014, the LYR experienced, by volume, only 25% of the scour and re-deposition detected previously between 1999 and 2006/2008 (Weber & Pasternack, 2017).

Hydrology

None.

IV. Methods supplements

Temporal scale and topographic surveys

Four high-resolution DEMs of the river bed and valley bottom have been generated for the LYR that provide historical snapshots of the river terrain in 1999, 2006/2008, 2014, and 2017:

- **1999 USACE DEM**. This map is primarily available as 0.6-m contours with supplementary points. Most of this mapping involved aerial photogrammetry and single beam echosounding.

- **2006/2008 USFWS/RMT DEM.** The United States Fish and Wildlife Service (USFWS) funded the Pasternack Lab group at UC Davis to map the Englebright Dam Reach and Timbuctoo Bend Reach of the LYR in 2006. That was done entirely by robotic total station and single beam echosounding tied to RTK GPS. Then in 2008, the Yuba Accord River management Team (RMT) agreed to map the remainder of the LYR downstream of the Highway 20 bridge using airborne near-infrared LiDAR, single beam echosounding tied to RTK GPS, and ground surveys to fill data gaps. The only sizable gap in the map is the Narrows Reach. There are many highly localized data gaps resolved through interpolation. This DEM and its development are thoroughly described in Pasternack (2009).
- **2014 RMT DEM.** The RMT funded a new map in 2014; the survey for this map involved primarily airborne LiDAR using both near-infrared (NIR) and green lasers, as well as multibeam echosounding tied to RTK GPS. There was also some single beam echosounding tied to RTK GPS and ground surveying. For inaccessible pools too deep for green LiDAR, a depth-to-water color calibration was used. There are no data gaps in this map, but in some parts of the Narrows Reach the color calibration has high uncertainty. This DEM and its development are thoroughly described in Weber and Pasternack (2016, 2017).
- **2017 YWA DEM.** In 2017 Yuba Water Agency (YWA) funded a new map using the same methodology used in 2014. Data gaps in the inaccessible Narrows Reach were filled with points estimated in 2014, so that area has

essentially the same topography in the 2014 and 2017 maps. This DEM and its development are thoroughly described in Silva and Pasternack (2018).

DEM differencing and topographic change detection

Conceptually, quantifying topographic change ought to be as simple as mapping the landscape at two times and then observing how it changed by subtracting the older DEM from the more recent one. The resulting subtraction raster(s), known as a DEM of difference (DoD), is commonly used to detect topographic changes (Carley et al., 2012; James, Hodgson, Ghoshal, & Latiolais, 2012). The process of determining which apparent changes in a raw DoD are real to a 95% confidence level is then the topographic change detection (TCD) analysis process. Locations where the combined uncertainty exceeds the raw topographic change are deemed to have not changed with sufficient confidence to count them in a topographic change analysis (**Figure S2**, white color).

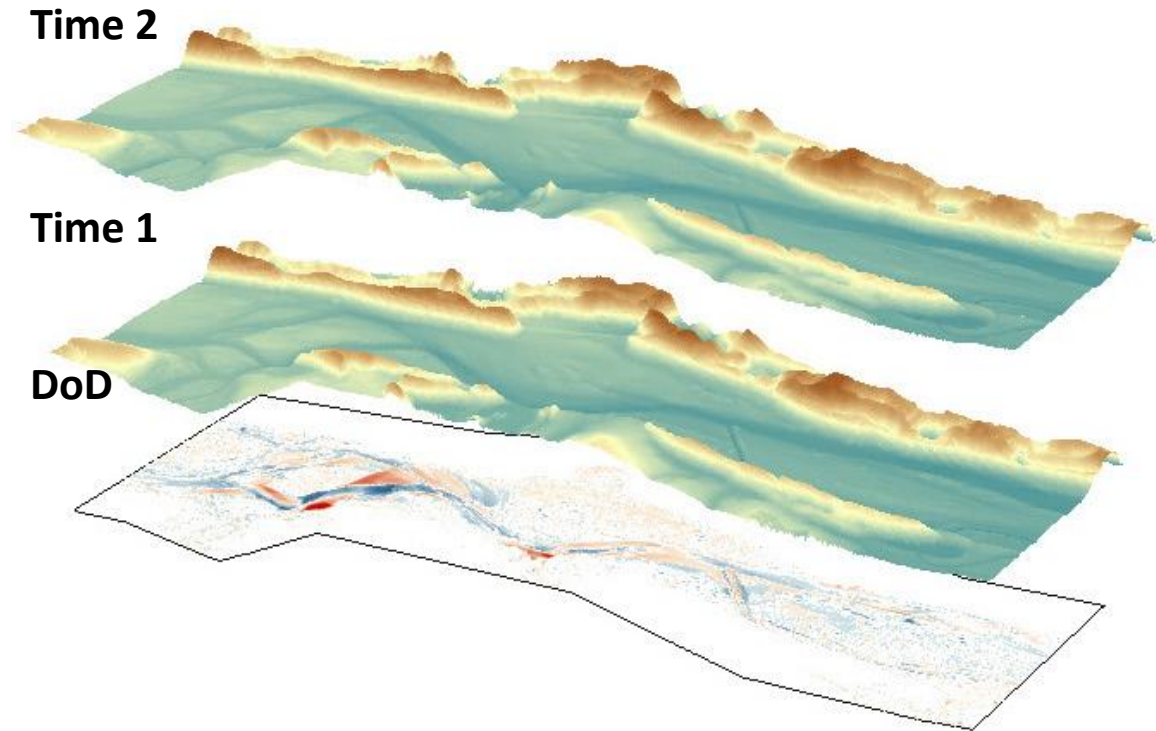


Figure S2. Topographic change in a spatially explicit, 2D map. Example DEM of difference (DoD) created by subtracting the older DEM from the more recent DEM. DoD indicated by colors in the bottom image. Intensity of red indicates more intense scour, while that of blue indicates more intense fill (in regards to depth change). White indicates area where the observed change is less than the uncertainty in the analysis and thus no change is accepted as real.

Uncertainty is detected and quantified in meters of depth change through the creation of a statistically significant Level of Detection (LoD) raster, using the workflow from Weber and Pasternack (2017). This LoD₉₅ raster (where the “95” subscript refers to the statistical confidence level in percent) is subtracted from the raw difference in the DEMs to obtain a DEM of Difference (DoD₉₅) (**Figure S3**). We are left with the statistically significant changes in terms of either fill or scour, to understand the natural phenomenon of topographic change within the river. The DEM Differencing workflow is diagrammed in **Figure S5** with example output rasters displayed in **Figure S6**. The full

process, including the steps used to calculate uncertainty for the LoD₉₅ raster for epoch 3 is further elaborated in the following steps:

- a. The ground classified points from LiDAR/bathymetric survey data collection were used to create a raster DEM for the start and end years (2014 and 2017), with 1.524 x 1.524-m² pixel resolution. The average point spacing for this point cloud dataset is 0.272 m.
- b. Each elevation value in a DEM's pixel is determined by averaging (or interpolating) the values of all the LiDAR or bathymetric survey points that fall within the pixel's area. Topographic variability (*SD_Z*) is the standard deviation of each DEM pixel's elevation value due to slope and uneven terrain. The *SD_Z* at each pixel was calculated with two methods: (i) Using LAStools (Isenburg, 2014) point cloud analysis software for the ground-classified point cloud. (ii) The method outlined in Carley et al. (2012) which interpolates over data gaps by generating a terrain and 0.3048 x 0.3048-m² DEM from the ground points before converting the DEM back into points, enabling a sample of 25 points within each pixel of a 1.524 x 1.524-m² grid to calculate a standard deviation value for the pixel. The two rasters generated using methods (i) and (ii) are combined, retaining only the larger of the two *SD_Z* values for each pixel to generate a topographic variability raster with no data gaps.
- c. A land cover raster was generated by whether the area's primary cover is water, ground, or vegetation using the topographic point cloud data. A standard survey error (*SE*) value was assigned to each land cover type. The chosen *SE* value for each land cover type were calculated using the following methods:

- i. **Vegetation SE** is an average LiDAR vertical error value for leaf-on conditions taken from the literature. A review of literature for vertical errors in LiDAR for forested settings was conducted by Weber and Pasternack (2017). For the 2017 Vegetation SE, the value used was the same value chosen by Weber and Pasternack (2017) for the 2014 data, because the 2017 LiDAR data was collected in the summer, which would represent leaf-on conditions. The studies that represent leaf-on conditions (Edson and Wing, 2015; Gould et al., 2013; Reutebuch et al., 2003) present a range of survey errors; averaging these values yielded a value of 0.30m. This value represents vegetated cover SE for both the 2014 and 2017 data.
- ii. **Water SE** was calculated by comparing the accuracy of points collected using bathymetric survey to points taken by airborne LiDAR in areas where the points overlap. Points from these two sources were spatially joined within a 5cm radius. The difference in elevation values between each pair of joined points was calculated and the standard deviation in error was calculated by each geomorphic reach (**Table S2**). The method used weighted the standard deviation of error in joined points for each reach by the number of total joined points. The values of the weight multiplied by the standard deviation of error for each reach are summed together to obtain an estimate of total error present for water cover across the entire LYR. For the 2017 data the total Water SE value was calculated as 0.233m. For the 2014 data, the Water SE was 0.074m.

Table S2. Comparison of elevation values using joined points from the LiDAR and bathymetric survey data sets.

Reach	MR	HR	DPDR	DCR	PBR	TBR	NR	TOTALS
Number of points	8,067	1,353	804	528	2,033	10,014	252	23,051
SD error (m)	0.207	0.117	0.092	0.070	0.960	0.133	0.589	2.169
Weight (pts/total pts)	0.350	0.059	0.035	0.023	0.088	0.434	0.011	1.000
SD*weight	0.072	0.007	0.003	0.002	0.085	0.058	0.006	0.233

iii. **Bare earth SE** was calculated by comparing the accuracy of survey LiDAR points collected at different times in areas where no topographic change occurred (ie. paved roads near the survey area). LiDAR data points from both the 2014 and 2017 data sets were selected using 8 polygons drawn on 3 different stretches of roads with bridges that cross the LYR. There are 4 polygons on each side of the river; 6 are downstream of Daguerre Point Dam and 2 are upstream of the dam. The 2014 and 2017 points were joined with a 5cm search radius, resulting in 2,147 sample pairs with a standard deviation in elevation of 0.041m (Table S3).

Table S3. Comparison of elevation values of joined points from the 2014 and 2017 LiDAR data sets on road surfaces throughout the LYR.

N	Mean Error (m)	Median (m)	Standard Deviation (m)
2147	0.016	0.024	0.041

d. Topographic variability (SD_Z) and survey error (SE) rasters were combined, using the equation below, to compute a total variability (SD) raster:

$$SD = \sqrt{(SD_Z)^2 + (SE)^2}$$

- e. A point density raster (N) was generated with LAStools (Isenburg, 2014) using the original point cloud data, identifying the number of survey points per raster cell.
- f. A Standard Error of the Mean (SEM) raster was generated using the raster formula:

$$SEM = \frac{SD}{\sqrt{N}}$$

- g. Steps a-g were completed for both the start and end survey years (t_1 , t_2).
- h. The Level of Detection raster at 95% confidence (LoD_{95}) was calculated for the time interval t_1 to t_2 (2014 to 2017). Vertical error ranged from 0.02 to 6.02 meters across the entire study site, and was log-normally distributed, with error concentrated at the lower end of the values (**Figure S4**). The mean error was 0.16 m, with a median of 0.10 m, skewness of 1.97, and a standard deviation of 0.17 meters. The raster calculation formula used was:

$$LoD_{95} = \sqrt{(1.96 \times SEM_{t_1})^2 + (1.96 \times SEM_{t_2})^2}$$

- i. The DEM at t_1 was subtracted from the DEM at t_2 to get the raw DEM difference. Then the LoD_{95} raster was subtracted from the raw results to yield the statistically significant erosion or deposition that occurred within each raster cell, or the DEM of Difference within 95% confidence (DoD_{95}) (**Figure S3**, **Figure S6**).

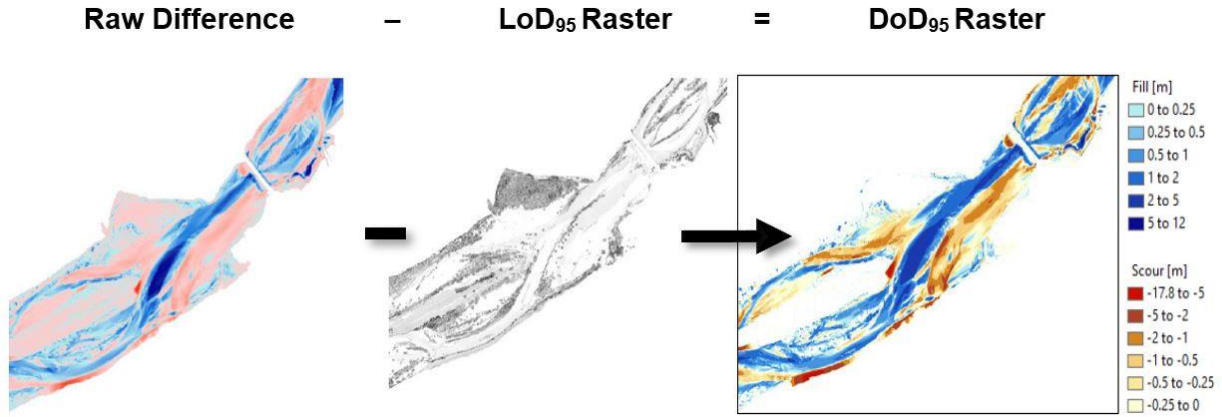


Figure S3. Illustration of the DoD₉₅ raster generation process. First the raw difference in the DEMs is separated into scour and fill and converted to absolute values. The Level of Detection (LoD₉₅) Raster is subtracted from the raw difference raster in order to obtain the statistically significant DEM of Difference (DoD₉₅). Raw elevation change values that are not greater than the LoD uncertainty value for that pixel become no detectable change areas and are removed (white areas) from the DoD₉₅. Positive change values indicate fill (blue) while negative change values (red) indicate scour.

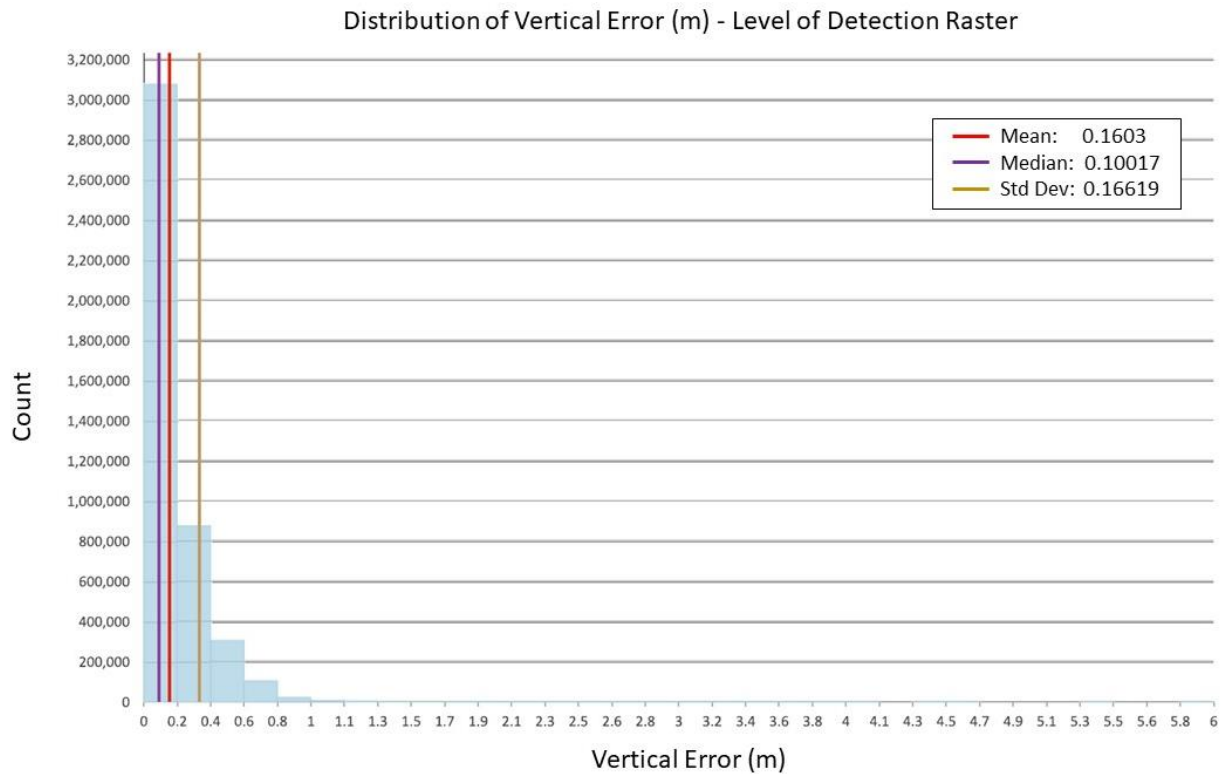


Figure S4. Distribution of vertical error values within the Level of Detection (LoD₉₅) Raster for the 2014-2017 epoch 3 data, which were subtracted from the raw difference to account for uncertainty.

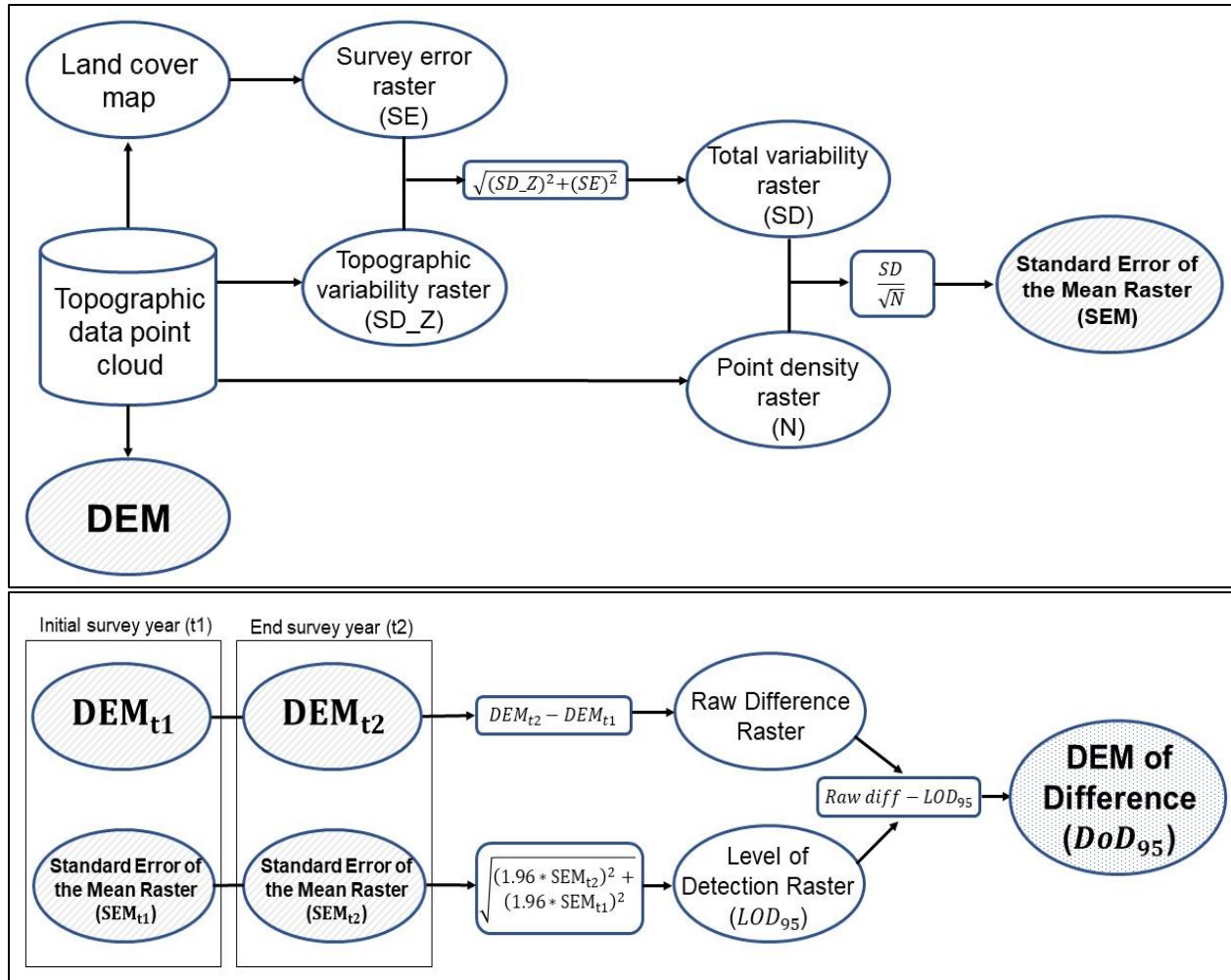


Figure S5. Panel 1) TCD analysis steps to create a Standard Error of the Mean Raster to account for both topographic uncertainty and land cover survey error. Panel 2) TCD analysis steps to combine Standard Error of the Mean uncertainty values for both the initial and ending survey years (t₁ and t₂). Level of Detection Raster (LoD₉₅) detects change within a 95% confidence interval. Subtracting LoD₉₅ raster from the raw DEM Difference yields the statistically significant erosion or deposition, or the DEM of Difference within 95% confidence (DoD₉₅).

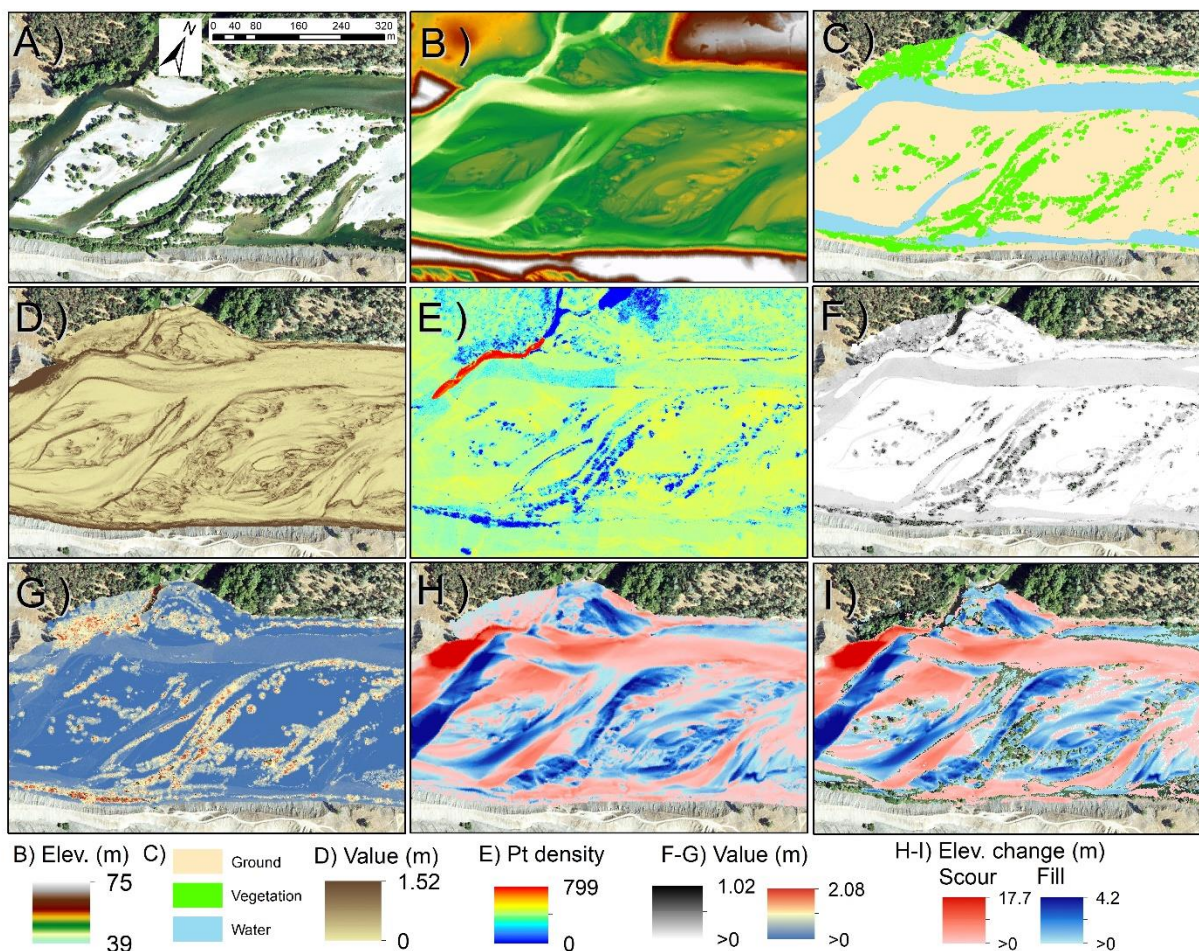


Figure S6. Example outputs from the DEM uncertainty and TCD analysis using the 2017 data. (A) Aerial photo from 2014. (B) 2017 raster DEM. (C) 2017 land cover map. (D) 2017 SD Total variability raster. (E) 2017 point density raster. (F) 2017 SEM raster. (G) 2014-2017 LoD₉₅ raster. (H) 2014-2017 raw DEM difference raster. (I) 2014-2017 Statistically significant DoD₉₅ raster.

There are two advantages of this TCD method. First, it takes into account multiple sources of uncertainty. It calculates error created by topographic variability, as areas with higher slope and more uneven terrain have less accurate elevation values in their resulting DEM pixels, and it takes into account different land cover types (water, ground, vegetation) which yield inherently different levels of accuracy in their elevation values during topographic survey data collection. Second, because the LoD₉₅ raster takes into account these unique characteristics within each pixel (slope, ground cover,

and survey point density), the uncertainty value varies for each pixel across the survey area. Thus, change values are maintained in areas where data quality is high, while values are reduced or discarded in areas where survey accuracy is low. This makes it less likely that significant change will be excluded from the resulting DoD₉₅ raster, especially when compared to other methods of uncertainty calculation, such as uniform-error thresholding (Carly et al., 2012).

The final DoD (synonymous with DoD₉₅) map represents the net change in topographic elevation or depth over the survey epoch for each pixel. Any variability that occurred between the two map dates cannot be accounted for with this methodology. For example, if a pixel scoured some amount one year, then filled in the same amount the following year, the data would show that as “no change”. Similarly, the exact timing of when the change occurred within the epoch cannot be determined.

The final resolution for all DoD rasters is 1.524 x 1.524-m² (5x5-ft²) pixels to standardize them for comparison. This dimension was chosen because larger pixels cause too much uncertainty in locations with steep side slopes, which are abundant along the LYR given extensive training berms. Smaller pixels lack enough survey points to enable robust statistical results. Each raster was resampled and aligned on a snap grid, and projected in NAD_1983_2011_StatePlane_California_II_FIPS_0402_Ft_US, ensuring that all DEMs and resulting DoDs were spatially aligned for TCD analysis.

Topographic change framework

Topographic changes were analyzed at segment, reach, and morphological unit (MU) scales to isolate patterns of change to address different scientific questions (Pasternack & Wyrick, 2016). The segment scale was sub-divided further into areas in-

channel vs overbank, above and below DPD, and longitudinal station boxes, only the first of which is discussed in the manuscript due to word constraints. Morphological units were not presented as they could not be replicated for all study epochs of change, but they yielded interesting insights into epoch 3's topographic changes and topographic drivers.

The segment scale refers to analysis of the entire 37-km LYR as one spatial unit. In this study that is modified to eliminate the upstream canyon section that has been subjected to river rehabilitation and gravel augmentation projects. Artificially placed sediment has not yet made it down to where the alluvial valley begins. TCD stratifications done at the segment scale as part of data analysis included above versus below DPD to assess the role of DPD as an artificial base level control that can yield significantly different scour and fill patterns (Wyrick and Pasternack, 2014).

In order to analyze longitudinal topographic change trends in the LYR, cross-sectional rectangles were used to capture sections of the river at equal interval distances from the downstream confluence with the Feather River. To accomplish this, a centerline was drawn for a pre-existing polygon of the valley bottom, and then stationed (segmented) every 6.096 meters. From these station points, perpendicular lines were extended out to the valley boundary and then buffered 3.048 meters in both upstream and downstream directions, thus creating a continuous coverage of the valley area with cross-sectional rectangles (**Figure S7**). These valley centerline station boxes were then clipped to the DoD analysis boundary.

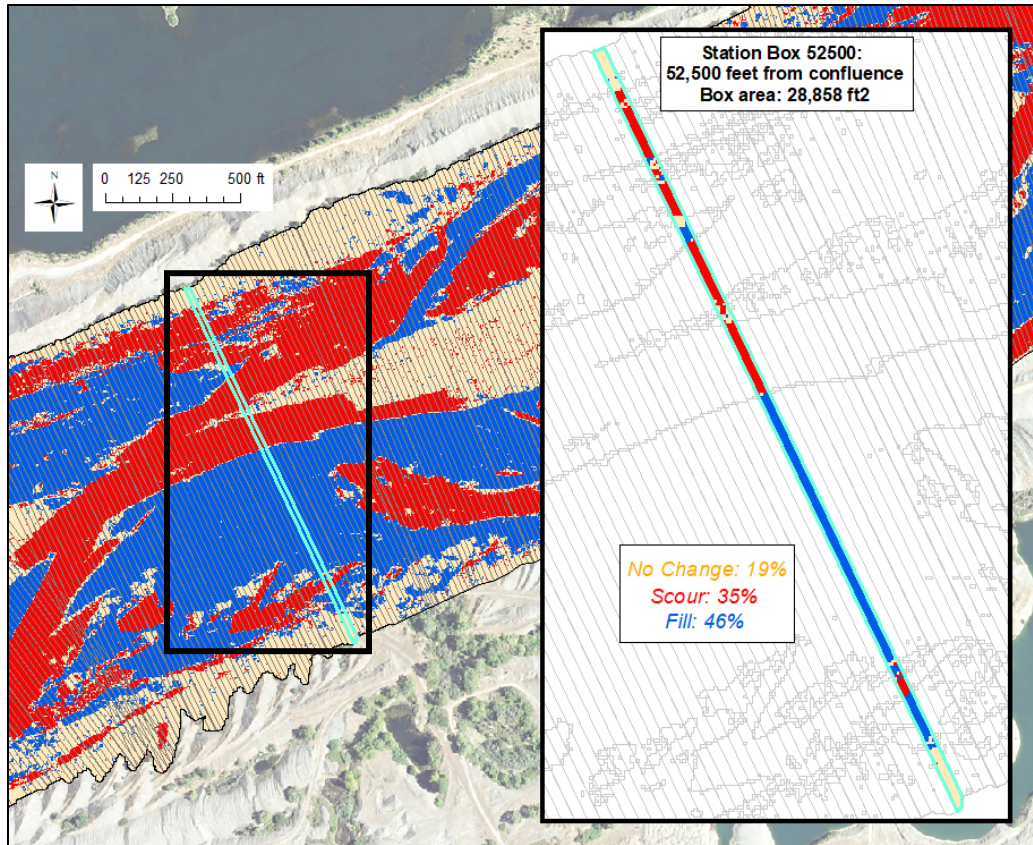


Figure S7. Example coverage area of the valley centerline station boxes used to generate longitudinal profile analyses along the LYR, clipped to the epoch 3 DoD boundary. Example station box shows areal analysis of scour, fill, and no change.

Wyrick and Pasternack (2012) delineated eight geomorphic reaches, of which the lower six are alluvial and upper two are in the bedrock canyon (**Figure S1**). Reach-scale analysis is significant because these geomorphic boundaries do not change from year to year, and it also provides a coarse-scale longitudinal assessment of scour and fill from upstream to downstream. Reach scale analyses only include results for the lower alluvial reaches free of gravel augmentation: MR, HR, DPDR, DCR, PBR, and TBR.

Because the geometries of inundation zones and morphological units (MUs) change over time, one must select whether to evaluate changes relative to the starting

pattern or the ending pattern. For the first epoch, there was no map of these two sets of areas in 1999, because the topographic data gaps were too large for requisite 2D hydrodynamic modeling to be possible. Therefore, Wyrick and Pasternack (2014) evaluated topographic change relative to the ending pattern. In other words, they reported what topographic changes 1999-2006/2008 caused the landform features in the river as observed in 2006/2008. For epochs 2 and 3 it has been possible to analyze topographic changes relative to both starting and ending formations. However, in both cases the reference frame has exclusively been the starting state. Therefore, for 2014-2017 analyses herein, the 2014 states of inundation zones and morphological units were used. For epochs 2 and 3, the change described did not drive MU formation, but is rather the change that occurred within the boundary of the MUs that existed at the beginning of the epoch. As such, epoch 2 and 3 results are directly comparable but epoch 1's results are not. Some MUs changed outside the DoD boundaries (such as backswamps and terraces) because the MU delineation at the starting epoch does not account for boundary expansion that typically occurs from the beginning to the end of the epoch. Man-made features (bridge piers and mining pits) were removed from analyses.

This study analyzed topographic change by scale using area (m^2 , %), volume (m^3 , $m^3/year$), and sediment depth ($mm/year$) metrics, with area and depth results reported here for brevity. Due to different durations and survey timing in epochs 1, 2, and 3, scour and fill results herein are presented in normalized volume per year ($m^3/year$) for direct comparison on a time-free basis and total volume (m^3). Because the three epochs volumetric changes reflect not only differences in driving process, but also

how long there was for change to occur, which varied from 3 to 9 years depending on the reach and epoch. Annual rates represent intensity of changes, while total volumes compare the overall geomorphic work.

Analysis of areas is different from that of the volume and height in that it does not require knowing the exact value of change at a location, just the direction of change as scour, fill, or no change. In that case, the procedure involved converting the fill and scour intensity rasters into presence/absence rasters. Presence area rasters were then converted into polygons.

A sediment budget is an accounting of inorganic particulate mass fluxes and abundances within an established control volume for a specified time period. In this study, the segment-scale control volume is the 37-km river valley from the onset of the alluvial river corridor at the head of Englebright Dam to the confluence of the Yuba River with the Feather River. Apart from turbid mud suspended in the water column as washload, there is zero influx of sediment into the LYR, because the Englebright Dam was specifically designed to block sediment. Both gaged tributaries (Dry and Deer Creek) downstream of the dam are themselves dammed, and Deer Creek is nearly pure bedrock downstream of its own dam, so the input from these tributaries was assumed nearly negligible for purposes of this study. A volumetrically small influx of boulders and angular rocks fractures off the bedrock-soil interface occurs where the perennial channel is against the hillside. In contrast, the valley floor stores on the order of ~ 200 million cubic meters of hydraulic-mining alluvium (Gilbert, 1917; James et al., 2005; James et al., 2009). As a result, the sediment budget for this control volume is greatly simplified and consists of net export equaled by a volumetric loss of sediment storage.

Despite the simplicity of the volumetric sediment budgets, there are assumptions and uncertainties to be mindful of. First, the volumetric sediment budget can only discern and quantify volumetric changes in which there is a net change within a cell. If a cell erodes and then fills back in within the re-survey time domain, then no change will be detected in that cell. Second, it is assumed that there are no non-transport mechanisms of volumetric change (i.e. bed deflation/contraction or inflation/dilation, sensu Merz et al. (2006) and Marquis & Roy (2012)). Also, these analyses allow for the detection of vertical change, but do not track sediment movement. Volumes are not spatially linked; however, one can still observe how much net scour and fill occurs in each region of the LYR. With a reach-scale analysis, these numbers can be used to calculate how much sediment is either transported to the next reach downstream or re-deposits within the reach, and sediment movement and transport is inferred from that.

Depth rate changes help to make direct comparisons across spatial regions of varying areal size, answering questions related to which regions are the most locally dynamic. The mean depths were obtained directly from the Zonal Statistics tool in ArcGIS 10.5, which calculates the mean change in depth for each zone of interest. For scour and fill depth rates, depth change was isolated only to places where the process occurred (i.e., the annual fill rates were described only across the net fill planform areas, and likewise for the annual scour). Net depth rate was calculated differently from the scour depth rate and fill depth rate. Net depth rate was calculated using the net volume rate (annual fill + annual scour) divided by the fill + scour + no change areas, so that this depth rate is calculated across areas even where no change occurred.

Hydrologic metric framework

None.

V. Results supplements

Objective 1: Topographic changes - segment scale

Across the entire LYR (excluding EDR and NR), the segment-scale percent of the annual volumetric sediment that moved classified as 51% scour and 49% fill by volume for epoch 1 (**Table S4**). The percent of the LYR that was scour increased relative to fill over the next two epochs, to 56% scour in epoch 2, and then to 63% scour in epoch 3. This defines LYR as net erosive for all survey epochs. The annual rate of sediment scoured for the entire LYR segment in epoch 3 was $-11.31 \times 10^5 \text{ m}^3/\text{yr}$, replaced by a fill volume of $+6.75 \times 10^5 \text{ m}^3/\text{yr}$ which yields an overall net sediment displacement of $-4.56 \times 10^5 \text{ m}^3/\text{yr}$ scoured out of the LYR system. In terms of annual rates of change, epoch 3 had the great intensity of changes relative to previous epochs.

In reviewing the volumetric rates of scour and fill above and below DPD, in all epochs a greater volume of scour than fill occurred above DPD, though in epoch 1, this difference was much more pronounced, with the rate of scour almost double the rate below DPD (**Table S4**). The areas below DPD were highly depositional in nature in epoch 1, with fill rates at 64% of total volumetric change, almost opposite to areas above DPD, which were about 68% scour. The areas below DPD became less depositional as time went on. In following epochs, scour and fill volumes did not show as much variation above versus below DPD, as the areas below DPD became

increasingly scour-dominant, progressing from 36% scour in epoch 1 to 55% scour in epoch 2, and finally 61% scour in epoch 3.

Table S4. Annual volumetric rates of change in $10^5 \text{ m}^3/\text{year}$ at the segment scale and above and below DPD for epoch 1 (A), epoch 2 (B), epoch 3 (C).

	<i>Annual Scour Rate ($10^5 \text{ m}^3/\text{yr}$)</i>	<i>Annual Fill Rate ($10^5 \text{ m}^3/\text{yr}$)</i>	<i>Annual Net Rate ($10^5 \text{ m}^3/\text{yr}$)</i>	<i>% Scour</i>	<i>% Fill</i>
(A) Epoch 1					
Segment	-2.93	2.76	-0.17	51	49
Above DPD	-1.86	0.87	-0.99	68	32
Below DPD	-1.07	1.89	+0.82	36	64
(B) Epoch 2					
Segment	-1.03	0.81	-0.22	56	44
Above DPD	-0.45	0.33	-0.12	58	42
Below DPD	-0.57	0.48	-0.10	55	45
(C) Epoch 3					
Segment	-11.31	6.75	-4.56	63	37
Above DPD	-6.15	3.44	-2.71	64	36
Below DPD	-5.16	3.31	-1.84	61	39

Table S5 presents the same volumetric results from the in-channel vs overbank analysis, but with scour and fill compared directly between regions, highlighting the relative amount of scour or fill that occurred either in the channel or the overbank as a percent of total scour or fill. Epoch 2 experienced only 54.6% of its total scour outside the channel. Epoch 3 experienced 78.7% scour volume in the overbank and epoch 1 experienced 80.3% of scour out of the channel.

Table S5. Percent of total scour and fill volume that occurred in either the in-channel region or the overbank region.

	% In-channel	% Overbank
(A) Epoch 1		
Scour (annual)	19.7%	80.3%
Fill (annual)	25.4%	74.6%
(B) Epoch 2		
Scour (annual)	45.4%	54.6%
Fill (annual)	83.1%	16.9%
(C) Epoch 3		
Scour (annual)	21.3%	78.7%
Fill (annual)	61.5%	38.5%

In epochs 1 and 2, the LYR showed clearer longitudinal sequencing of scour and fill areas; the main trends seen in epoch 3 were that scour increased moving upstream from Daguerre Point Dam and was most dominant in TBR. Below DPD there were two areas dominated by no change, between which there was an area dominated by deposition (**Figure S8**).

Comparing all epochs, there are large zones of deposition and no change present just downstream of DPD common to all epochs and flow scenarios. For epoch 1, there was a zone of scour directly upstream of DPD, whereas in epoch 2, this appears directly below the DPD, and in epoch 3, one distinct scour zone does not appear.

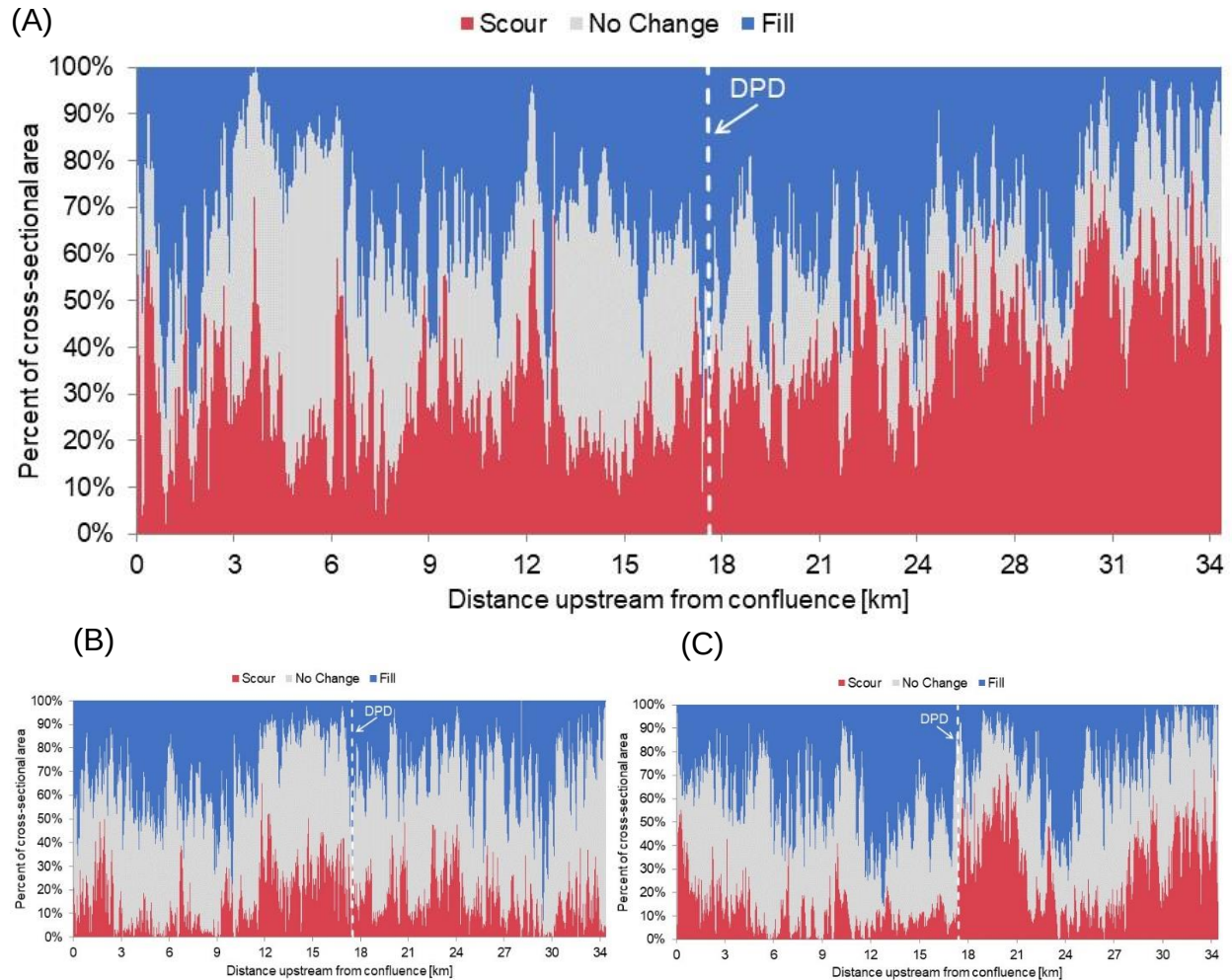


Figure S8. Percent area segment-scale longitudinal patterns of change class for (A) epoch 3, (B) epoch 2, and (C) epoch 1. For reference, DPD is located 17.8km upstream of the Feather River.

Objective 1: Topographic changes - reach scale

None.

Objective 1: Topographic changes – morphological units

Over epoch 3, changes within MUs delineated within the 2014 topography revealed that only three MUs accounted for over 50% of total scour volume: terraces,

tailings, and floodplains (**Figure S9**), which contributed 18.8%, 15.3%, and 22.1% by volume, respectively (**Table S6**). High floodplains were another major contributor, accounting for 11.5% of total scour. Interestingly, although floodplains were highly net scour ($-32 \times 10^4 \text{ m}^3$), they also experienced the greatest fill volume of any MU ($43 \times 10^4 \text{ m}^3$), accounting for 21.2% of total fill volume in the LYR. Riffle transition MUs were the greatest net fill, and accounted for the second greatest fill volume after floodplains, at 9.4% of total fill. Other in-channel MUs, especially fast glides and pools, also experienced notable fill volumes; after riffle transitions, these two MUs experienced the next greatest fill volumes, together accounting for 14% of total fill/re-deposition.

When MUs were analyzed by rate of depth change, this revealed which MUs were locally the most dynamic, when controlling for the overall size of the MU and the volumetric contribution. Tailings exhibited the greatest local vertical dynamism by far, at net scour rates of nearly 10 meters per year over epoch 3 (**Figure S10**; not shown on axis). Terraces were second most net scour, at 1.2 m/year. Therefore, tailings and terraces were significant scour contributors both at the volumetric and local scales. Agriplains, banks, and cutbanks were shown to be more significant locally than at the volumetric scale; these units only exported a small volume relative to the other units because they exist in only a small area of the LYR valley. At the local scale though, those topographic changes were highly relevant and dynamic, each accounting for net scour between 50-100 cm/year. At the other end of the processes continuum, the most dynamic net fill locations were the in-channel chute and run units (at +25 cm/year and +18 cm/year, respectively), putting them at a higher net fill rate relative to riffle

transitions.

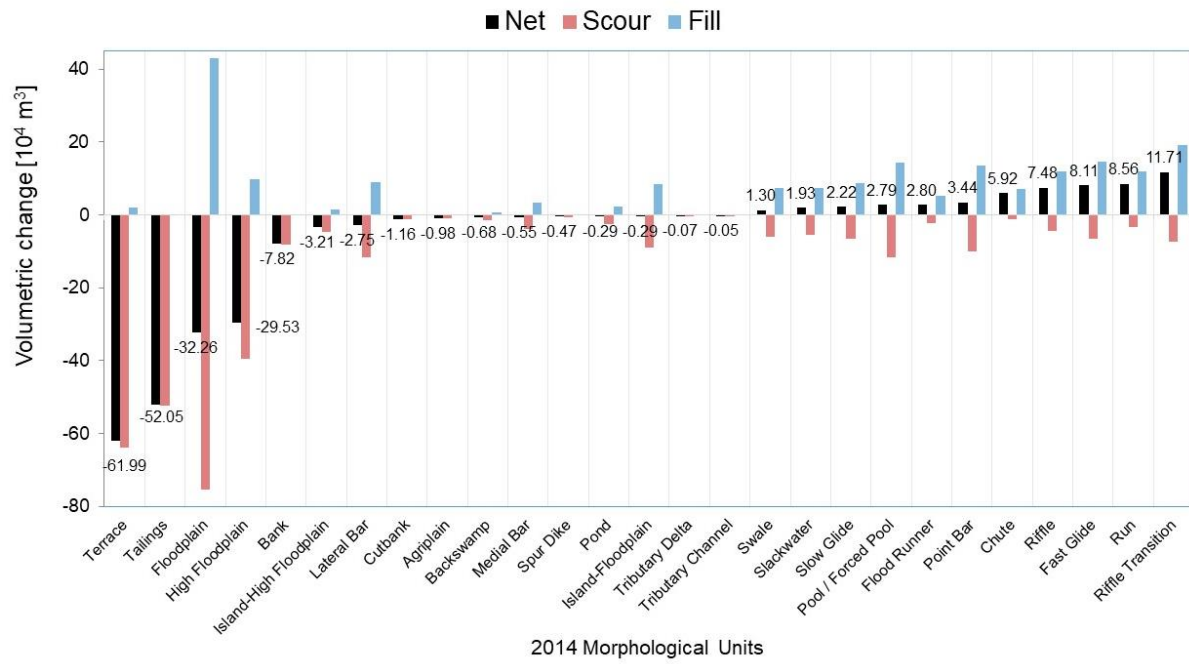


Figure S9. Total volumetric change in 10^4 m^3 within 2014 MUs in epoch 3, sorted from greatest to least net change.

Table S6. Total volumetric change in 10⁴ m³ within 2014 MUs in epoch 3, sorted from greatest to least net change. Includes the MUs delineated but excluded from chart (mining pits, hillside/bedrock, bridge piers).

2014 Morphological Unit	Scour Vol. [10K m3]	Fill Vol. [10K m3]	Net [10K m3]	% Scour	% Fill
<i>Terrace</i>	-63.98	1.99	-61.99	18.8%	1.0%
<i>Tailings</i>	-52.24	0.19	-52.05	15.3%	0.1%
<i>Floodplain</i>	-75.37	43.10	-32.26	22.1%	21.2%
<i>High Floodplain</i>	-39.36	9.84	-29.53	11.5%	4.8%
<i>Bank</i>	-8.03	0.22	-7.82	2.4%	0.1%
<i>Island-High Floodplain</i>	-4.76	1.55	-3.21	1.4%	0.8%
<i>Lateral Bar</i>	-11.71	8.96	-2.75	3.4%	4.4%
<i>Cutbank</i>	-1.23	0.07	-1.16	0.4%	0.0%
<i>Agriplain</i>	-1.00	0.02	-0.98	0.3%	0.0%
<i>Backswamp</i>	-1.42	0.74	-0.68	0.4%	0.4%
<i>Medial Bar</i>	-3.97	3.43	-0.55	1.2%	1.7%
<i>Spur Dike</i>	-0.54	0.07	-0.47	0.2%	0.0%
<i>Pond</i>	-2.53	2.24	-0.29	0.7%	1.1%
<i>Island-Floodplain</i>	-8.83	8.54	-0.29	2.6%	4.2%
<i>Tributary Delta</i>	-0.17	0.10	-0.07	0.0%	0.0%
<i>Tributary Channel</i>	-0.10	0.05	-0.05	0.0%	0.0%
<i>Bridge Pier</i>	-0.04	0.01	-0.03	0.0%	0.0%
<i>Hillside/Bedrock</i>	-0.66	0.86	0.20	0.2%	0.4%
<i>Mining Pit</i>	-0.01	0.21	0.21	0.0%	0.1%
<i>Swale</i>	-5.96	7.26	1.30	1.7%	3.6%
<i>Slackwater</i>	-5.50	7.43	1.93	1.6%	3.7%
<i>Slow Glide</i>	-6.46	8.68	2.22	1.9%	4.3%
<i>Pool / Forced Pool</i>	-11.59	14.38	2.79	3.4%	7.1%
<i>Flood Runner</i>	-2.36	5.16	2.80	0.7%	2.5%
<i>Point Bar</i>	-9.99	13.43	3.44	2.9%	6.6%
<i>Chute</i>	-1.29	7.21	5.92	0.4%	3.5%
<i>Riffle</i>	-4.49	11.97	7.48	1.3%	5.9%
<i>Fast Glide</i>	-6.55	14.65	8.11	1.9%	7.2%
<i>Run</i>	-3.38	11.94	8.56	1.0%	5.9%
<i>Riffle Transition</i>	-7.46	19.17	11.71	2.2%	9.4%
TOTAL	-340.96	203.46	-137.50	100%	100%

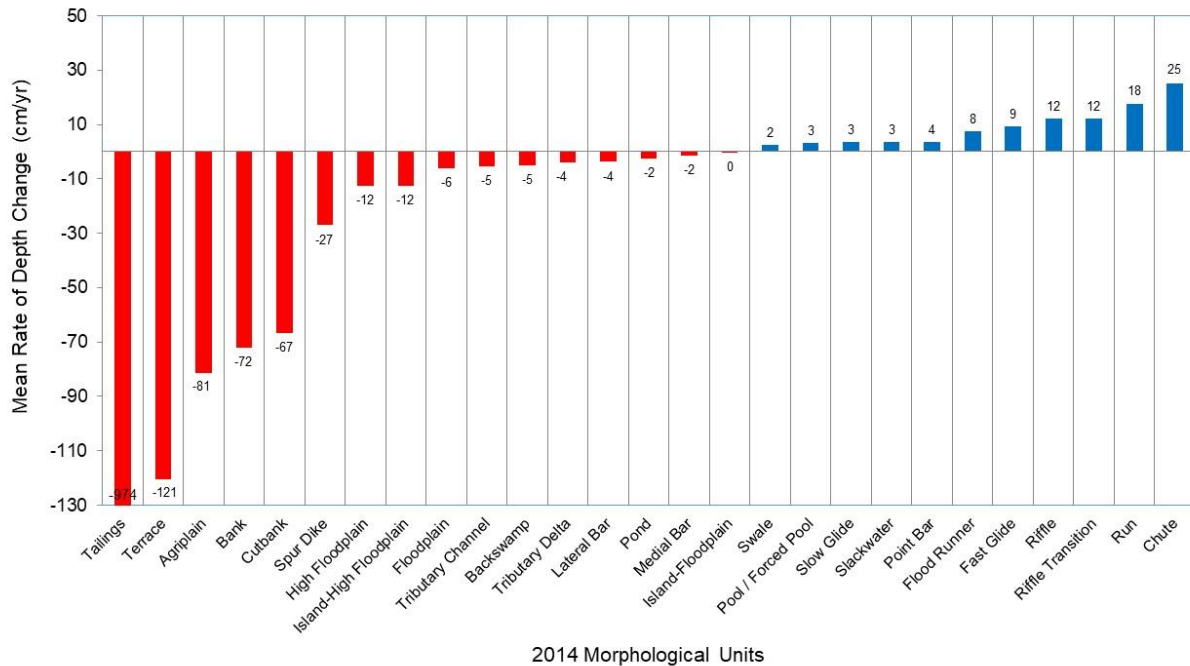


Figure S10. Mean net rate of depth change in cm/year within 2014 MUs for epoch 3, sorted from greatest to least net change.

Objective 2: Hydrologic metrics - peak

The 15-minute and daily average flow data provide significantly different hydrologic analyses. The Marysville gage reveals that the instantaneous peaks from 2006 and 2017 had a much greater disparity in flow rate intensities than was implied by looking at the daily average peaks only, which were instead 2,384 m³/s (compared to an instantaneous peak of 3,206 m³/s) and 2,217 m³/s (compared to an instantaneous peak of 2,466 m³/s), respectively (**Figure S11**). Using the daily data, the peak flow for epoch 2 was 762 m³/s in 2011, but 15-minute data pinpoints a much higher peak of 1,245 m³/s in 2013. For epoch 3, the daily averaged peak flow occurs in February 2017 (**Figure S11**), while the instantaneous peak occurs in January 2017.

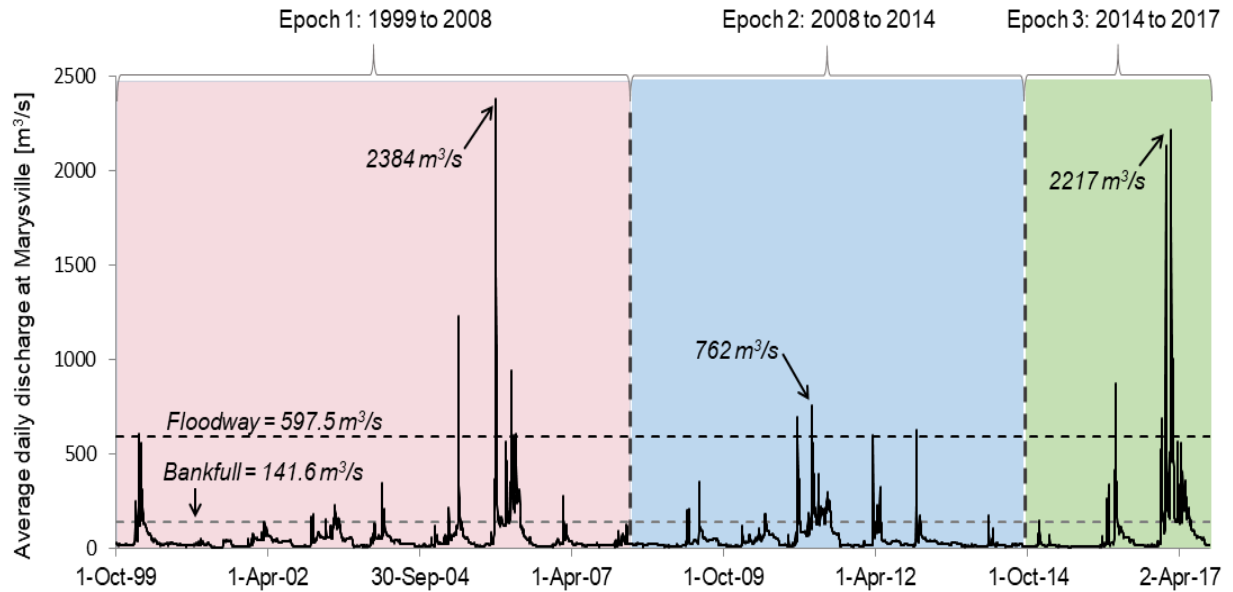


Figure S11. Hydrograph comparing average daily discharge rates (m^3/s) recorded at Marysville gage across survey epoch 1 (shaded red), 2 (shaded blue), and 3 (shaded green). Peak daily discharge for each epoch labelled and indicated with an arrow. X-axis covers October 1st 1999 to September 31st 2017.

For the latest study period, the 2017 peak instantaneous discharge corresponds to a 13-year recurrence interval, while the epoch 1 peak flood corresponds to a 23-year event and 22.6 times bankfull discharge (**Figure S12**).

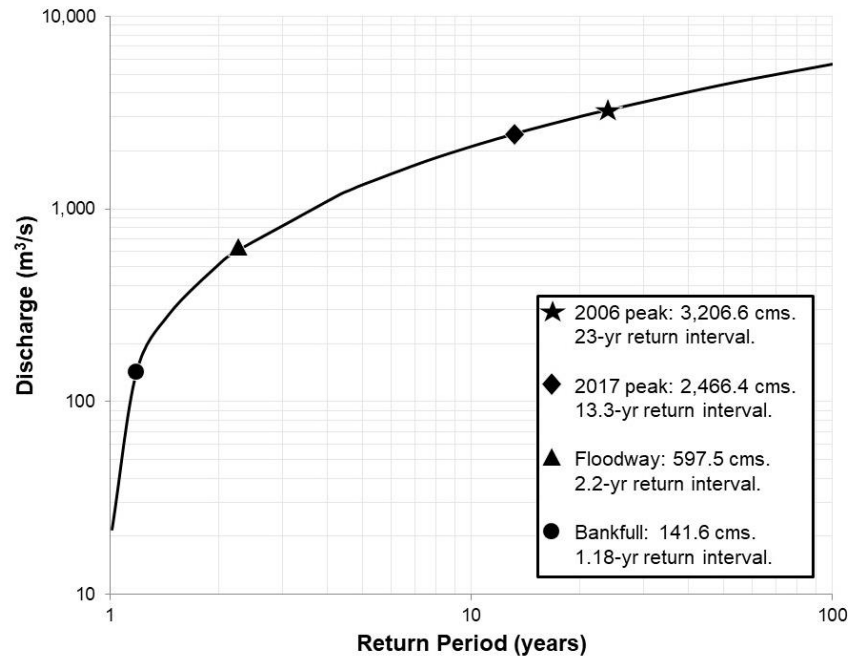


Figure S12. Return periods for selected flows in the LYR. Calculated using Bulletin 17-B method in HEC-SSP with flow data from 1970-2019.

Objective 2: Hydrologic metrics - volume

None.

Objective 2: Hydrologic metrics - duration

The instantaneous gage data also provides a significantly different hydrologic analysis in terms of the duration and volume above inundation zone thresholds. Initial analysis using the daily average data yielded the result that epoch 1 spent 193 days above bankfull and 23 days above floodway, epoch 2 spent 161 days above bankfull and 4 days above floodway, and epoch 3 spent 200 days above bankfull and 18 above floodway (**Table S7**). When the duration analysis was repeated with the 15-minute flow data, the order from least to most days above bankfull is instead epoch 1, epoch 2, and epoch 3.

Table S7. Duration analysis above bankfull (141.6 m³/s) and floodway (597.5 m³/s) using the daily averaged flow at the Marysville gage.

Epoch	Days above bankfull	Days above floodway
Epoch 1	200	18
Epoch 2	161	4
Epoch 3	193	23

VI. Discussion supplements

A non-incising channel and net scour river corridor

For epoch 1, percent scour and fill were nearly opposite in the regions above and below DPD (**Table S4**), with below DPD highly depositional by 64% and above DPD highly erosional at 68%. This trend did not continue as time went on, to where stratifying by above and below DPD yielded the same percent scour and fill as for the whole channel, and in epoch 3 this translated to 61-64% scour both above and below DPD.

The scour zone in TBR, seen in epochs 1 and 3, has been attributed by Wyrick and Pasternack (2014) to three factors: (1) valley constriction limiting width expansion during floods, and thereby increasing velocity as flood discharge increases, (2) “hungry water” (Kondolf, 1997) with water carrying less sediment than its capacity due to a lack of sediment supply generated by the blockage of Englebright Dam, and (3) upstream migration of the “wave” of adjustment of the river’s longitudinal profile to digest hydraulic mining sediment after Englebright Dam was built.

So while the consistent scour trend above DPD, especially in TBR, is unsurprising, the change in scour and fill rates below DPD has a less straightforward explanation. One reason suggested for higher net scour in the epoch 2 drought period was that lower

flows do not increase the water elevation levels enough to grant access to the wide valley and floodplains in the reaches below DPD. Because the valley widens and slope decreases significantly in the areas below DPD, it would typically be assumed they would be dominated by fill, and they did indeed provide the majority of depositional zones in the epoch 1 flood period (**Table S4**). The large zones of deposition and no change present just downstream of DPD are common in almost all epochs (**Figure S8**) and flow scenarios. These areas likely exhibit this consistent behavior because (1) sediment keeps being sent down the river from above DPD as the river continues to adjust there and (2) the floodway widens out considerably allowing for dissipation of flows into surrounding floodplains and side channels. Thus, epoch 3 results necessitate more thought about the driving processes and antecedent conditions.

Longitudinal profiles of scour, fill, and no change areas show distinct patches of areal abundance of scour and fill in epochs 1 and 2 (**Figure S8**). In epoch 1, there were two large patches of scour above DPD, while in epoch 2, the largest patch of scour occurred directly downstream of DPD. Epoch 3 showed less of these distinct patches and scour and fill rates of similar magnitude were usually laterally correlated along the river profile. Scour exhibits a trend in epoch 3, continuously increasing by area and volume as distance increases going upstream, especially above DPD.

For epoch 1, it is conjectured by Wyrick and Pasternack (2014) that the zone of scour directly upstream of DPD (**Figure S8**) was caused by the fact that the 1997 flood deposited excessive sediment in this zone, causing the DPD to be at capacity with sediment. The excess was consequently scoured out by the 2006 flood during epoch 1. In epoch 2, there appears to be a large area of scour directly below DPD; this could be

explained if that sediment scoured out in the 2006 flood migrated here, and then became the material scoured during the 2008-2014 period. Epoch 3 does not appear to have one distinct scour area above or below DPD, suggesting that this material was already flushed out the area before the 2017 flooding occurred.

The longitudinal profiles of erosion and deposition show these processes tended to be more co-located in epochs 2 and 3 than in epoch 1 (**Figure S8**). Weber and Pasternack (2017) calculated and confirmed that in epoch 2, locations of erosion and deposition were positively correlated with each other. This is typical for patterns of lateral migration, where erosion and deposition occur simultaneously in the same cross section (i.e., erosion at the cutbank and deposition on the point bar). In epoch 2, sediment was laterally redistributed in this manner within LYR; whereas in epoch 1, per Wyrick and Pasternack (2014), higher flow events caused more vertically dominated topographic change processes (e.g., avulsion, overbank scour, and downcutting).

In all survey epochs, the in-channel inundation zone experienced net fill, while the overbank inundation zone experienced net scour. This indicates that in each epoch, as the channel migrates or avulses from its initial location to its final location at the end of the epoch, it tends to fill in its old channel while scouring through the banks and cutting new pathways over floodplains. To test this theory, for epoch 3 the 2014 overbank areas were further divided into areas that became the 2017 channel through channel migration and areas that remained overbank in 2017. Areas that became 2017 channel accounted for 62% of the total scour volume in the 2014 overbank area; this supports the idea that the majority of scour in the overbank was due to channel migration for epoch 3. One of the explanations for the lack of channel incision is simply

the due to the channel carving into easily accessible steep banks and mining tailings. These MUs (banks, tailings, and cutbanks) were indeed net scour and had locally high rates of erosion in epoch 3 (**Figure S10**). However, this alone does not explain the erosive nature of the epoch 3 flood event. While steep surfaces like tailing and banks may only be erosional, given their shape, flat surfaces like floodplains and terraces may be both erosional and depositional. The epoch 3 event yielded more balance between net erosion of flat surfaces (whether by lateral or vertical dynamics) and net erosion of tailings and banks (**Figure S9**).

Additionally, the overbank scour contribution to total sediment scoured in epochs 1 and 2 were 80.3% and 54.6%, respectively (**Table S5**), which correlates with the peak flood experienced by the epoch. This trend suggests that higher peak flows lead to a greater percent of total overbank scour and supports the conclusion from Wyrick and Pasternack (2012) that the undersized channel is well-connected to its floodplain, promoting flood-induced scour of the floodplain preferentially over in-channel regions.

Reach scale influences

Observation of the DoD rasters reveal patterns indicative of lateral channel migration in DCR (**Figure S13**) and a high degree of topographic changes within the flood stage-activated Daguerre alley side channel in DPDR (**Figure S14**) over the epoch 3 study period.

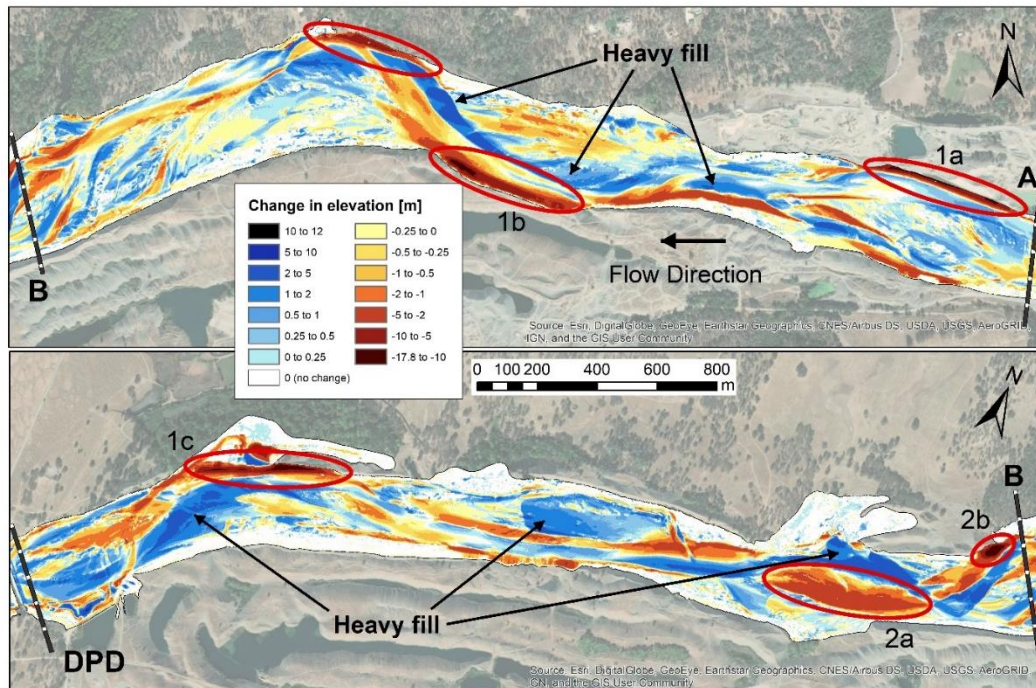


Figure S13. Epoch 3 DoD shows DCR (B-DPD) and the lower half of PBR (A-B) exhibited lateral channel migration, with high scour accompanied longitudinally by heavy fill in floodplains and inside bends. Scoured areas circled in red were mining tailings (1a, b, c) and floodplains (2a, b).

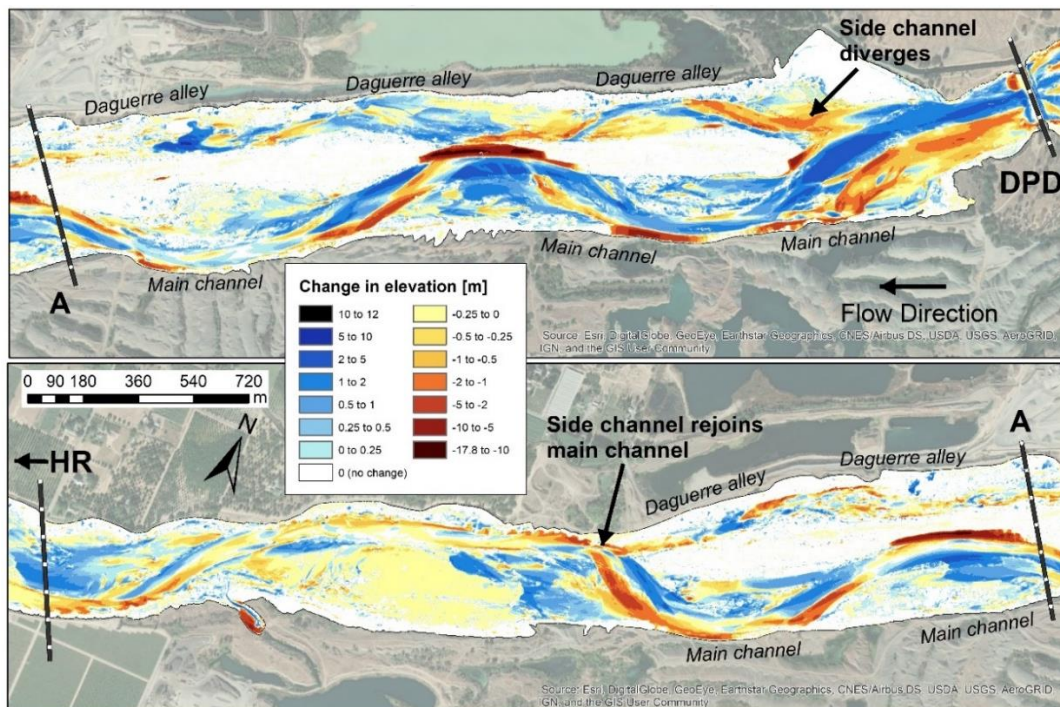


Figure S14. Epoch 3 DoD for DPDR shows a high degree of scour and fill in the northern side channel ("Daguerre alley").

Flood peak magnitude not correlated with erosion and export

None.

In-channel vs overbank dynamics

None.

Effects of flow variability and antecedent conditions

None.

VII. Conclusions supplements

None.

VIII. Supplemental acknowledgements

None.

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