1 Valley-scale morphology drives differences in fluvial sediment budgets and incision
2 rates during contrasting flow regimes

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Abstract

High-resolution topographic surveys using LiDAR and multibeam sonar can be used to characterize and quantify fluvial change. This study used repeat surveys to explore how topographic change, fluvial processes, sediment budgets, and aggradation and incision rates vary across spatial scales and across two contrasting decadal flow regimes in a regulated gravel/cobble river. A novel method for quantifying digital elevation model uncertainty was developed and applied to a topographic change detection analysis from 2006/2008 to 2014. During this period, which had four modest ~3-5 year floods, most sediment was laterally redistributed through bank erosion and channel migration. Erosion primarily occurred in the floodplain (97,000 m³), terraces (80,000 m³), and lateral bars (58,000 m³); while deposition occurred in the adjacent pools (73,000 m³), fast glides (48,000 m³), and runs (36,000 m³). In contrast, significantly higher magnitude and longer duration floods from 1999 to 2006/2008 caused sediment to be displaced longitudinally, with the upstream reaches exporting sediment and the downstream reaches aggrading. The river maintained floodplain connectivity during both periods, despite different processes dominating the type of connectivity. Larger floods promoted overbank scour and avulsion, while smaller floods promoted bank erosion and lateral migration. This study explores and illustrates how the geomorphic response to contrasting flood regimes in a nonuniform river is highly dependent on which landforms are controlling hydraulics.

Keywords: topographic change detection; DEM differencing; river morphology; fluvial sediment budgets

1. Introduction

Gravel/cobble-bedded rivers with diverse fluvial landforms exist worldwide (Shen et al., 1981; Buffington and Montgomery, 1999; Wheaton et al., 2015) and have been highly degraded by cumulative anthropogenic impacts on all aspects of their ecogeomorphology (Ligon et al., 1995; Liébault and Piégay, 2001; Hancock, 2002; Lisle and Church, 2002). Nevertheless, these systems remain important because of their ecosystem functions and services, including aquatic habitat provision and renewal, riparian inundation, fish passage, sediment and nutrient outflux, local land loss, flood control, water supply, and navigation (e.g., Boulton et al., 2008; Arthington et al., 2010).

While much effort has been put into understanding the physics, geomorphology, and sediment transport of uniform gravel river channels (often using rectangular, uniform flumes; e.g., Parker, 1979; Wilcock, 1997; Millar, 2005), Ashworth and Ferguson (1986) observed a lack of studies that described and explained nonuniform rivers, including their morphodynamic patterns and mechanisms. That essential finding holds today, though meaningful progress has been made with flume experiments (e.g., Wu and Yeh, 2005; Wilkinson et al., 2008; Tal and Paola, 2010), numerical modeling (e.g., Nicholas et al., 2013; Oorschot et al., 2015), and field-based approaches (e.g., Carboneau et al., 2012; Pasternack and Wyrick, 2016). More recently, Kleinhans (2010) reviewed studies of river patterns and concluded that the remaining inability to obtain dynamic meandering and braiding in laboratory experiments and physics-based models is indicative of our lack of understanding of morphodynamic mechanisms. Furthermore, White et al. (2010) compiled literature and evidence that make the case against assuming uniform flow for understanding many gravel rivers, and Gonzalez and

Pasternack (2015) showed that cross-sectional sampling as a ubiquitous methodology in fluvial geomorphology does not yield representative gravel-river attributes the way it is often assumed. Clearly, different approaches are needed to take the next steps to improve our understanding of nonuniform gravel/cobble rivers.

Thanks to technological advances (Passalacqua et al., 2015), submeter-scale topographic mapping of shallow gravel/cobble rivers has rapidly escalated with the emergence of commercially available multibeam sonar (MBS) systems (Hazel et al., 2010; Hensleigh, 2014), airborne bathymetric LiDAR (Hilldale and Raff, 2008; Mandlbürger et al., 2015), terrestrial laser scanning (Vericat et al., 2014; Williams et al., 2014), structure-from-motion collected with unmanned aerial vehicles (Westoby et al., 2012; Fonstad et al., 2013; Javernick et al., 2014), and multispectral remote sensing data (Legleiter et al., 2009). These surveying methods allow researchers to explore the diversity and patterning of fluvial landforms (e.g., Wyrick and Pasternack, 2014; Casado et al., 2015; Brown and Pasternack, 2017), simulate how nonuniform topography drives a diversity of hydraulic patch behaviors (Strom et al., 2016), and more accessibly obtain repeat topographic surveys in support of topographic change detection (TCD) to reveal fluvial morphodynamics (e.g., Wheaton et al., 2013; Mandlbürger et al., 2015; Wyrick and Pasternack, 2015).

Many gravel/cobble rivers behave differently than assumed because they have multiple layers of nested topographic heterogeneity (Gangodagamage et al., 2007; Brown and Pasternack, 2017). This means that the topographic patterns that steer flow within the base-flow channel are not the same as those for the larger bankfull channel or the

floodprone valley— drawing on three common scales of scientific interest. This concept of stage-dependent topographic steering of flow produces patches of diverse hydraulic behaviors that change as flow increases and different landforms yield or take control of flow paths (Macwilliams et al., 2006; Strom et al., 2016). Brown and Pasternack (2014) applied this concept to explain topographic change and described bedload deposition mechanisms in a mountain river. This finding provides the impetus to explore fluvial morphodynamics at multiple sites, across a range of discharges, and using high-resolution topographic mapping to better understand the spatial structure of fluvial topographic change.

Considering this emerging understanding, we present and analyze novel field results comparing how fluvial morphodynamics in a topographically heterogeneous gravel-bed river corridor differ when forced by two significantly different hydrologic regimes. Both regimes involved a similar average annual runoff; but in the first period the water was distributed with larger floods and lower base flows, while the second period had long durations of moderate base flows and a few short, modest floods. This study illustrates how the geomorphic response to contrasting flood regimes in a nonuniform river is highly dependent on which landforms are activated and for how long.

1.1. Modern topographic change detection methods

In a topographic change detection (TCD) analysis (sometimes referred to as a geomorphic change detection analysis or GCD), two digital elevation models (DEMs) are differenced, and the raw results are adjusted based on an estimate of uncertainty within each DEM. Currently, most TCD analyses involve differencing raster-based

99 DEMs with spatially distributed error estimates. Researchers generally use one of the
100 following strategies to account for DEM uncertainty: applying the fuzzy inference system
101 (FIS) presented by Wheaton et al. (2010), using bootstrapping or Monte Carlo
102 simulation to create multiple realizations of the DEM (Wechsler and Kroll, 2006;
103 Wheaton et al., 2008), developing error functions based on the survey method and
104 measures of topographic variability (Heritage et al., 2009; Milan et al., 2011; Carley et
105 al., 2012), or using a geostatistical approach such as kriging (Kraus et al., 2006;
106 Mandlbürger et al., 2015). All the methods above represent legitimate ways to
107 incorporate uncertainty into a TCD analysis.

108 No proposed method can unequivocally account for the uncertainty associated with a
109 sampled topographic surface. Thus, each method has its limitations. The FIS relies on
110 user-defined error thresholds and values to apply to combinations of categories (e.g.,
111 low/high point density or gentle/steep slopes) to prescribe a level of vertical elevation
112 uncertainty. This provides a framework for incorporating multiple layers of uncertainty,
113 but submeter resolution data sets may allow the development of deterministic statistical
114 measures of uncertainty, which reduce the subjective nature of FIS. Bootstrapping
115 methods are useful for interpreting the sensitivity of the resulting topographic map by
116 subsampling the data, but bootstrapping methods are computationally expensive to
117 create confidence intervals for large data sets. Field campaigns that relate spatial
118 uncertainty to topographic variables are infeasible for large topographic surveys (e.g.,
119 >10 km of river corridor) and using past reported values may be insufficient given the
120 unique characteristics of each landscape and survey method. Lastly, surfaces made
121 using kriging do not adhere to the actual survey point data, which may not be

appropriate for high-resolution data in steep and topographically complex terrain. With these concerns in mind, this study developed a new deterministic and efficient approach to characterize uncertainty using traditional statistical metrics at the raster-cell level.

1.2. Study objectives

The purpose of this study was to use the lower Yuba River (LYR), a regulated gravel-cobble river in northern California, as a testbed to explore gravel/cobble river morphodynamics during two decadal time periods with contrasting flow regimes. The specific scientific objectives were to compare topographic change at multiple spatial scales during each time period by (i) differentiating sediment budgets, (ii) calculating rates of vertical change for different inundated areas, and (iii) identifying the landforms that were the sources and sinks of sediment.

The two time periods analyzed were 1999 to 2006/2008 (time period 1) and 2006/2008 to 2014 (time period 2). Carley et al. (2012), Wyrick and Pasternack (2015), and Pasternack and Wyrick (2016) detailed the topographic change within LYR for time period 1, a period that included an ~23-year flood event (see section 2.4). This study analyzes topographic change in LYR using high-resolution topographic surveys (airborne NIR and bathymetric LiDAR and boat-based multibeam sonar) for time period 2, a period with four modest 3-5 year flood events (see section 2.4). Where applicable, we compared the results from time period 2 to the results for time period 1. Thus, the overall goal of this study was to revisit LYR, analyze topographic change during time period 2, and quantify fluvial topographic change and sediment budgets at multiple scales: the river segment (~100-1000 channel widths), geomorphic reach (~10-100

channel widths), and morphological unit (~0.1-10 channel widths) scales. We hypothesized that stage-dependent topographic steering would yield significantly different patterns of topographic change at each of the spatial scales for the two periods.

In the following sections, we provide an overview of LYR, topographic data collection efforts, and the analytical methods for this paper. More information on LYR, topographic data processing, and topographic change uncertainty methods are provided in the supplementary materials.

2. Study site – lower Yuba River

The Yuba River is a tributary of the Sacramento River in north-central California that drains 3480 km² of the western Sierra Nevada range (Fig. 1). The study segment is the alluvial lower Yuba River (LYR), a 37.1-km stretch that flows from east to west downstream of Englebright Dam to its confluence with the Feather River. This river segment is largely a single-threaded channel with ~20 emergent bars/islands at bankfull discharge, low sinuosity, high width-to-depth ratio, and slight to no entrenchment (Wyrick and Pasternack, 2012). Flows into LYR come primarily from three tributaries: the North, Middle, and South Yuba Rivers. Although the North Yuba tributary has a large reservoir that heavily regulates its outflow year-round, the absence of large reservoirs on the Middle and South Yuba tributaries translates to a broad range of discharges for LYR. Flows frequently (i.e., nearly annually) overtop Englebright Dam during large winter storms and spring snowmelt. Daguerre Point Dam (DPD), an 8-m-high run-of-the-river dam, is located near the middle of the study segment, 17.8 river

kilometers (RKm) upstream from the Feather River. Storage behind DPD is filled with sediment, allowing bedload to pass downstream during flood events.

2.1. Geomorphic reaches

Wyrick and Pasternack (2012) identified eight geomorphic reaches within LYR based on the location of tributary junctions and changes in lateral confinement and bed slope. The Englebright Dam reach (1-EDR) and Narrows reach (2-NR) define the upper portion of LYR, where the river corridor is confined within a steep-walled bedrock canyon. Because of the lack of alluvium, these reaches are excluded from the TCD analysis. The Timbuctoo Bend reach (3-TBR) marks the emergence of the alluvial river valley, followed by significant valley widening in the Parks Bar reach (4-PBR). The Deer Creek reach (5-DCR) and Daguerre Point Dam reach (6-DPDR) have the widest floodplain. Finally, in the Hallwood reach (7-HR) and Marysville reach (8-MR), the bed slope significantly decreases; and the river corridor becomes laterally constrained by levees that protect the City of Marysville. Geomorphic reach breaks are presented in Figs. 1 and 3, and more information on the geomorphic reaches is provided in the supplementary materials.

2.2. Morphological units

Morphological units (MUs) are distinct landforms delineated at the scale of ~0.1-10 channel widths. In-channel bed MUs (e.g., pool, riffle, and chute) for LYR were delineated by Wyrick et al. (2014) using a two-dimensional (2D) hydrodynamic model of the 2006/2008 topography at a base-flow discharge. Other MUs within the active valley corridor (e.g., medial bar, floodplain, and terrace) were mapped by Wyrick and

Pasternack (2012) with the aid of 2D hydrodynamic modeling of flood discharges, which were reported by Barker (2012) and Abu-Aly et al. (2014). Thirty-one MUs were delineated and grouped into four categories defined by their inundation thresholds: in-channel bed MUs (inundated at a base-flow discharge), in-channel bank MUs (inundated at bankfull discharge), floodway MUs (inundated at the floodway filling discharge), and valley MUs (areas outside the floodway). A description of each of the MUs is provided in the supplementary materials.

2.3. Hydraulic mining and geomorphic history

The LYR has a complex geomorphic history because of the cumulative impacts of several historical human activities: deposition of large volumes of fill derived from historic hydraulic gold mining in the watershed (Gilbert, 1917; Adler, 1980; James, 2005; James et al., 2009), dredging of the ~4000-ha Yuba Goldfields and other areas in the ancestral river migration belt (James et al., 2009), installation of a high concrete arch sediment-barrier dam (Englebright Dam) in the canyon at the entrance to LYR in 1941 (Snyder et al., 2004, 2006), and moderate flow regulation from a suite of hydroelectric facilities throughout the catchment.

From 1852 to 1906, LYR aggraded by as much as 26 m near the exit of 3-TBR, declining to ~8 m of aggradation near the confluence with the Feather River (Adler, 1980). This large wedge of hydraulic mining sediment is up to 5 km in width through an area called the Yuba Goldfields. The California Debris Commission estimated that the LYR valley accumulated 10,380,000 m³ of mining sediment, nearly 90% of which was still contained within the valley in 1980 (Adler, 1980). This period of rapid aggradation

turned LYR into an anastomosing channel that was void of vegetation. Aggradation was followed by rapid channel incision after hydraulic mining ceased and the California Debris Commission began installing sediment control structures to limit sediment from being exported downstream and provide flood protection for the City of Marysville. Adler (1980) calculated that the channel from 1906-1912 underwent 33.5 cm/y of incision, which tapered off to an average of 6.4 cm/y from 1912 to 1979. Pasternack and Wyrick (2016) recently reported mean incision rates from 1999 to 2006/2008 with 3-TBR and 5-DCR incising ~4.5 and 5.9 cm/y, respectively. In the same study, the other geomorphic reaches analyzed were slightly aggrading, with 4-PBR, 6-DPDR, 7-HR, and 8-MR averaging ~0.1, 1.9, 1.6, and 0.1 cm/y of aggradation, respectively.

2.4. Flow regime

Hydrological records for LYR are available from three USGS flow gages: Smartsville (#11419000) below Englebright Dam, Marysville (#11421000) near the confluence with the Feather River, and Deer Creek (#11418500), a tributary. Pasternack et al. (2014) conducted a flood frequency analysis using data from 1970-2010. Relevant flows for this paper include 28.32 m³/s as the representative base flow, 141.6 m³/s as the estimated bankfull discharge, and 597.5 m³/s as the floodplain-filling discharge. The return period of the bankfull discharge is ~1.25 years, which is more frequent than other similar rivers. The implication of this (and the high frequency of floodplain-filling flows) is that the channel may be undersized and flows spill onto the floodplain more often than expected.

Despite time period 1 (1999-2006/2008) and time period 2 (2006/2008-2014) having nearly similar total water and average annual flows (Table 1), the two time periods provide a contrast in the timing, duration, and magnitude of peak floods (Fig. 3). For the current study period (time period 2), four floodplain-filling events occurred, ranging from 838.2 to 1246 m³/s instantaneous flow, which corresponds to ~3-5 year recurrence interval events (Wyrick and Pasternack, 2012) and 6-9 times bankfull discharge. These floods were short-duration events spread over three years. The prior TCD analysis (time period 1) included a maximum recorded instantaneous flow of 3207 m³/s on 31 December 2005, which corresponds to a 23-year event and 22 times bankfull discharge. This event was preceded by a flood of 1480 m³/s on 20 May 2005 and was followed by a series of three floods ranging from 637.0 to 1056 m³/s in April 2006. Thus, time period 1 experienced three floods of much greater magnitude over a shorter period than time period 2. The duration above bankfull discharge was 200 days for time period 1 and 163 days for time period 2. The duration above floodplain-filling discharge was 18 days for time period 1 and 4 days for time period 2. Table 1 provides an overview of the peak annual flows for each time period, the average annual volume of water, and a characterization of each water year with respect to historical averages.

3. Methods

This study analyzed and compared topographic data from two high-resolution topographic surveys, one conducted in 2006/2008 and one conducted in 2014. To address the study objectives, we developed a new spatially distributed method for estimating topographic uncertainty for raster DEMs. This uncertainty analysis was applied to the two topographic data sets and the DEM difference raster computed from

them. Volumetric sediment budgets were calculated at multiple spatial scales to assess the patterns of erosion and deposition within LYR. The sediment budget for LYR assumes no sediment input from the upper watershed, as Englebright Dam blocks all bedload and Deer and Dry Creeks contribute negligible amounts of sediment. In addition, no landslides or other significant lateral sediment fluxes occurred from outside the TCD region. Thus, the sediment budget must result in net erosion with the value yielding the net volumetric export of sediment out of LYR to the Feather River.

At each of three relevant spatial scales, the river segment (~100-1000 channel widths), the geomorphic reach (~10-100 channel widths), and the morphological unit (~0.1-10 channel widths) scales, a series of analyses were conducted to assess the river's topographic adjustment. At the segment scale, longitudinal profiles of volumetric change and percent area of change aimed to provide an understanding of how patterns of erosion and deposition are organized. At the segment and geomorphic reach scales, the 2008 bankfull channel was delineated and used to stratify results into in-channel vs. overbank areas. This analysis aimed to provide insight into sediment connectivity between the channel and the floodplain and to help answer whether morphological diversity is maintained through channel migration or avulsion events. Furthermore, vertical topographic change rates were calculated across incrementally wetted areas provided by a 2D hydrodynamic model. These results were designed to explicitly test whether the river is becoming more entrenched by comparing the rate of vertical change at different inundation levels. Finally, at the morphological unit scale, volumetric sediment budgets were calculated to reveal the landforms that are the sources and sinks of sediment within LYR.

Notably, a different set of survey methods, point densities, and error analyses were used for time period 1 (Carley et al., 2012). Uncertainties for time period 1 are higher, as the first survey in 1999 did not involve meter-scale topographic mapping with terrestrial LiDAR. Nevertheless, the values reported are the best estimates of topographic change within LYR for each time period.

3.1. Topographic data collection

3.1.1. 2006/2008 surveys

For the 2006/2008 DEM, 3-TBR was surveyed in 2006 using a robotic total station for terrestrial areas and wadable bathymetry, and boat-mounted single-beam sonar (SBS) was used for unwadable bathymetry. The reaches downstream of 3-TBR were primarily surveyed in 2008. Aero-Metric, Inc. (Seattle, WA) flew airborne near-infrared (NIR) LiDAR for terrestrial mapping on 21 September 2008 when flows were $24.4 \text{ m}^3/\text{s}$ above DPD and $17.6 \text{ m}^3/\text{s}$ below DPD (the difference caused by irrigation diversions at DPD). River bathymetry was primarily mapped by SBS, except for inaccessible areas that were surveyed by a real-time kinematic global positioning system (RTK-GPS) or robotic total station. The 2006/2008 surveying effort was reported by Carley et al. (2012) and is summarized in the supplementary materials.

3.1.2. 2014 Surveys

The 2014 DEM involved a new survey of LYR during an extended drought that left LYR at its lowest point since new environmental flow schedules were fully implemented by the Lower Yuba River Accord in 2008. Quantum Spatial, Inc. (Sheboygan, WI) collected airborne bathymetric LiDAR data (using combined NIR and green laser scanners) on 27

299 September 2014 when flows were 15.3 m³/s above DPD and 11.3 m³/s below DPD.
300 Low flows allowed more of the river valley to be mapped by the NIR laser and reduced
301 the depths required for the green laser to penetrate through the water column. To map
302 the riverbed at depths greater than the green laser could penetrate, Seafloor Systems,
303 Inc. (El Dorado Hills, CA) collected MBS data on 11-14 August 2014, when flows were
304 40.0 m³/s above DPD and 22.7-24.5 m³/s below DPD. The higher water levels facilitated
305 overlapping of MBS and LiDAR data. Several days were spent using SBS and RTK-
306 GPS survey points to map data gaps and areas where submerged vegetation precluded
307 accurate aerial and sonar mapping. A full account of 2014 mapping efforts and post-
308 processing of data is included in the supplementary materials. Data resolutions by land
309 cover type are presented in Table 2 for the 2006/2008 DEM and the 2014 DEM.

310 3.2. DEM uncertainty for the 2006/2008-2014 TCD

311 Even though topographic data involves points, a raster cell is commonly the
312 fundamental unit for most topographic change analyses. Topographic change is
313 reported when elevation change within a raster cell, ΔZ_r , exceeds the level of detection
314 (LOD) determined by the DEM uncertainty method.

315 The DEM uncertainty method developed for this study creates confidence limits for each
316 raster cell using a traditional statistical approach for Gaussian distributions by
317 calculating the standard error of the mean (SEM), yet this has not been done before in
318 the published literature. The approach uses the density of the survey data, N (which is
319 the number of surveyed ground points contained by each raster cell) and the standard
320 deviation, SD (which is an estimate of the variability of the survey data, to calculate the

SEM; Eq. 1). The *SEM* is governed by a simple equation that is functionally equivalent to doing statistical bootstrapping, where a sample mean is calculated from a specified number of observations (N) that are pulled randomly from a population of data with a given standard deviation (SD). If this is done enough times, the resulting distribution of errors in sample mean is characterized by the *SEM*, which follows a normal distribution. An *SEM* is calculated for each survey period (Eq. 1) for every raster cell, and then the two *SEM* rasters are combined at the 95% confidence interval to obtain the *LOD* (Eq. 2),

$$SEM_{2014} = \frac{SD_{2014}}{\sqrt{N_{2014}}} \quad (1)$$

$$LOD_{95} = \sqrt{(1.96 * SEM_{2008})^2 + (1.96 * SEM_{2014})^2} \quad (2)$$

where the subscripts on the right side of the equation are the survey year (Lane et al., 2003), and SD is an estimate of the variability of the data.

To apply Eqs. (1) and (2), SD is needed for each raster cell. This variability can come from at least two sources: topographic variability (e.g., substrate size or slope) or survey error (SE). For remote sensing methods like LiDAR and MBS, a significant proportion of the SE involves distinguishing between ground vs. nonground returns, which depends on the land cover. For this method, SD is determined by incorporating both sources of variability. Topographic variability, SD_Z , is calculated from the ground-classified point cloud for the area contained by each raster cell as well as by the method outlined in

Carley et al. (2012). The larger of the two SD_Z values is used. The SE s were calculated for different land cover classes (bare ground, water, and vegetated ground) and represent the ability for a survey method to correctly identify ground within each land cover. A detailed explanation of how the SE s were calculated is included in the supplementary materials. Lastly, both sources of variability are combined by taking the square root of the sum of the squares (Eq. 3):

$$SD_{2014} = \sqrt{(SD_Z_{2014})^2 + (SE_{2014})^2} \quad (3)$$

An overview of the steps involved for the DEM uncertainty method is included below, and a visualization of the outputs is provided in Fig. 4.

1. Use a LiDAR or point cloud software package (e.g., LAStools or TerraScan) to classify all survey points as ground, vegetation, structure, or noise.
2. Use the ground classified points to create a raster DEM where Z_r is the height in each raster cell (Fig. 4B).
3. Create a land-cover raster (Fig. 4C) from the point classifications, and assign the survey error (SE) associated with each land-cover class.
4. Calculate the topographic variability, SD_Z , in each raster cell using the approach by Milan et al. (2011) or Brasington et al. (2012) (Fig. 4E).
5. Calculate an estimate of the total variability, SD , by applying Eq. (3).
6. Create a raster with the number of ground points per raster cell, N (Fig. 4D).
7. Calculate the standard error of the mean, SEM , using Eq. (1) (Fig. 4F).

8. Complete the steps above for each year's DEM. Then calculate the 95% confidence level of detection, LOD_{95} , using Eq. (2) (Fig. 4G).
9. Difference the two DEMs (Fig. 4H) and subtract the LOD_{95} raster values from the raw results to yield the statistically significant erosion or deposition that occurred within each raster cell (Fig. 4I).

3.3. Sediment Budgeting

After completing the DEM uncertainty analysis and subtracting the LOD_{95} from the raw DEM-difference raster, sediment budgets were created at river-segment, geomorphic-reach, and morphological-unit scales. This computation assumed no nontransport mechanisms of volumetric change, previously termed bed *deflation* or *contraction* and *inflation* or *dilation* (Merz et al., 2006; Marquis and Roy, 2012). In addition, if a raster cell erodes and then fills in between surveys, no change will be detected in that cell: a process known as compensating scour and fill (Lindsay and Ashmore, 2002).

3.3.1. River-Segment Scale

Longitudinal profiles of erosion and deposition were created by delineating the valley centerline in ArcGIS and creating regularly spaced rectangular station boxes (shown in the supplementary materials). The station boxes are orthogonal to the valley centerline, span the width of the river valley, and are 1.524 m in width. Their position along the valley centerline represents the distance upstream from the confluence with the Feather River. The total volume [m^3] of erosion and deposition within each station box was calculated, as well as the percent area of erosion, deposition, or no detectable level of change within the floodway. To explore the correlation between locations of peak

erosion and deposition, the Pearson's product-moment correlation was calculated using the longitudinal series of erosion and deposition volumes. The correlation values range from -1 to 1, with positive values indicating that the locations of peak erosion and deposition coincide. A negative value indicates that peak locations of erosion coincide with the low values of deposition and vice versa. Lastly, the volumetric rate of change [m^3/y] for the entire study area was calculated for erosion and deposition. The difference between these two values represents the average rate of sediment eroded out of the LYR valley.

3.3.2. *Geomorphic-Reach Scale*

At the geomorphic-reach scale, the volumetric rate of change [m^3/y] was calculated for each geomorphic reach to understand the relative balance of erosion and deposition within each reach. Because 3-TBR was mapped in 2006, it is averaged over 8 years (2006-2014), while the rest of LYR is averaged over 6 years (2008-2014). Results were also stratified across in-channel vs. overbank areas. The in-channel areas are defined by a wetted area polygon determined by a 2D hydrodynamic model of the 2006/2008 topography at bankfull discharge ($141.6 \text{ m}^3/\text{s}$). Lastly, net rates of vertical change were estimated by calculating the net volumetric rate of change [m^3/y] within a wetted area polygon developed by the 2D hydrodynamic model at several discharges (28.32, 141.6, 283.2, and $597.5 \text{ m}^3/\text{s}$; see below) and dividing by the inundated area [m^2] of the model to yield the average vertical change per year [mm/y]. This analysis was applied to the areas that are incrementally wetted as discharge increased from $28.32 \text{ m}^3/\text{s}$ (base flow), $141.6 \text{ m}^3/\text{s}$ (bankfull), $283.2 \text{ m}^3/\text{s}$ (intermediate), and $597.5 \text{ m}^3/\text{s}$ (floodplain filling) (Fig. 5B). For example, the values reported for the bankfull wetted area exclude the areas

that are wetted at base flow discharge. This analysis explores how vertical topographic change occurs at different positions within the river valley (e.g., how is the channel responding in contrast to different floodplain areas?) and provides estimates of valley-wide incision rates, which were previously reported by Adler (1980) and Pasternack and Wyrick (2016) discussed in section 2.3.

3.3.3. *Morphological-unit scale*

Sediment budgets presented at the morphological-unit scale were developed using the MUs discussed in section 2.2 and are expanded upon in the supplementary materials. The sediment budgets calculated for the MUs provide a summary of the topographic change that occurred to the former 2006/2008 landforms within LYR. This provides an understanding of the sources and sinks of sediment movement; however, it does not represent the net gain or loss of a morphological unit. For example, as a river channel migrates or avulses, new in-channel MUs are created in areas that were previously floodplain. Therefore, even though 2006/2008 pools may show net fill, this does not necessarily indicate that pool habitats have filled in or decreased overall. Instead, the former location of a pool filled, whereas a new pool may be created in an area that was previously floodplain. Further analysis would be needed to delineate the new 2014 MUs to assess net impacts to the MUs and is beyond the scope of this study.

4. Results

4.1. DEM Uncertainty

The *SEs* calculated by land cover type for the 2006/2008 to 2014 TCD were 0.039 m for bare ground and 0.074 m for water. A value of 0.30 m was chosen for vegetated

ground, which comes from a review of the relevant literature for vertical error estimates for LiDAR in leaf-on forested settings (Reutebuch et al., 2003; Hodgson and Bresnahan, 2004; Gould et al., 2013; Tinkham et al., 2013; Edson and Wing, 2015). Figure 4 shows how uncertainty was influenced by land cover, point density, and topographic variability. In bare ground areas, point densities were high and survey errors were low, resulting in small raster elevation uncertainties, even in topographically complex areas. In vegetated areas, point densities were low and survey errors were high, yielding larger uncertainties.

4.2. River-Segment Scale

For the flow regime in time period 2, erosion was the dominant process in LYR. The TCD analysis estimates 103,000 m³/y of erosion and 80,800 m³/y of deposition within the LYR valley (i.e., in-channel and overbank areas), a net change of 22,200 m³/y of erosion. This net change represents the average annual volume of sediment exported to the Feather River.

A comparison of net topographic change between in-channel vs. overbank areas revealed that, during time period 2, LYR was strongly depositional within the 2006/2008 bankfull channel, with a net topographic change of 20,300 m³/y of deposition, and strongly erosional in the overbank region, with a net topographic change of 41,600 m³/y of erosion. The large bank collapse in 7-HR accounts for 13,700 m³/y of erosion, which is 13.3% of the total erosion within the LYR valley and 33.9% of the net erosion in the overbank areas.

The longitudinal series of deposition and erosion volumes for time period 2 show that the locations of peak values of deposition and erosion are moderately correlated with one another (Fig. 6). The Pearson's product-moment correlation of erosion and deposition volumes was 0.47 ($p < 0.001$). The longitudinal series of deposition and erosion by area (Fig. 7) shows significant variation, with erosion being the dominant process by area within 6-DPDR, deposition being the dominant process by area in 7-HR, and more balance across the other geomorphic reaches. Averaged across the entire floodway, 22% of the area experienced erosion, 25% experienced deposition, and 53% indicated no change.

4.3. Geomorphic-Reach Scale

At the geomorphic-reach scale, all reaches were net erosional for time period 2, except for 7-HR, which had a nearly equal balance of valley-wide erosion and deposition (Fig. 8B). The 5-DCR and 6-DPDR were the most imbalanced reaches with 51% and 77% more erosion than deposition, respectively. Every geomorphic reach during time period 2 was strongly erosional for overbank areas, but the results for in-channel areas vary by reach (Table 3). All in-channel areas of reaches were net depositional, except for 3-TBR (230 m³/y of net erosion) and 6-DPDR (500 m³/y of net erosion).

Rates of vertical change varied significantly by geomorphic reach and by the incremental wetted areas. The 2008 base-flow channel (wetted by 28.32 m³/s) aggraded in all geomorphic reaches, though 3-TBR was nearly neutral with just 0.86 mm/y of aggradation (Table 4). The wetted areas above the base-flow channel were all erosional, with incision across all geomorphic reaches. Net volumetric changes

averaged across the 2008 floodway (wetted by 597.5 m³/s) show minor incision of 1.5-3.1 mm/y for all but 7-HR, which aggraded at 9.7 mm/y during the study period.

4.4. Morphological-Unit Scale

Topographic change results during time period 2 for the 2008 MUs are consistent with observations at the segment and reach scale. Most in-channel base-flow MUs (e.g., runs, fast glides, and pools) were strongly depositional; whereas overbank MUs (e.g., terraces, floodplains, and high floodplains) were strongly erosional (Fig. 9). However, several in-channel bank units were net erosional, including lateral bars (58,000 m³), banks (12,000 m³), cutbanks (11,000 m³), medial bars (6000 m³), and point bars (4000 m³). Two in-channel bed MUs were net erosional: slackwaters (7000 m³) and riffles (2000 m³). Though within those results, slackwaters, medial bars, point bars, and riffles had similar magnitudes of erosion and deposition.

5. Discussion

5.1. Segment-scale sediment budget differences

The TCD analysis for time period 2 (2006/2008 to 2014) yielded different magnitudes, patterns, and rates of erosion and deposition compared to the TCD reported for time period 1 (1999 to 2006/2008) by Carley et al. (2012). The longitudinal profiles of erosion and deposition show that the locations of each process are more balanced in time period 2 than in time period 1. In time period 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). Visual inspection of the TCD

raster and local knowledge of the river suggest that eroded material moves a short distance downstream before being deposited. Locations of intense scour were often followed by locations of intense deposition. Thus, in time period 2, sediment was laterally redistributed within LYR with all reaches net erosional, whereas in time period 1, higher flow events caused more vertically dominated processes (e.g., avulsion, overbank scour, and downcutting) that yielded either net erosion or deposition by reach.

Despite the higher flood peaks and longer durations of flood flows during time period 1, the magnitude of net annual export of sediment to the Feather River was similar for the two time periods, with 25% more sediment export during the drought period (time period 2) than during the flood period ($17,000 \text{ m}^3/\text{y}$ in time period 1 vs. $21,300 \text{ m}^3/\text{y}$ in time period 2). Time period 1 had 20% more days of bankfull flow than time period 2, but it had 25% less net export.

5.2. Reach-scale sediment budget differences

At the reach-scale, erosion and deposition were more imbalanced between the geomorphic reaches for time period 1 than time period 2, with 3-TBR and 5-DCR being strongly erosional and 6-DPDR and 7-HR being strongly depositional. To thoroughly understand this would take an evaluation of the hydraulics during the events in these time periods, but these topographic change patterns correspond well with valley-scale morphological differences. Specifically, we believe that differences in topographic steering between modest vs. large floods are a key contributor to the observed differences in topographic change. Abu-Aly et al. (2014) conducted 2D hydrodynamic flood modeling for LYR (accounting for spatially distributed vegetation roughness), and

some of the wetted extents they obtained for relevant flows are provided in Figure 10 to help illustrate the hydraulic mechanism that explains the reach-scale erosion and sedimentation results found in this study.

The two strongly aggradational reaches during time period 1, 6-DPDR and 7-HR, are wider and upstream of 8-MR, which is leveed (Fig. 10C, see zone of constriction). The engineered levees constrict the river corridor in 8-MR by nearly two-thirds (average floodway width decreases from 313 m in 6-DPDR to 116 m in 8-MR). During flood events, this lateral topographic constriction causes water stages to rise higher than they would without the levees, a phenomenon called *levee surcharge* by Heine and Pinter (2012). The levee surcharge would cause a backwater effect upstream of the levees, decrease the water surface slope, and reduce transport capacity. Furthermore, at high discharge, a large secondary channel becomes active within 6-DPDR, creating the widest active floodway within LYR (Fig. 10c, see zone of expansion) and reducing the rate of increase in velocity relative to the other geomorphic reaches (Strom et al., 2016). Together, the flood-stage backwater effect of the levees and the wide floodway in 6-DPDR and 7-HR yield lower flood velocities in these reaches and appear to promote deposition of sediment. Although not part of this study, reach-scale at-a-station hydraulic geometry relations were developed for LYR using 2D hydrodynamic modeling for both in-channel (Gonzalez and Pasternack, 2015) and overbank hydraulics, and the results show reach-scale velocity reversals. First, the mean velocity in 8-MR exceeds that in 7-HR at 212.4 m³/s, and then it exceeds that in 6-DPDR at 283.2 m³/s. Above this flow, 8-MR has a significantly higher average velocity than 6-DPDR and 7-HR. In fact, the levees in 8-MR were created to do this by design for the purpose of slowing

537 down the export of LYR hydraulic mining debris to the Feather and Sacramento rivers
538 (Adler, 1980).

539 In contrast to the dynamics in 6-DPDR, 7-HR, and 8-MR, the reaches that eroded
540 during time period 1, 3-TBR and 5-DCR have the lowest entrenchment ratio (i.e., most
541 entrenched), meaning that flood flows in these reaches are constrained within a
542 narrower floodway. As a result, they have higher reach-average velocities and
543 preferentially scour during floods. Overall, the dominant mechanism at work during time
544 period 1 appears to be driven by valley-scale morphological differences within each
545 reach as large floods activate these hydraulic controls.

546 Given the smaller floods and a shorter overall duration of floodplain-filling flows during
547 time period 2, the hydraulics would have been less impacted by the valley-scale
548 differences between the geomorphic reaches. Furthermore, even though time period 1
549 had a significantly longer duration of large flooding, the duration above bankfull was
550 only 20% more in time period 1 than in time period 2. This can explain why lateral
551 channel migration processes dominated in time period 2 and why the erosion and
552 deposition patterns were more balanced between the geomorphic reaches. Specifically,
553 at flows at and just above bankfull flow, erosive forces are focused in the channel and
554 on the banks; whereas, after the water spills onto the floodplain, channel velocity can
555 decline, and the patches of peak velocity shift onto the floodplain (Abu-Aly et al., 2014).
556 Thus, apparently the hydraulics in time period 2 were substantially different than in time
557 period 1, and as a result, the topographic change processes and net export were
558 different. This finding provides an important lesson, that more flow does not always

mean more erosion (as assumed by specific stream power analysis and commonly applied in geomorphic studies), because the processes of topographic change are stage dependent.

In addition to the differences in flood magnitudes and their associated topographic change processes, topographic changes during time period 2 may be heavily influenced by what happened in time period 1 and the effect that prior floods had on sediment supply and accommodation space. In time period 1, 6-DPDR was strongly depositional, but in time period 2 it was net erosional. Furthermore, for time period 2, 6-DPDR is one of only two reaches where net erosion occurred within the 2008 bankfull channel, and it is the only reach where erosion was the dominant process by area. During time period 2, the channel and floodplain may have been responding to the previous wave of sediment deposition. This highlights the need for repeat topographic change analyses over many time periods in order to understand the role of antecedent conditions prior to interpreting fluvial topographic change results. Along these lines, a large ~ 34-year flood occurred in 1997, and how this changed the distribution of sediment in the river segment is not known. However, it certainly would have established conditions that would influence the results of the 1999 to 2006/2008 TCD analysis.

5.3. Incision rates

Average vertical change rates for time period 1 and time period 2 were similar with 2.4 mm/y of incision for time period 1 and 1.5-3.1 mm/y of incision for time period 2. Although the average values were similar, results at the reach scale were significantly

580 different, with reaches during time period 1 aggrading by as much as 19 mm/y (6-
581 DPDR) and incising by as much as 69 mm/y (5-DCR).

582 The analysis of vertical change by inundation threshold for time period 2 showed that,
583 while each geomorphic reach was net erosional, incision rates were low (~1.5 to 3.1
584 mm/y) for the floodway corridor. Furthermore, the base-flow channel aggraded across
585 all geomorphic reaches, whereas the incrementally added wetted areas above base-
586 flow discharge eroded for all geomorphic reaches across all higher discharges. This
587 result further confirms that even as LYR continues to slowly incise, the river is staying
588 well connected to its current floodplain through lateral migration.

589 The vertical change results for 7-HR may appear to be contradictory as net erosion was
590 calculated for the reach ($310 \text{ m}^3/\text{y}$), while 9.1 mm/y of aggradation occurred during time
591 period 2 for the 2008 floodway area. This is because of a large bank collapse that
592 eroded a terrace outside of the 2008 floodway (Fig. 5B). Thus, a large amount of
593 erosion occurred outside of the 2008 floodway as the river migrated laterally and
594 deposited material within the former channel. Events like this occurred in several other
595 locations, such as in 5-DCR, where the river eroded into tailings of hydraulic mining
596 debris.

597 *5.4. Sources and sinks of sediment*

598 The bulk of the sediment eroded within LYR between 2006/2008 and 2014 came from
599 three MUs: floodplain ($112,000 \text{ m}^3$), terraces ($82,600 \text{ m}^3$), and in-channel lateral bars
600 ($79,500 \text{ m}^3$). A smaller but significant amount of sediment came from riffles ($36,700 \text{ m}^3$),

slackwater (35,700 m³), high floodplain (35,400 m³), and tailing (25,300 m³) MUs. The sediment sourced from terraces, high floodplains, and tailings represent landforms that are outside of the 2008 floodway but are being reincorporated into the active river valley as the river migrates. This analysis shows that these landforms higher on the landscape can be a significant component of the sediment dynamics within LYR, with 26% of the sediment being sourced outside of the floodway during time period 2. At the same time, the results continue to support the conclusion that the floodplain and channel are the dominant sources of sediment, even though tailings and terraces produce more visible patterns of topographic change.

5.5. Contrast with other regulated gravel/cobble rivers

Typically, rivers that incise abandon their floodplains. This study presents an uncommon case where the river is incising and evacuating sediment while maintaining channel-floodplain connectivity. In some places along the river, such as in 7-HR and 5-DCR, the extent of the floodplain expanded as the river migrated laterally into former terraces and mining tailings. Historically, LYR did incise and abandon its floodplain in some places, as evident by the presence of intermittent terraces; but from 1999 to 2014, the flood flows and sediment regime remain well connected to the existing floodplain. In time period 1, the sediment connectivity was largely through overbank scour and avulsion; whereas, in time period 2, the connectivity was largely through lateral channel migration.

The LYR, despite being a regulated river, has been able to resist significant, interdecadal bed armoring because of an abundance of alluvium and a heterogeneous

flow regime that diversifies its sediment transport mechanisms (Parker et al., 2003). Both time periods found that sediment was preferentially scoured from the floodplain and deposited within the former channel. This redistribution of sediment prevents the persistence of an armored layer. The abundant alluvial fill within the floodway consists of a variety of sediment sizes, with about 10-20% fine gravel [2-32 mm], 20-40% small cobble [32-90 mm], 20-30% cobble [90-128 mm], and 10-20% large cobble [128-256 mm] (Jackson et al., 2013). Furthermore, as LYR migrates laterally and erodes terraces and mining tailings, new material is added to the floodway. Terrace sediments are poorly sorted and consist of sands, gravels, and cobbles (Jackson et al., 2013).

6. Conclusions

This study provided insights into how sediment budgets and incision/aggradation rates differ within LYR during two contrasting decadal flow regimes. During the large flood events of time period 1, sediment within LYR was displaced longitudinally, with reaches above DPD eroding sediment and reaches below DPD accumulating sediment. This finding corresponds with the valley-scale morphological features that are activated at high river stages, such as the levees in 8-MR and 7-HR, the secondary bypass channel in 6-DPDR, and the narrow valley walls in 3-TBR. These valley-scale morphological features drive the hydraulics and sediment movement within LYR at high flow. During the modest floods of time period 2, from 2006/2008 to 2014, the majority of the sediment was laterally redistributed with erosion outside of the base-flow channel (e.g., floodplain, terrace, and lateral bar MUs) and deposition within the former base-flow channel (e.g., pools, runs, and fast glide MUs) as the river channel migrates. The results from 6-DPDR during time period 2 suggest that the previous wave of sediment

deposition in that reach influenced the type of topographic change processes that occurred. This finding highlights the need for repeat topographic change studies to understand antecedent conditions and interpret the results. Modern day incision rates averaged across the entire floodway were ~2.5 mm/y for time period 1 and 1.5 mm/y for time period 2. These incision rates are significantly slower than the 6.4 cm/y previously reported by Adler (1980) from 1912 to 1979. Overall, this paper presents the complexities of a gravel/cobble river that experiences vastly different morphodynamics based on the interaction of a dynamic flood regime and multiple layers of topographic heterogeneity.

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878 Figure Captions

879

880 Fig. 1. Site map of the lower Yuba River (LYR) in northern California. The grey area in
881 the bottom map depicts the estimated inundated area for a flow of 1195 m³/s.
882 LYR begins at the downstream end of Englebright Dam and continues until its
883 confluence with the Feather River.

884 Fig. 2. Longitudinal profile of the 2014 bed elevation along the thalweg for the lower
885 Yuba River with geomorphic reaches delineated. Elevations were derived from
886 bathymetric LiDAR and multibeam sonar data with respect to NAVD88.

887 Fig. 3. Instantaneous flow hydrograph for time period 1 (1999-2006/2008) and time
888 period 2 (2006/2008-2014) for LYR at the Marysville USGS gage (11421000).
889 Time period 2 is shaded.

890 Fig. 4. Example outputs from the DEM uncertainty and TCD analysis using the 2014
891 data. (A) 2014 aerial photo. (B) 2014 raster DEM. (C) 2014 land cover raster. (D)
892 2014 point density raster. (E) 2014 SD_Z raster. (F) 2014 SEM raster. (G) 2008-
893 2014 LOD95 raster. (H) Raw topographic change results. (I) Statistically
894 significant topographic change results.

895 Fig. 5. (A) Example of TCD results in the Hallwood Reach, where lateral migration
896 caused the collapse of a forested terrace and orchard with >10 m of vertical
897 scour. Deposition primarily occurred within the 2008 base-flow channel. (B) Map
898 of wetted areas produced by a 2D hydrodynamic model. The location of scour
899 outside the floodway demonstrates how the river expanded its active floodway in

this stretch by eroding a terrace. (C) Map of the 2008 MUs delineated by Wyrick and Pasternack (2012, 2014).

Fig. 6. Longitudinal series of deposition and erosion volumes in the lower Yuba River valley for the 2006/2008 to 2014 time period.

Fig. 7. Longitudinal series of deposition and erosion as a percentage of the floodway area for the 2006/2008 to 2014 time period. On average, 22% of the floodway experienced erosion, 25% deposition, and 53% did not change, though significant variation exists among the geomorphic reaches.

Fig. 8. Sediment budget by geomorphic reach for time period 1 (A) and time period 2 (B). The numbers are reported as volumetric rates in $10,000 \text{ m}^3/\text{y}$. Each geomorphic reach is presented as a control volume with their inputs and exports of sediment shown by the horizontal arrows. The net change in sediment storage for each reach is shown in parentheses below the reach label, where positive values indicate net deposition and negative values indicate net erosion. Within each reach, the downward arrows indicate the gross rates of deposition and the upward arrows indicate the gross rates of erosion within each reach. The value left of the Feather River confluence marker is the average annual volume of sediment exported out of the LYR valley to the Feather River.

Fig. 9. Volumetric change within the 2006/2008 morphological unit delineations during time period 2. The black bars and data labels show the net volumetric change in $10,000 \text{ m}^3$.

Fig. 10. The panels show wetted extents from Abu-Aly et al. (2014) for three different discharges. The lines show geomorphic reach breaks with reach labels in panel

A. (A) Wetted extent for bankfull discharge ($141.6 \text{ m}^3/\text{s}$). (B) Wetted extent for the floodway filling discharge ($597.5 \text{ m}^3/\text{s}$), which is approximately the peak daily-averaged flow for time period 2. Notice that the sinuosity of the base-flow channel is still apparent in the wetted extent for this discharge, indicating that the bankfull channel is still steering the hydraulics. (C) Wetted extent for $2390 \text{ m}^3/\text{s}$, which is approximately the peak daily-averaged flow for time period 1. Notice that the sinuosity of the base-flow channel is no longer visible in the wetted extent for this discharge. Instead, expansion and contraction of the wetted extent occurs at multiple scales. An overall zone of expansion begins just below the entrance of 6-DPDR, where the floodway splits in two. Then, an overall contraction occurs at the downstream end of the figure in 7-HR, where the wetted width more than halves. In addition, multiple smaller scale expansion and contractions occur throughout this section of river.

Fig. 1

Fig. 2

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Fig. 9

Fig. 10

Table 1 Summary of water yeara statistics for the study period Summary of water yeara statistics for the study period

Water year ^a	Peak discharge (m3/s)		Avg. annual volume	
	Instantaneous	Daily averaged	(m3 x 106)	Water year type
2000	642.0	608.8	1779.0	Above Average
2001	63.5	55.8	696.0	Dry
2002	149.3	142.7	1241.0	Below Average
2003	236.2	231.1	1830.0	Above Average
2004	418.9	345.5	1354.0	Below Average
2005	1480.0	1229.0	1829.0	Above Average
2006	3207.0	2384.0	4794.0	Wet
2007	375.0	283.2	904.0	Dry
2008	138.2	130.3	817.0	Dry
2009	566.3	356.8	1243.0	Below Average
2010	189.6	181.2	1422.0	Below Average
2011	875.0	761.7	3837.0	Wet
2012	961.1	603.1	1367.0	Below Average
2013	1246.0	628.6	1265.0	Below Average
2014	217.8	178.1	595.0	Dry
Period 1 ('00-'08)	3207.0	2384.0	1694.0	N/A
Period 2 ('09-'14)	1246.0	761.7	1621.0	N/A
^a The California water year begins on 1 October and ends on 30 September. For example, water year 2000 began on 1 October 1999 and ended on 30 September 2000.				

Table 2 Data resolution (pts/m2) comparisons by land-cover type

Land cover	2006/2008 DEM	2014 DEM
Bare Earth	5.71	13.17
Water	0.59	5.12
Vegetated Ground	1.37	3.05

Table 3 Volumetric change per year as separated by in-channel (i.e., bankfull) vs. overbank areas; the numbers reported are the net results within each area (the in-channel vs. overbank analysis was not possible for time period 1)

Reach	Volumetric change per year [1000 m ³ /y]			
	Time period 1	Time period 2		
	Net all	Net in-channel	Net overbank	Net all
3-TBR	-45.0	-0.2	-1.8	-2.0
4-PBR	2.7	0.3	-4.7	-4.4
5-DCR	-57.0	0.5	-6.4	-5.9
6-DPDR	45.0	-0.5	-6.4	-6.9
7-HR	37.0	17.0	-17.0	-0.3
8-MR	0.9	2.4	-5.1	-2.7
All LYR	-17.0	20.0	-42.0	-22.0