Title

Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales

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Publication Date

2016-10-11

DOI

10.1002/esp.4064

Data Availability

The data associated with this publication are available upon request.

Title: Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales

Short title: Fluvial response to large flood

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Keywords: topographic change; DEM differencing; river morphology; regulated rivers; geomorphic change

Citation: Pasternack, G. B., and Wyrick, J. R. 2016. Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales. Earth Surface Processes and Landforms, doi: 10.1002/esp.4064.

Abstract

Regulated rivers generally incise below dams that cut off sediment supply, but how that happens and what the consequences are at different spatial scales is poorly understood. Modern topographic mapping at meter-scale resolution now enables investigation of the details of spatial processes. In this study, spatial segregation was applied to a meter-scale raster map of topographic change from 1999 to 2008 on the gravel-cobble, regulated lower Yuba River in California to answer specific scientific questions about how a decadal hydrograph that included a flood peak of 22 times bankfull discharge affected the river at segment, reach, and morphological unit scales. The results show that the river preferentially eroded sediment from floodplains compared to the channel, and this not only promoted valley-wide sediment evacuation, but also facilitated the renewal and differentiation of morphological units, especially in the channel. At the reach scale, area of fill and mean net rate of elevational change were directly correlated with better connectivity between the channel and floodplain, while the mean rate of scour in scour areas was influenced by the ratio of slope to bankfull Froude number, a ratio indicative of lateral migration versus vertical downcutting. Hierarchical segregation of topographic change rasters proved useful for understanding multiscalar geomorphic dynamics.

Introduction

Quantification of changes in river morphology provides a means for monitoring rates and directions of landform change relevant to ecosystem services and human activities (Ferguson and Ashworth, 1990; Wheaton et al., 2010b). Although landform change is naturally driven by tectonic and climatic processes (Hack, 1960; Tucker and Slingerland, 1997), there may also be a dominant role for land use (Trimble *et al*., 1987; Pasternack *et al*., 2001; Warrick and Rubin, 2007) and the damming of rivers (Williams and Wolman, 1984; Brandt, 2000) in the industrial era of human civilization. Observational studies of these problems in the 20^{th} century used a range of techniques (often together) with different kinds of sampling strategies and limitations (Lawler, 1993), including (i) historic map and aerial photo interpretation with spot measurements (Hadley and Schumm, 1961), (ii) intensive planimetric surveys of small sites with limited extrapolative capability (Ferguson and Ashworth, 1992; Valle and Pasternack, 2006), (iii) rapid reconnaissance of qualitatively evaluated metrics (Thorne, 1998), or (iv) statistical analysis of a small sampling of cross-sections (Leopold *et al.*, 2005), with locations distributed based on expert judgment depending on the scale of problem at hand. In the last 20 years, diverse, cost-effective technologies have been developed for meter-scale topographic mapping and fluvial remote sensing over hundreds of kilometers of river length (e.g., Fonstad *et al*., 2013; Glennie *et al*., 2013). Processing such vast and complex raw datasets has proven a challenge unto itself (e.g., Drăguţ and Eisank, 2011; Mandlburger *et al*., 2015; Schaffrath *et al*., 2015), but it is essential to move forward envisioning what a new paradigm of science and management would look like making use of such data (e.g., Wyrick *et al*., 2014; Gonzalez *et al*., 2015; Wyrick and Pasternack, 2015). How do we use meter-scale data to answer fundamental scientific questions about the mechanisms and rates governing fluvial geomorphology and what new understanding can we make with an appreciation of spatial complexity (Passalacqua *et al*., 2015)?

The term 'near-census' is used to describe comprehensive, spatially explicit, process-based approaches using the 1-m scale as the basic building block for investigating rivers. This approach avoids the confounding problems associated with statistical sampling (Gonzalez *et al*., 2015). The concept of a 'near-census' implies that meter-scale data represents variables in great detail that approaches the population of conditions, but that there remains a finer level of detail in the domain of continuum mechanics that technology already resolves over small areas (Brasington *et al*., 2012) and will eventually resolve at the landscape scale. Previously, 10-m resolution was recognized as suitable for hillslope analyses (Zhang and Montgomery, 1994; Tarolli and Tarboton, 2006), but for rivers many questions about physical and ecological processes require data and models at submeter to meter resolution.

The potential value of near-census data hinges on recognizing that data is not an end to itself, but requires analysis to gain improved scientific understanding over sample-based approaches of the past (Passalacqua *et al*., 2015). Excluding approaches that use near-census data for numerical model set-up (e.g. Casas *et al*., 2010; Pasternack, 2011) and validation (Williams *et al*., 2016), new geomorphic analytics are rapidly emerging and generally apply continuum or object-oriented methods. In the former approach, near-census data (point clouds or rasters) are analyzed along continuous profiles or as a 3D surface (e.g., Gangodagamage *et al*., 2007; Lashermes *et al*., 2007; Booth *et al*., 2009; Scown *et al*., 2015; Buscombe, 2016). These methods allow for understanding, even predicting, landscape patterning (e.g., Legleiter and Kyriakidis, 2008; Perron *et al*., 2008; Tarolli, 2014), as well as revealing how spatially explicit process variables, such as fluvial hydraulics, are driven by that patterning and in turn promote patterns of sediment erosion and deposition (Brown and Pasternack, 2014). Continuum-based metrics of such process-morphology linkages have even been turned into a topographic design tool for river engineering (Brown *et al*., 2014).

Alternatively, and as is employed in this study, near-census data may be segregated into discrete fundamental spatial units of analysis with object-oriented methods, and then the attributes of the units may be compared. A key advantage of segregation and averaging within units is that this avoids the serious problem of spatial autocorrelation when considering individual points or pixels as if they are independent and identically distributed data, which has been neglected in many near-census studies thus far. Herein, no differentiation is made for edge or special-feature detection/extraction, compared to complete data segregation, as these are just presence/absence variations on the more general concept of segregation. Geomorphologists have long divided the landscape into discrete units for a wide variety of reasons and purposes (Evans, 2012), and this practice continues with near-census data. Arguably, this has been the most widespread application of near-census data to date, with dozens of segmentations on the basis of sediment facies, landforms, process domains, inundation thresholds, hydraulics, land use/land cover types, and physical habitat types (e.g., Brennan and Webster, 2006; Brandtberg, 2007; Hauer *et al*., 2009; Milan *et al*., 2010; Nelson *et al*., 2014; Wyrick and Pasternack, 2014, 2015).

Segmentation has also been essential for sediment budgeting (e.g., Fuller *et al*., 2003; Milan *et al*., 2007; Wheaton *et al*., 2010a).

Fluvial geomorphologists recognize that landforms and processes exhibit multiple spatial scales of organization (Frissell *et al.*, 1986; Grant *et al*., 1990; Sear, 1994), and as a result have advocated for a multi-scalar, hierarchical approach to understanding and managing rivers (Brierley and Fryirs, 2005; Beechie *et al*., 2010). In light of near-census developments, multi-scalar frameworks are needed for using near-census data to answer a wide range of multi-scalar scientific questions about rivers, especially about processes that affect rivers and their management, but these do not yet exist. Hay *et al*. (2001) illustrated a multi-scalar approach to addressing terrestrial ecology that involved applying object-oriented analysis to remote sensing data over a range of scales, notably to identify important scales. In fluvial geomorphology many important scales are already known, so the focus is on ascertaining what a multi-scalar framework would involve and what kinds of process-based questions it could answer integrating diverse data inputs. Recently, Wheaton *et al*. (2015) proposed a multi-scalar, near-census framework for mapping landforms, which is an excellent beginning.

The overall goal of this study was to apply near-census data and object-oriented analyses within a multi-scalar framework to quantify how topographic changes in a regulated gravel-cobble river are spatially organized at segment (10^2 to 10^3 channel widths, W), reach (10^1 to 10^2 W), and morphological-unit (10^{-1} to 10^1 W) scales in response to a hydrologically heterogeneous period that included a flood with an instantaneous peak flow of ~ 22 times bankfull discharge. These scales derive from the widely used system of Frissell *et al.* (1986), who proposed the idea of hierarchically nested scales of analysis in river classification drawing on pre-existing ecological theories about nested scaling. The only common scale not considered in this study is the finest scale termed microhabitat by Frissell et al. (1986) and hydraulic unit by many other systems. This study was motivated by practical management needs and fundamental questions about regulated yet dynamic gravel-cobble rivers, which are a worldwide phenomenon. At the segment scale, when a regulated river has much less downstream sediment supply after regulation than before and somewhat less frequent occurrence of sediment transporting flows after than before (i.e., low S^* and medium T^* *sensu* Grant *et al.*, 2003), then it is going to exhibit a net export of sediment as it evacuates valley-scale sediment storage (Williams and Wolman, 1984), but a key question is whether the channel necessarily disconnects from its floodplain? At the reach scale, are there differences in the amounts of sediment scour and deposition between reaches, and if so what hydraulic processes and geomorphic controls explain them? At the morphological-unit scale, does an incising regulated river necessarily lose differentiation between unit types (perhaps because of flow homogeneity) or may local factors promote renewal of units even as the river loses elevation? In light of natural fluvial heterogeneity and spatial patterning in landforms and processes, these questions are best answered by collecting repeat surveys of near-census data over a long river segment and aggregating the data to the correct spatial scale for each analysis. The fundamental scientific questions explored in this study illustrate the merits of a multi-scalar framework for not only mapping landforms, but also analyzing how rivers change through time.

Study Site

The 3480 km^2 Yuba River is a tributary in the Sacramento River basin flowing from the western slopes of the Sierra Nevada to the confluence with the Feather River at Marysville (Fig. 1). The montane-Mediterranean climate is characterized by cool, wet winters and hot, dry summers (Storer *et al*., 2004). Heavy flooding can occur in the winter when weather systems driven by the Pacific Ocean El Niño Southern Oscillation produce warm rain-on-snow events. Spring runoff is dominated by snowmelt during April-June as temperatures warm.

Flow coming out of the mountains and into the valley primarily comes from the North, Middle, and South Yuba River tributaries that join a short distance upstream of a high concrete dam (Englebright Dam) and secondarily from the small, regulated tributary Deer Creek. Englebright Dam marks the start of the lower Yuba River segment. It was constructed as a sediment barrier in 1941 to protect the lower Yuba River from further impact associated with the hundreds of millions of tons of sediment blasted off hillsides throughout the watershed during hydraulic gold mining (Gilbert, 1917). Downstream at river kilometer 17.8, Daguerre Point Dam is an 8-m high irrigation diversion structure that creates a slope break and marks the reach-scale transition from net incision upstream to net deposition downstream.

The ~ 37.1 km long section between Englebright Dam and the Feather River confluence is termed the Lower Yuba River (LYR). It exhibits a straight to slightly meandering planform geometry, little entrenchment, a cobble-gravel bed, an average channel slope of 0.16%, and an average wetted baseflow width of 59.4 m (Wyrick and

Pasternack, 2012). Even though Englebright Dam blocks bedload, the LYR remains a wandering gravel-bed river due to the gravel-cobble-rich hydraulic-mining deposits (James *et al*., 2009; White *et al*., 2010). The mean substrate size in the bankfull channel is 0.1 m, with local size decreasing downstream from 0.3 m near Englebright Dam to 0.04 m near the mouth.

Instantaneous stage-discharge has been continuously recorded on the LYR at two USGS gages: Smartsville near Englebright dam (#11418000), and Marysville near the mouth (#11421000). Wyrick and Pasternack (2012) defined a representative baseflow discharge for research purposes of 24.9 m^3/s above DPD and 15.0 m^3/s downstream of DPD (accounting for irrigation withdrawals), which is equivalent to ~ 75% daily exceedence probability. The winter flood regime is highly dynamic despite some flow regulation (controlled releases up to 118.9 m^3/s by Englebright Dam), with a field-determined bankfull discharge of ~ 141.6 m^3/s occurring every ~ 1.25 years and a field-determined floodplain-filling flow of ~ 597.5 m^3/s occurring every ~ 2.5 years (Wyrick and Pasternack, 2012). Above this flow the primary exposed alluvial surfaces in the river valley are terraces and artificial “training” berms that isolate the modern river corridor from a high disturbed mining area known as the Yuba GoldFields.

Methods

Experimental Design

An overview of the experimental design is laid out, and then methodological details are presented in the following subsections. Spatial object-oriented analysis of rivers may be delineated according to patterns that are arranged longitudinally and laterally relative to the flow direction in a river. This study evaluated fluvial processes associated with a large flood at three spatial scales using such methods. Data used consisted of (i) topographic digital elevation models (DEMs) of the same river segment in 1999 and 2006-2008 (Carley *et al*., 2012) and (ii) polygons delineating different landform features at three spatial scales of interest (Wyrick *et al*., 2012, 2014). At the largest scale, the river valley for the entire LYR was mapped as a single polygon by hand, guided by aerial photography and DEMs (Fig. 2). At this scale, laterally discrete but longitudinally continuous landforms in a river corridor relate to the hydrologic regime necessary to inundate different topographic levels, such as bankfull, floodplain, and terraces. In this study, only two inundation regions were considered- within the bankfull channel and the overbank region. At the next scale down, longitudinally discrete landforms were delineated in terms of geomorphic reaches that spanned the valley's width. Finally, at the smallest scale, morphological units (MUs) ranging in size from ~ 0.3 to 10 channel widths were mapped on the basis of 2D baseflow hydraulics computed with a numerical model and other landform indicators, as explained below. At each spatial scale, area of each topographic change type (i.e. no detectable change, scour, or fill), net volumetric change, and mean depth of topographic change were computed for each segregating unit (i.e. whole segment, in-channel or overbank, geomorphic reach, and MU type). This allowed for comparison of these variables between the different regions of interest at each spatial scale. Given only six reaches, correlation and regression analyses were challenging, but were undertaken to look for reach-scale landform variables that might explain the differences in topographic change metrics. Topographic change maps were used to interpret regression results. As longer segments are analyzed in the future, this approach will become more statistically robust, so it is worthwhile to pioneer the concept.

Data

Survey and DEM data

Two topographic DEM datasets spanning the downstream-most 34 km of the lower Yuba River (i.e., from the onset of Timbuctoo Bend to the mouth, Fig. 2) were compared to create a detailed map of the areal and vertical changes in topography in response to a hydrologically heterogeneous period that included a flood with a peak daily flow of 2384 m^3/s and an instantaneous peak of 3206 m^3/s on the Marysville gage. Complete details of the methodology, including spatially explicit uncertainty analysis, are available in Carley *et al*. (2012), but are summarized herein. This study applied the existing data to address new, specific scientific questions about topographic change and sediment budgets, making a new contribution.

In 1999, topographic and bathymetric survey data were collected by contractors for the US Army Corp of Engineers to yield a 0.6-m contour map of the LYR. Topographic contours and available point data were combined to produce a 1.5 x 1.5 m^2 (5 x 5 ft^2) raster DEM in the State Plane California Zone II (feet) coordinate system

(NAD83 datum), with the elevations updated from the original NGVD29 datum to the modern NAVD88 datum. A more recent topographic map of the LYR was produced between 2006 and 2008 (with negligible amount of surveying in 2009) during an extended dry period through a phased effort based on iterative assessment of map quality. Timbuctoo Bend Reach was mapped in 2006, whereas the other reaches were mapped in 2008. Subsequent analyses that hinge on the duration between topographic maps from section to section of river accounted for different epochs for different areas. Additionally, areas of data gaps within each map (especially from areas avoided in the 1999 mapping campaign) and known man-made alterations (e.g., mining pits and dredging spoils) between mapping efforts were removed from both DEMs before differencing.

The 1999 contour map is a dataset that was provided to the authors as is. For the 2006-2008 surveys, the authors had more control of the survey methods and map production. For this latter DEM, a comprehensive set of uncertainty analyses was performed to ensure that the multiple surveys used to create the single map were accurate and comparable. Ground points on the uneven natural surface were compared between ground-based and boat-based surveys, ground-based and LIDAR surveys, and boat-based and LIDAR surveys. Surveys were also compared at carefully surveyed water surface elevation locations along the water’s edge, where surface variability was less. Vertical datums were checked between survey methods. Overall, mean survey differences between methods were within the river’s mean grain size (0.1 m). A thorough uncertainty assessment was reported by Barker (2010). A final set of TINs were produced spanning the entire LYR corridor.

DEM difference map

Carley *et al*. (2012) undertook an extensive analysis of uncertainty for each DEM and in the combination between the two to identify the best methods for this data set. No longitudinal trend in deposition or erosion was present, so there was no need for continuous longitudinal detrending. Thirteen different approaches for removing uncertain changes cell-by-cell were tested. Given any Level-of-Detection (LoD) raster combining the survey and interpolation errors of each individual DEM, one can either subtract the LoD raster from the DEM difference raster or keep the same differences, but exclude any cell whose LoD exceeds its DEM difference, so Carley *et al*. (2012) tested the effects of both options. For exclusion, five different types of LoDs were evaluated, consisting of different levels of statistical significance for spatially distributed uncertainty and/or excluding the uniform half-contour interval of the 1999 data (i.e., 0.3 m). Note that with a 0.1-m mean grain-size in the river corridor, removal from geomorphological consideration of changes that are less than three grains thick is sensible for this quality of data. It is a common problem in current DEM difference studies with near-census data that thin sheets of erosion and deposition cannot be resolved. Spatially distributed uncertainty was computed by evaluating point density and elevation variability within each cell, building on the method of Heritage *et al.* (2009). For subtraction, the same five LoDs were evaluated, and an additional three were also tested in which the spatially distributed LoD was subtracted and then afterwards the uniform 0.3-m half-contour interval LoD was applied as an exclusion. This uniform exclusion is identical to a uniform subtraction of 0.3 m for values within 0.3 m because it removes the values either way, but it retains higher values of change to keep them as they were observed after spatially distributed LoD subtraction. Of the thirteen approaches, the one that was found to perform best involved subtracting the spatially distributed 95% confidence level LoD raster and then excluding the uniform 0.3-m half-contour interval raster. A summary workflow for the final, best Carley *et al*. (2012) method using ArcGIS 10.0 is presented in Figure 3.

The final DEM difference map accounting for uncertainty represents the net change in topographic elevation over the 7- or 9-year epoch for each pixel. Any ephemeral topographic changes that occurred between the two map dates but did not persist until the second survey cannot be accounted for with this methodology, which is a long-standing constraint on the repeat survey approach (Horne and Patton, 1989; Lindsay and Ashmore, 2002). The final DEM difference map was reclassified into a presence/absence map of no detectable change, scour, or fill (Fig. 4), which was used to compute the area of each of these categories within different regions.

Channel and overbank regions

To evaluate topographic change and sediment budgets for the whole LYR differentiating between in-channel versus overbank regions, ideally there would exist an inundated area map for exactly bankfull discharge in 1999, but no such map or aerial photo exists for the LYR. One solution would be to reconstruct planform channel regions at the same discharge using a hydrodynamic model. In this case that was infeasible, because there were enough DEM data gaps in key locations of the 1999 map to inhibit 2D modeling of the river segment. Instead, the approach taken was to use aerial imagery from 1999 when flow was reasonably close to bankfull discharge. Specifically, a wetted area polygon was hand digitized using 0.3-m resolution greyscale aerial imagery collected by Towill, Inc. on April 14, 1999 when the USGS streamflow record indicates a mean daily discharge of 109 m^3/s at the Smartsville gage (Fig. 2).

Geomorphic reaches

A geomorphic reach is a longitudinally distinct section of river with a characteristic set of attributes controlled by the balance of sediment transport capacity, sediment supply, topography, and possibly other factors such as geology, vegetation, and artificial structures and modifications. On the LYR these governing factors were evident in the following variables: 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. Major changes in these variables were used to delineate six distinct reaches (~ 25-80 channel widths long) in the alluvial LYR, and then numerous topographic change variables were computed at the reach scale to go along with previously determined geomorphic variables from companion studies (Table 1).

Morphological units

River landforms, referred to as channel units (appropriate only when within the bankfull channel), geomorphic units, or morphological units, are commonly mapped at a scale of ~ 0.5 to 10 channel widths and are considered to be the basic building blocks of fluvial morphology (Grant *et al*., 1990; Wadeson, 1994; Wheaton *et al*., 2015). Wyrick *et al*. (2012, 2014) developed a new concept and approach for mapping in-channel landforms at this scale on the basis of how they steer two-dimensional hydraulics at a representative base flow at which the landform dominates hydraulic expression. Using this approach, Wyrick and Pasternack (2014) mapped and analyzed the in-channel morphological units for the whole LYR, including a supplementary file containing the MU map of the whole river over several pages. In addition, Wyrick and Pasternack (2012) mapped overbank morphological units on an expert basis drawing on many spatially explicit geospatial indicators from geomorphic datasets and two-dimensional hydrodynamic modeling of floods performed by Abu-Aly *et al*. (2013). Considering both in-channel and overbank landforms a total of 27 distinct alluvial MU types were identified, described, and mapped. This MU map was used for segregating topographic change and computing sediment budgets in this study. The assemblage of MUs varied by reach (Fig. 5). For example, among the 8 in-channel bed units, the wetted area of Timbuctoo Bend Reach had 20.2 % pools and 18.4% riffles, that for the Daguerre Point Dam Reach had 5.2% pools and 13.6% riffles, and that for the Marysville Reach had 52.2% pools and 2.2% riffles. In the bank region, the wetted area of Timbuctoo Bend had 15% medial bar, while that for the Daguerre Point Dam Reach had 1.5% medial bar.

As previously mentioned, surveying data gaps in 1999 precluded 2D hydrodynamic modeling and MU mapping of the LYR, so this study cannot address the fate of MUs during a flood, which is an important question for future inquiry. Instead, MUs were mapped for the 2006-2008 DEM, so this study was able to assess the topographic changes that drove their formation and/or rejuvenation. This enables the study to answer whether the LYR maintains a strong differentiation between MUs after a flood, which is an equally important question.

Analysis Methods

Area, volume, and mean depth

At each spatial scale, area of each topographic change type (i.e. no detectable change, scour, or fill), net volumetric change, and mean depth of topographic change were computed for each segregating unit (i.e. whole segment, channel region, reach, or MU type). The final spatially explicit, uncertainty-adjusted DEM difference map provided a net change in elevation for each 1.524x1.524-m^2 (5x5-ft^2) pixel, so the volume of change within each was simply this value times the area of the pixel (2.323 m^2, 25 ft^2). For each scale of analysis, these pixel volumes were then summed within the appropriate segregating unit.

Uncertainty in volumetric change estimation from DEM difference data is a highly challenging topic with no clear method outshining others, or none at all. In common statistics, one would normally compute the raw mean volume and then apply uncertainty bands (computed through repetition) around that, which in this case might be the volume of the 95% confidence LoD for any given area. However, in DEM difference studies the raw mean elevational value in each cell is known to be uncertain, so it should not be used to compute the expectation for the mean volumetric change. For example, in this study, the net volumetric change of the raw DEM difference was a fill of 1.20 x 10^5 m^3, which is impossible given that the river segment begins at a high dam and there is virtually no other sediment influx, so the net change has to be negative (Carley *et al.,* 2012). Thus, an elevational correction has to be applied before the expected volume is computed, but then what is the appropriate variance around the adjusted number as opposed to that for the raw number? It is probably not the same thing, as the distribution of DEM difference values changes after adjustment, but there is no method to account for this yet. As an example of an aggressive volumetric uncertainty approach, Wheaton *et al.* (2013) began with a raw DEM difference raster and then subtracted the 95% confidence LoD raster from it, similar to what was done in this study. They then computed volumes the same way as proposed in the preceding paragraph and termed those the "mean estimate" of change, but clearly this is the adjusted mean, not the raw mean. To get some measure of volumetric uncertainty, they then computed a new LoD for the raw DEMs using the 68% confidence level, and computed volumes for areas on that raster. Finally, they considered the volumetric uncertainty around the mean estimate for any area to be the corresponding volume of the 68% confidence level LoD in that same area. That assumes that the variance around the adjusted volumes is identical to that around the raw ones. Overall, this is a double counting of the same elevational uncertainty in the raw DEMs, rather than an independent accounting of elevational and volumetric uncertainty. Wheaton *et al.* (2013) showed evidence that this is an excessive loss of real change, but the tendency is to want to do something. Further complicating matters is the fact that there are significant differences in the datasets people have in different studies, making the best method of volumetric uncertainty accounting uncertain. Thus, technically sound and scientifically meaningful approaches for spatially explicit volumetric uncertainty analysis (on top of elevational uncertainty analysis) in different settings are presently unreliable, so no such procedure was used in this study.

Due to different time epochs measured for different regions of the river, the volumetric analyses presented are in units of volume per year, thus enabling easier comparisons among all river regions and spatial scales. For scales that transcend different time epochs, the river was segregated into regions of each time epoch, and then the annual rates were calculated for each epoch region and summed for the whole segment. The time epoch was seven years (1999-2006) for Timbuctoo Bend and nine years (1999-2008) everywhere else.

Mean depths of topographic change were calculated by dividing each net volumetric change by total area of a segregating unit. Additionally, mean depths of change were isolated for only those regions that experienced scour or fill (i.e., the net fill volumes were only divided by the net fill planform areas, and likewise for the net scour, within the segment, reach, or MU scales). These stratifications highlight how much dynamism occurred within certain regions as compared to the overall net depth changes at each spatial scale.

Segment scale methods

Four analyses of topographic change were performed considering the river segment as a whole. Recall that the guiding question posed in the introduction was to ascertain whether regulated river incision would disconnect the channel from the floodplain, which is a common concern for regulated rivers (Williams and Wolman, 1984; Brandt, 2000). First, aggregate statistics of topographic change volumes and depths were computed. A reclassified DEM difference raster was used to obtain the overall area of each category of topographic change. Second, topographic changes were segregated by channel region (i.e., in-channel versus overbank) to determine the extent to which topographic change intensified channel-floodplain separation or ameliorated it. Third, the segment was divided longitudinally into two areas on the basis of being above or below the run-of-the-river dam, Daguerre Point Dam, to determine how it was affecting erosion and deposition at the segment scale.

Finally, longitudinal profiles in topographic change were assessed to look for secular trends at the segment scale. To analyze the longitudinal trend, the relative area of each change class was determined within discrete, contiguous cross-sectional rectangles. To accomplish this, a centerline was drawn for the valley polygon, which was then stationed every 6.1 m (20 ft). From these station points, perpendicular lines were extended out to the valley boundary and then buffered 3 m (10 ft) in both the upstream and downstream direction, thus creating a continuous coverage of the valley area with cross-sectional rectangles (Wyrick and Pasternack, 2012). The areas of each change class within each rectangle were then calculated in ArcGIS, with the areas being assigned to the longitudinal station of each rectangle. These areas were then converted into percent of total area at each station to create a longitudinal profile that highlights the spatial patterns of areal dominance/subordinance of each change class.

Reach scale methods

To analyze topographic change at the reach scale, the same approach as was used for the segment-scale channel regions was used, but this time geomorphic reach polygons were the segregating boundaries. Two broad topics were addressed at the reach scale. First, this is the appropriate scale to perform a longitudinal sediment budget. Second, statistical analyses were done to see if any hydrogeomorphic variables related to metrics of reach-scale topographic change patterns.

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 LYR valley and the sediment budget involves the flux and storage of sediment among the reaches within the segment. Apart from turbid mud suspended in the water column as wash load and a few very small tributaries, there is negligible influx of sediment into the LYR valley, because Englebright Dam blocks influx. Both gaged tributaries (Dry and Deer Creeks) downstream of the dam are themselves dammed and Deer Creek is almost purely bedrock downstream of its dam. Dry Creek likely does export some sediment to the LYR, which may explain the broadening that occurs just downstream of its confluence. A volumetrically small influx of boulders and angular rock fractured off the bedrock-soil interface occurs where the perennial channel is against the hillside. In contrast, the valley floor stores on the order of ~ 100 million cubic meters of hydraulic-mining alluvium (Gilbert, 1917; James, 2005; James *et al.*, 2009, 2010). 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 sediment budget, there are still sources of uncertainty and a need to be clear about what is accounted for and what is not. First, similar to areal analysis, 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 all within the re-survey time domain, then no change will be detected in that cell- a process known as compensating scour and fill (Lindsay and Ashmore, 2002). If the sediment came from an upstream cell within the control volume, then the change would be detected in both; however, the two volumes will not be spatially linked (i.e., we cannot determine which sediment moves to where).

Second, it is assumed that there are no non-transport mechanisms of volumetric change (i.e. bed “deflation” or “inflation”). Merz et al. (2006) reported that gravel-placements sites experienced up to 20% volumetric loss (i.e., deflation). Marquis and Roy (2012) reported that a gravel bed may undergo “dilation” or “contraction” (analogous to inflation and deflation in Merz et al. (2006)) due to injection or loss of finer particles from the bed during a state of partial transport. In the case of the LYR, there were no gravel-placement projects and the bed had two years to deflate and adjust after the significant 1997 flood. Nevertheless, there is uncertainty caused by unknown mechanisms of non-transport and partial transport deflation/contraction and inflation/dilation.

Beyond evaluating the sediment budget, statistical analysis was used to investigate what hydrogeomorphic controls explained differences in the amounts of sediment scour and deposition between reaches. Drawing on the data in Table 1, binary correlations were calculated between topographic change metrics and potential controlling variables. For those showing statistically significant results in terms of high correlation coefficients and low p-values, regression analysis was done to inspect the relation to see if the results were scientifically meaningful. Also, topographic change maps of example sites are presented for visual corroboration of the interpreted geomorphic mechanism.

Morphological unit scale methods

To analyze topographic change that drove the pattern of MUs, the same approach as was used for the segment-scale channel regions was used, but this time the boundaries used to segregate the area, volume, and depth data were the MU polygons. The key test was whether areas that became different MU types exhibited similar or differential topographic changes. Further, if the river and valley are downcutting, did all landforms necessarily decrease? Sorted column plots were used to visualize MU-specific volumes and depths of change on an annualized basis, again accounting for the two different epochs in the study as described earlier.

Results

Segment Scale Results

Aggregate changes

For 1999 to 2008, the LYR exhibited massive internal changes in topography (Fig. 4), yet had a very small net loss of sediment from the river corridor. In terms of area, 46.7% of the total area experienced no detectable change, while 31.0% filled and 22.3% scoured. The annualized scour and fill volumes were 2.93 x 10^5 m^3/yr (51.5% of total change) and 2.76 x 10^5 m^3/yr (48.5%), respectively, which means a net annual export of 1.70 x 10^4 m^3/yr. The mean rate of depth change for the full valley width was a net scour of 1.8 mm/yr. By stratifying the segment into regions of either net scour or net fill, the dynamism of the processes are better exhibited. In scour areas, there was a net downward elevation change of 13.5 cm/yr, while in fill areas there was a net upward elevation change of 9.1 cm/yr. Thus, even though fill processes covered more total planform area, scour processes moved more volume of sediment and caused more elevation change. These results make sense, because there is nearly zero influx of sediment due to Englebright Dam, so a net fill result would be physically impossible. Further, the river experienced a large flood between surveys, as well as several small to moderate magnitude floods. This indicates that there was ample transport capacity during the study epoch to create diverse local changes and induce a net sediment export out of the river.

In-channel versus overbank

When the segment was stratified into in-channel and overbank regions, it was revealed that the latter were as dynamic as the former. The in-channel region had no detectable change for 49.5% of its area, while the overbank region had that for 46.0% of its area. Slightly more in-channel area experienced scour than did overbank area (24.1% versus 21.5%), while the overbank region experienced more area of fill (32.5% versus 26.4%). Considering change volumes, the opposite was found as for area, with in-channel region experienced net fill, while the overbank region experienced net scour. The 1999 near-bankfull wetted channel region experienced a net fill rate of 5.8 mm/yr as the channel migrated to its 2006-2008 location. The overbank regions experienced a net scour rate of 3.8 mm/yr. This indicates that as the channel migrated to the 2006-2008 location, it tended to fill in its old channel, scour through the banks, and cut new pathways over floodplains.

The overbank net scour rate can be attributed to both the fact that the wetted channel migrated through the floodplain, eroding out a new channel, and that overbank floods provide enough transport capacity to erode the floodplains. The in-channel net fill rate can be attributed to the fact that as the channel migrated, its old channel regions became depositional zones for the overbank flows, thus effectively filling them in.

Longitudinal changes

The LYR shows a distinct downstream scour and fill trend in which there are three zones with a predominance of scour and two with a predominance of fill (Fig. 6). The results for this analysis were similar for area, volume, and depth of change. Most of the scour tended to occur upstream of DPD, with the most occurring in the upper ~ 6 km of the study segment. That section experienced a net annual scour rate of 4.48×10^4 m^3/yr. The scour zone in this upstream area is explained by valley constriction and "hungry water" in which over-dam floods have significant sediment transport capacity but no supply due to the dam, so sediment stored at the head of the valley is entrained.

The rest of the LYR valley above DPD experienced a net scour rate of 5.44×10^4 m^3/yr, for a total annual scour rate of 9.92×10^4 m^3/yr above DPD. The maximum local net scour rate was 28 cm/yr and occurred just upstream of DPD. The zone of scour upstream of DPD is interpreted to be due to the 1997 flood depositing excessive sediment in this zone followed by the 2006 flood scouring that material out. This is professional interpretation, but it is known from direct experience and management activities that the accommodation space upstream of DPD was full of sediment prior to the 2006 flood and had no additional storage capacity. The maximum relative areas of fill occurred upstream of the Dry Creek confluence, and near the downstream end of the Daguerre Alley training berm. These are both areas that experience backwater effects and are very wide compared to the rest of the river corridor.

The region of the LYR below DPD experienced a net annual fill rate of 8.22×10^4 m^3/yr. The maximum local fill rate was 11.3 cm/yr and occurred where an overflow anastomosing channel re-connects to the mainstem river. It is interesting that the river is filling in downstream of DPD and scouring above it, as this is the exact opposite of the conventional wisdom of the effects of dams. The reason is that these processes are not being driven by the dam, but rather the river is driven by larger forces of sediment redistribution associated with valley recovery to the end of hydraulic mine sediment being delivered since Englebright Dam was built in 1941. The maximum relative areas of fill in the river occurred in areas that experience backwater effects and are very wide compared to the rest of the river corridor. The scour zone at the downstream end is explained by base level drop in the Feather River causing knickpoint retreat through the LYR. Also, levees confine this eroding section, focusing flow to yield high flood velocities.

Reach Scale Results

Comparing among the six geomorphic reaches, there were significant differences in relative percent area of scour (11-55%) and fill (10-45%) as well as in mean net rate of change (-5.9 to 1.9 cm/yr), mean scour rate in scour areas (10.3-17.3 cm/yr), and mean fill rate in fill areas (8.6-14.7 cm/yr) (Table 1). Delineating volumetric change by reach, only two, both upstream of DPD, were net scour, while the other four reaches were net fill (Fig. 7). The DPD and Hallwood reaches experienced the most net fill, while the Parks Bar and Marysville reaches experienced relatively small net fill rates. The upstream-most reach, Timbuctoo Bend, experienced scour over 44.5% of its area and fill only over 10.4% (the least relative fill area of all reaches). It is notable that scour was not limited to the channel, but occurred over the whole width of the river corridor in this valley-constricted reach. This reversed in the Parks Bar reach immediately downstream, which experienced much less scour than fill (19.7% and 32.9% of the area, respectively). The Dry Creek reach exhibited the most relative area of scour (55.3%), while the adjacent downstream reach, DPD, exhibited the most relative area of fill (44.9%) among all reaches. The Hallwood and Marysville reaches experienced the smallest areas of detectable change (< 50%, whereas all other reaches had > 50% detectable scour plus fill). Only two of the six reaches exhibited more relative areas of scour than fill (Timbuctoo Bend and Dry Creek), while scour areas were clearly subordinate in the DPD and Hallwood reaches (12% and 11%, respectively). The relative areas of scour and fill are most similar in the Marysville reach, whereas the other reaches can easily be identified as either scour- or fill-dominant.

Statistical analysis at the reach scale found that many commonly measured reach-scale variables, especially ones used in river classification, failed to show binary correlations with any of the topographic change metrics at the reach scale. For example, all of the following variables yielded no statistically significant influence: channel sinuosity, channel bed slope, substrate size, bankfull width to depth ratio, specific stream power, mean baseflow width, mean bankfull width, mean floodway width, river valley width (minimum, mean, and maximum), bankfull wetted area, or floodway wetted area. The only statistically significant ($p<0.02$), high regressions ($r>0.88$) found to explain topographic change metrics between reaches involved the entrenchment ratio and the ratio of bed slope (S) to bankfull Froude number (Fr_b) (Fig. 8). By definition, the entrenchment ratio is the ratio of the width of the valley at an elevation of twice bankfull depth versus the width at bankfull depth (*sensu* Rosgen 1996), and thus the higher the value, the less entrenched the channel is. According to the data, channels that are incrementally better connected to their floodplains exhibit incrementally more fill area. On the LYR, the greatest contrast in this process comes from comparing the Daguerre Point Dam Reach with the Timbuctoo Bend Reach. The former has a highly connected channel and floodplain as well as an anastomosing pattern with a secondary channel on the northern flank that activates when flow is between 2-3 times bankfull discharge. This extra secondary channel area preferentially fills. In contrast, Timbuctoo Bend is in a confined valley and scouring throughout the river corridor, so it has little area of fill. Thus, the entrenchment ratio yields a scientifically comprehensible influence over the area of fill. Compared to other potential controlling variables, it shows higher correlations with other topographic change metrics, but none that are statistically significant given only six data points.

Meanwhile, the ratio of S/Fr_b showed a relation with the mean scour rate in scour areas (Fig. 8b). In the plot, higher scour is represented by a more negative number, so the effect is a direct correlation, with a higher S/Fr_b corresponding with a higher mean scour rate. The data in this analysis showed one point with a low S/Fr_b, one with a high value, and then four with similar intermediate values, thus it is easiest to interpret by comparing the two extremes. Once again, the Daguerre Point Dam Reach is involved, as it has the highest S/Fr_b, but this time the issue relates to its processes at bankfull flow. The pattern of scour in this reach is easily interpreted as lateral migration, because there is scour at every outer cutbank along the bankfull channel and deposition on each inner point bar (Fig. 9a). This is objectively identifiable in that the area of scour is just outside the 1999 wetted area polygon along the outsides of the meander bends. In contrast, the Marysville reach has the lowest S/Fr_b and its scour is easily interpretable as in-channel downcutting, because it is located predominantly inside the 1999 wetted area polygon, which remained the location of the bankfull wetted area in 2008 (Fig. 9b). Thus, S/Fr_b is revealed to be a controlling variable over the relative roles of lateral migration versus vertical downcutting at the reach scale in the LYR.

Morphological Unit Scale Results

There were three MU types that mostly experienced no detectable change - hillside/bedrock, tributary delta, and agriplain, and therefore were more likely to have been the same MU in 1999 and 2008. All other MU types were delineated in regions that experienced significant change. Island high floodplain units were delineated in regions that experienced the most relative area of change (~ 90%), with ~ 82% of those areas altered by fill. Regions that became MU types in which scour was clearly dominant and fill was clearly subordinate, in terms of relative areas, included pool, chute, tributary channel, run, cutbank, and fast glide. For point bar, 67% of its area experienced some detectable change, with ~88% of those areas being fill. This aligns with the unit definition used by Wyrick and Pasternack (2012), who identified point bars as regions of deposition on the inside bank of a river meander.

Interpretation of the volumetric changes at the MU scale is the same as discussed for the areal analyses. The reported values are the volumes that scoured or filled into areas that became these delineated landforms (Fig. 10). With that in mind, the floodplain and high floodplain units occurred in areas that experienced the most net fill (5.15 x 10^4 and 2.85 x 10^4 m^3/yr, respectively), while the dredger tailings and pool units in areas that experienced the most net scour (3.47 x 10^4 and 3.31 x 10^4 m^3/yr, respectively). All of the in-channel units were formed by net erosional processes, but they did exhibit significantly different rates amongst themselves.

One landform type of geomorphic interest is the swale, which experienced relatively high values of both scour and fill; however, the net volumetric movement is only ~2.5% of the total dynamism. Other unit types of interest are those that constitute the baseflow channel bed – riffle, pool, chute, run, riffle transition, fast glide, slow glide, and slackwater. All the regions that became these units were net scour, with only small portions of their dynamism attributed to fill processes. Riffle transition regions experienced the most volumetric fill (~ 28 % of total volumetric sediment movement), while pool regions experienced the least (~ 1%). Riffles and pools are often complementary end-members in river morphology studies, and are therefore also generally linked as end-members for discharge-dependent transport regimes that describe river "self-maintenance". Because the regions that ended up as riffles experienced 18% deposition, they appear to have been rejuvenated relative to the regions that ended up as pools, which experienced 99% scour. This contributes to the concept of self-maintenance in the LYR. Nevertheless, it is important to understand that even the places that became riffles at the end of the epoch scoured a lot during the main flood, and thus generally may be interpreted as erosional plateaus rather than depositional bars.

Whereas the story at the segment and reach scales are very similar between areal, volumetric, and depth analyses, the MU scale analyses shows some striking differences in the rate of depth changes (Fig. 11) versus the areas and volumetric rates. This is due to the vastly different areas covered by various MU types. For example, the MU-scale regions that exported the most net volume of sediment were those that began and ended as dredger tailings, but their depth of change was middling. Conversely the regions that became cutbank only exported a small volume relative to the other units, but exhibited the greatest local dynamism with a mean scour rate of 16.8 cm/yr. Regions that became pools and chutes were also locally erosive. These units tend to be located near the center of the channel; however, because it is impossible to speculate whether these same pools and chutes existed in the 1999 channel, we cannot with any certainty fully ascribe these high depth change rates to either entrenchment processes or channel migration and the need to carve out deeper locations for its new pools and chutes.

At the other end of the processes continuum, regions that became floodplain experienced the most volume of sediment fill, but because this unit was so large, the rate of depth changes was fairly mundane at 2.0 cm/yr (Fig. 11). The most dynamic fill locations were within the regions that became point bar and island high floodplain (both 5.4 cm/yr). Thus, during the 7-9 year survey epoch, point bars grew at a faster rate than any other MU type, highlighting the meandering nature of the LYR channel. The fact that island high floodplain and island floodplain units also grew at a higher than average rate highlights the restorative deposition regimes of large floods in the LYR.

Discussion

Valley fill evacuation

This study provides new insights into the processes, rates, and patterns of alluvial valley evacuation of sediment at reach and segment scales after dramatic, rapid changes to flow and sediment supply regimes. The LYR valley was first filled in with sediment during a few decades, and then had all further supply stopped by a tall dam. For ~ 70 years the river has been internally redistributing and exporting that material. At this time, terraces and artificial dredger tailing berms from historic anthropogenic disturbances yield visually charismatic erosion, given their height and conspicuousness. They are composed of historic hydraulic mining sediment laden with inorganic mercury (used in historic gold extraction) of concern to downstream biogeochemisty in oxygen-poor aquatic and emergent habitats. However, they are not in fact the major source of sediment (and mercury) that deposits downstream or leaves the system now, or even likely in the next two centuries and possibly the one after that. Singer et al. (2013) speculated that eventually these will be important sources of mercury export, because the valley floor will have achieved equilibrium, but this study shows that it will be in a distant future or may not happen at all, also depending on management decisions.

Large floods on the LYR tend to be ~ 2000 to 5000 m^3/s, with the largest recorded daily peak flow (1904 to 2015) occurring in December 1964 at an estimated 5097 m^3/s at the Marysville gage. Such a large flood occurred on December 31, 2005 during the epoch investigated, with daily average and instantaneous peak values at the same gage of 2384 and 3206 m^3/s, respectively, with a long duration of flow above bankfull stage in the 2006 water year, so this study bears on the issue of mercury export potential. The results found that a large flood has a far greater effect of sediment erosion on the valley floor than from remnant terraces and artificial training berms, but both are contributing to allowing the valley to be exhumed as a whole. Based on interpreting the segment-scale topographic change patterns relative to lateral inundation zones, vertical downcutting in the channel, vertical scour on the floodplain floor, and channel bank migration at the channel-floodplain margin were the primary mechanisms of sediment erosion during this large-flood epoch.

Historic sedimentary fill that underlies riverbed and floodplain surfaces at any moment in time will become available to the river as the valley downcuts. Upon inspection through excavation, these materials are well-mixed deposits in terms of particle sizes and composed of the same hydraulic mining sediment, including mercury-laden fine sediment, as in the tailings and terraces, which makes sense as they are all from the same mining sources and deposited in a relatively brief historical period (Pasternack, 2008). Samples taken from the surficial layer of the riverbed are quite different from these underlying sediments and should not be presumed to represent them.

Further, Timbuctoo Bend, the upstream-most alluvial reach, was found to be downcutting valley-wide 1999-2006 and was doing so the fastest of all reaches. Considering the net of erosion and deposition, this study found a mean net downcutting rate for the reach's valley alluvium of 4.55 cm/yr during this epoch. Considering only net erosional pixels, the mean downcutting rate in the reach was 13.6 cm/yr. These are fast topographic changes and reflect the capability of a large flood in a constricted valley to access and erode anywhere in the flood zone.

To determine how long remains before valley-wide downcutting will cease to dominate erosion and when remnant peripheral terraces in Timbuctoo Bend will be the primary source of sediment, one has to consider the total supply of stored hydraulic mining sediment in this reach above base level. Pasternack (2008) did some simple estimates of the volume of remnant mining sediment in Timbuctoo Bend above the base level at the end of the reach and concluded that there was ~ 6.1-16 million m^3, with a best intermediate estimate of 11.9 million m^3. Based on the export rate within TBR alone, the remnant mining sediment would be removed in ~ 266 years.

Erosion and net export is also occurring in a large quantity downstream of Timbuctoo Bend and upstream of Daguerre Point Dam (a larger area of scour at a lower rate of valley-wide downcutting). Given ~ 100 million cubic meters of hydraulic-mining alluvium and the net export rate 1999-2008, the LYR would need on the order of 6000 years to excavate it all, all other things being equal and assuming that the regional base level could be returned to the pre-mining elevation, which is likely impossible.

These evacuation estimates provide a rough guideline to what might happen, but heavily depend on the future hydrologic regime and continued presence of dams, which are both uncertain. For example, the future of the ~ 10.3-m high Daguerre Point Dam (that is important for irrigation diversions) is uncertain, with some constituents calling for its removal. If that happened, the valley upstream of it would be evacuated to a much larger depth than the current base level imposed by the dam, and that would take perhaps an additional century (e.g., ~ 10 m thickness divided by ~ 5 cm/yr average scour depth yields 200 additional years to evacuate) or more, depending on unpredictable river management decisions, such as efforts to build valley floor forests that would stabilize existing deposits. Even with speculation about a greater potential for a more aggressive climate producing more large floods than in the past in California (Das et al., 2011; Singer et al., 2013), the valley floor has ample sediment to continue to export well into the future and appears to be currently eroding terraces without a changed climate. Thus, whatever fine sediment and mercury is leaving the LYR, it will be quite a long time, likely beyond two centuries, before the primary concern might be on any remnant terraces, assuming they remain unforested and unprotected in place and are not eroded concomitant with the valley floor as has been happening.

Looking beyond the LYR, the remarkable and novel finding that is more universal is that a cobble-gravel river with substantial stored sediment in a confined valley, such as might occur downstream of an alpine glacier, can effect valley-wide downcutting when subjected to flows of > 15 times bankfull discharge every ~ 10 to 20 years. A remarkably small amount of material is being left behind as remnant peripheral terraces.

Differential rates form MUs

The guiding scientific question at the MU scale in this study was whether an incising, regulated river loses differentiation between unit types or do local factors promote renewal of units even as the river loses elevation? Highly regulated rivers with negligible sediment supply, little sediment storage, and homogeneous flows are widely known to exhibit a loss in relief. Long durations of low flows keep scour focused on riffles, cutting them down and armoring them, while pools fill in, creating long, homogeneous runs and glides. Flow heterogeneity has previously been shown to be important to morphological diversity in flumes (Parker et al, 2003).

This study provides strong field-based evidence that a dynamic flow regime can maintain and enhance MU differentiation, even in the absence of sediment influx, as long as there is adequate sediment in storage for redistribution. Twenty-seven different MU types were present in the LYR at the end of the study period, and the results showed that the final MUs were formed as a result of strongly differential intensities and volumes of topographic change over 7-9 years. In the channel, pools and chutes formed in the places scoured most intensely, while riffles, slow glides, and slackwaters formed in less intensely scoured areas. In the bank region, point bars filled the most, medial bars filled less than half as much, and lateral bars along straightaways scoured. All of these changes are signs of a dynamic, rejuvenating geomorphic regime.

Although not explored in this study, two-dimensional hydrodynamic modeling studies by Sawyer et al. (2010) and Abu-Aly et al. (2013) revealed hydraulic mechanisms for the geomorphic processes on the LYR. Flows of ~ 0-2, 2-8, and 8-25 times bankfull discharge tended to preferentially scour riffles, pools, and overbank regions, respectively. Thus, each range of flows provides a different geomorphic functionality. From a management perspective, this suggests that environmental flows for geomorphic purposes should not aim for a single peak, but should be varied to drive differential processes.

Conclusions

This study demonstrated the utility of a multi-scalar approach to segregating meter-scale topographic change data for the purpose of answering different basic scientific questions that each depend on a unique spatial scale. At the segment scale, the LYR is net erosional and its large floods effectively evacuate sediment from the full width of the river corridor. Fill dominated within the channel, whereas scour dominated overbank. Often it is assumed that deposition will occur upstream of a dam and erosion downstream of it, but in this study the opposite was found at a run-of-the-river dam. Effects of a dam need to be evaluated in the local context given the unique history of sediment supply and transport capacity, and not presumed based on idealized dogma. Finally, at the scale of morphological units, the presence of areas with significantly different intensities and volumes of scour and fill was found to produce a diverse array of MUs. Stage-dependent local hydraulics control the occurrence and pattern of differential topographic change, hence the need for variable flow regimes. Overall, near-census topographic change studies are well served by segregating results at multiple scales to investigate different scientific questions.

Acknowledgments

Primary funding for this study was provided by the Yuba County Water Agency (Award #201016094), the Yuba Accord River Management Team, and the USDA National Institute of Food and Agriculture (Hatch project number #CA-D-LAW-7034-H). We thank the anonymous peer reviewers for helpful comments and editing.

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Table 1. Hydraulic, geomorphic, and topographic change metrics for the reaches of the lower Yuba River.

(A) Length and area metrics

Reach	Mean Baseflow* Width (m)	Mean Bankfull* Width (m)	Mean Floodway* Width (m)	Valley Width (m) min	Valley Width (m) mean	Valley Width (m) max	Bankfull wetted area (m^2)	Floodway wetted area (m^2)	Tributary inflow?	Thalweg length (m)	Valley centerline length (m)
Englebright Dam*	36.6	51.5	72.2	55.5	94.8	175.6	62654	24186	no	1259	1217
Narrows*	-	-	-	49.4	90.8	181.7	-	-	yes	2044	1859
Timbuctoo Bend	62.5	84.4	134.4	96.9	165.8	411.2	480109	285203	no	6337	5766
Parks Bar	60.7	96.3	206.7	94.8	297.5	434.0	665885	772746	no	7919	6920
Dry Creek	75.6	130.1	263.7	238.7	307.5	489.8	458149	483367	yes	3799	3579
DPD	60.0	119.8	313.3	198.4	448.7	554.1	585155	955056	no	5639	4974
Hallwood	55.8	102.1	210.9	70.7	271.0	569.1	766540	809597	no	8382	7785
Marysville	53.0	70.4	115.5	68.3	171.3	381.3	336449	192730	no	5334	5005

(B) Geomorphic classification metrics

Reach	Entrenchment Ratio	Width/ Depth Ratio	Sinuosity	Slope	Substrate (mm)	Substrate Class	Rosgen (1996) classification	Spec Strm Power W/m^2	Fr_b	S/Fr_b
Englebright Dam	1.62	31.3	1.04	0.0031	298	small boulder	B2c	83.7	0.25	0.0124
Narrows	-	-	-	-	-	-	-	-	-	-
Timbuctoo Bend	2.12	82.4	1.10	0.0020	164	large cobble	B3c	33.1	0.36	0.0056
Parks Bar	2.93	107.9	1.14	0.0019	117	small cobble	C3	27.2	0.31	0.0061
Dry Creek	2.45	122.3	1.06	0.0014	87	small cobble	C3	14.4	0.25	0.0054
DPD	3.54	85.4	1.13	0.0018	87	small cobble	C3	20.4	0.25	0.0071
Hallwood	2.61	70.8	1.08	0.0013	61	coarse gravel	C4	17.8	0.22	0.0060
Marysville	2.61	23.1	1.07	0.0005	40	coarse gravel	C4c-	10.3	0.15	0.0034

(C) Topographic change metrics. Negative numbers indicate scour.

Reach	Scour Area (%)	Fill Area (%)	No Change Area (%)	Mean rate in scour areas (cm/yr)	Mean rate in fill areas (cm/yr)	Mean net rate (cm/yr)
Englebright Dam	-	-	-	-	-	-
Narrows	-	-	-	-	-	-
Timbuctoo Bend	44.5	10.4	45.1	-13.6	14.7	-4.5
Parks Bar	19.7	32.9	47.4	-13.9	8.7	0.1
Dry Creek	55.3	12.8	31.9	-13.0	10.1	-5.9
DPD	12.0	44.9	43.0	-17.3	8.9	1.9
Hallwood	11.0	34.9	54.1	-12.7	8.6	1.6
Marysville	22.9	24.8	52.3	-10.8	10.3	0.1

*Englebright Dam and Narrows Reaches were not investigated in this study, but their data are included for completeness.

Figure Captions

Fig. 1. Location map of the lower Yuba River segment within its catchment and in California.

Fig. 2. Inundation area maps of the lower Yuba River. Black is the inundation area for a flow of 109 m^3/s and grey shows the alluvial valley area used in the DEM difference analysis. White voids in the valley are areas where there were topographic survey gaps in the 1999 DEM. Dashed double lines perpendicular to the river are geomorphic reach breaks.

Fig. 3. Workflow for creating DEM difference raster using methodology from Carley et al. (2012)

Fig. 4. Patterns of scour (red), fill (blue), no change (cream), and no data (white) in river reaches (black) for the epoch from 1999 to 2006-2008.

Fig. 5. Morpholoigcal unit example maps illustrating how different the assemblages are between reaches.

Fig. 6. Longitudinal profile of the percent area of scour, fill, and no change across the river valley at each centerline station for the epoch from 1999 to 2006-2008.

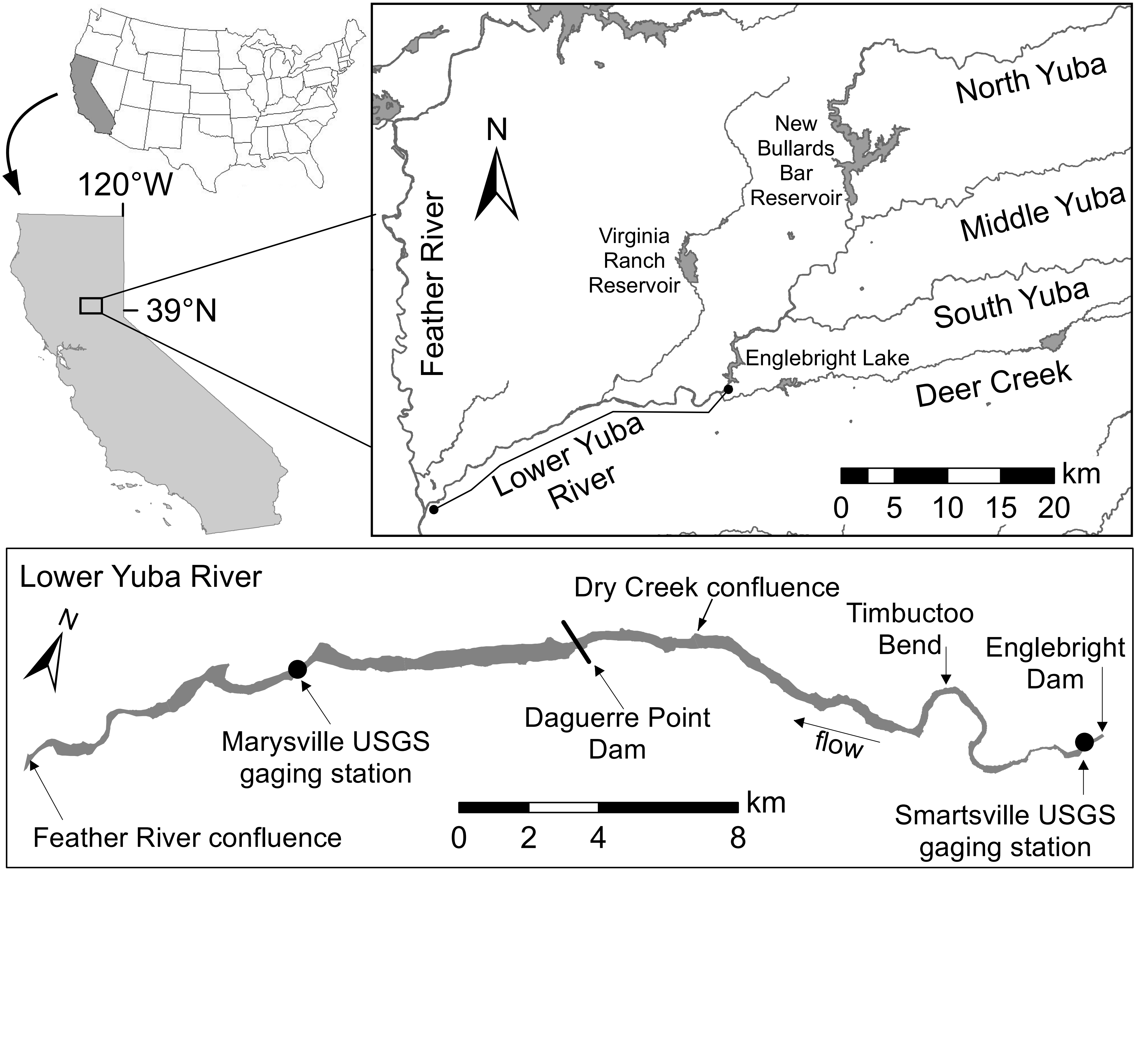
Fig. 7. Annualized sediment budget rates at the reach scales (10^4 m^3/yr). Dark grey horizontal arrows with dashed outline denote scour volumes and light grey vertical arrows with solid outline denote fill.

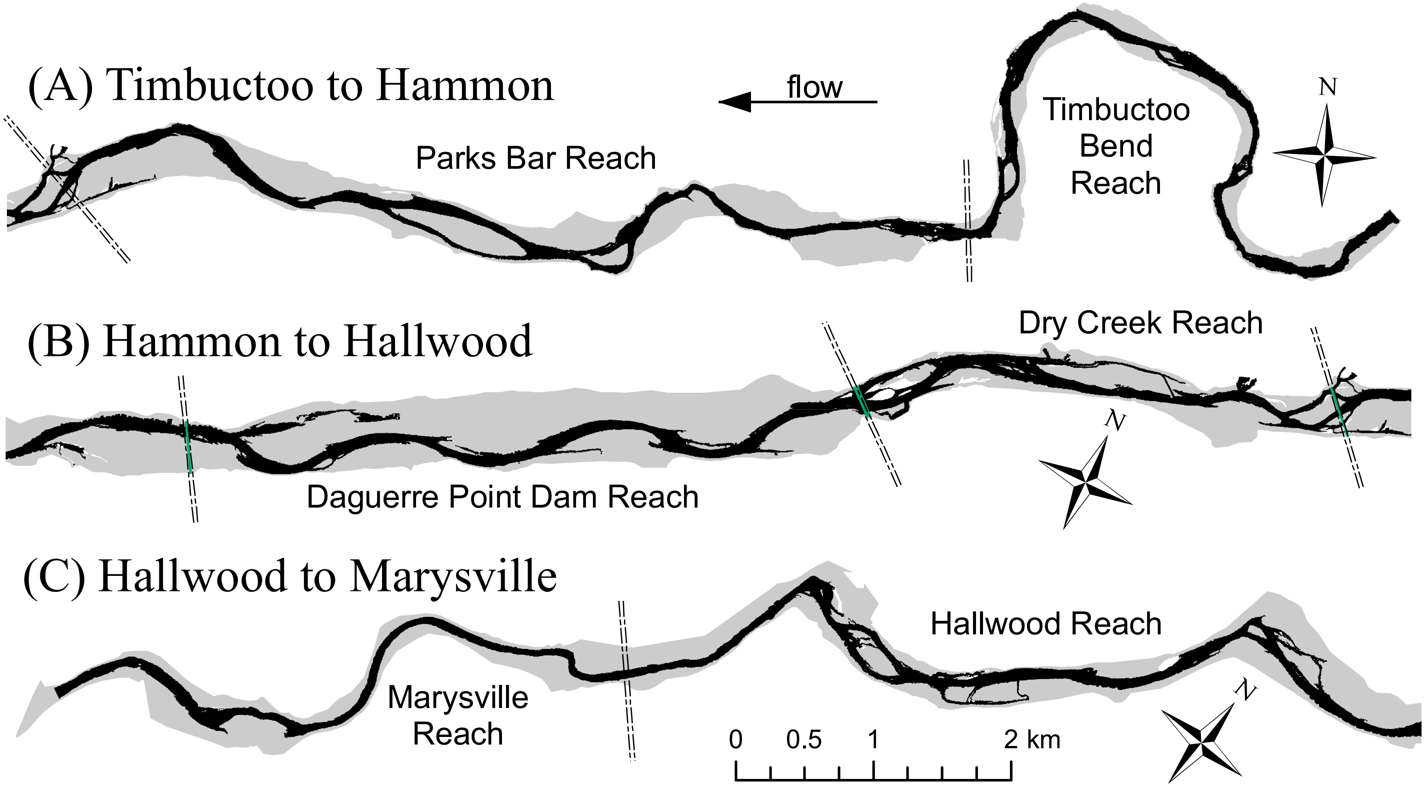
Fig. 8. Reach-scale regressions between geomorphic controls and topographic change metrics. Note that deeper scour corresponds with more negative values.

Fig. 9. Topographic change maps for two small parts of contrasting reaches, (A) DPD and (B) Marysville. The former shows lateral migration relative to the 1999 channel boundary (thick black line) with intense scour (red) just outside the channel at outer banks and deposition (blue) inside the channel. The latter shows in-channel downcutting and overbank deposition.

Fig. 10. Net volumetric change in morphologic units, sorted from most depositional to most erosional. These are the changed that caused the MUs to be formed.

Fig. 11. Mean rates of elevation change for the morphological unit types as mapped at the end of the study epoch. These are the changes that caused the units to be formed.


120°W
39°N
North Yuba
New
Bullards
Bar
Reservoir
Middle Yuba
Virginia
Ranch
Reservoir
South Yuba
Feather River
Englebright Lake
Deer Creek
Lower Yuba
River
N
km
0 5 10 15 20
Lower Yuba River
Dry Creek confluence
Timbuctoo
Bend
Englebright
Dam
N
Marysville USGS
gaging station
Daguerre Point
Dam
flow
Smartsville USGS
gaging station
Feather River confluence
km
0 2 4 8


(A) Timbuctoo to Hammon
flow
Timbuctoo Bend Reach
Parks Bar Reach
N
(B) Hammon to Hallwood
Dry Creek Reach
Daguerre Point Dam Reach
N
(C) Hallwood to Marysville
Hallwood Reach
Marysville Reach
0 0.5 1 2 km
N

Topographic change detection workflow

a. Create a uniform {x,y} point grid with 0.3 m point spacing.

b. Elevate the 0.3 m point grid using the topographic data for each map to create oversampled topographic point datasets for $\{x,y,z\}_{time1}$ and $\{x,y,z\}_{time2}$ that capture all available topographic information in the source DEMs.

c. For each 0.3 m {x,y,z} topographic dataset, create a raster of standard deviation (SD) of point elevation with a 1.5 x 1.5 m cell size (yielding 25 points per cell in the statistical computation).

d. Apply the appropriate survey and instrument error (SIE) empirical equation from Heritage *et al*. (2009) to the SD rasters to obtain the SIE raster for each topographic map.

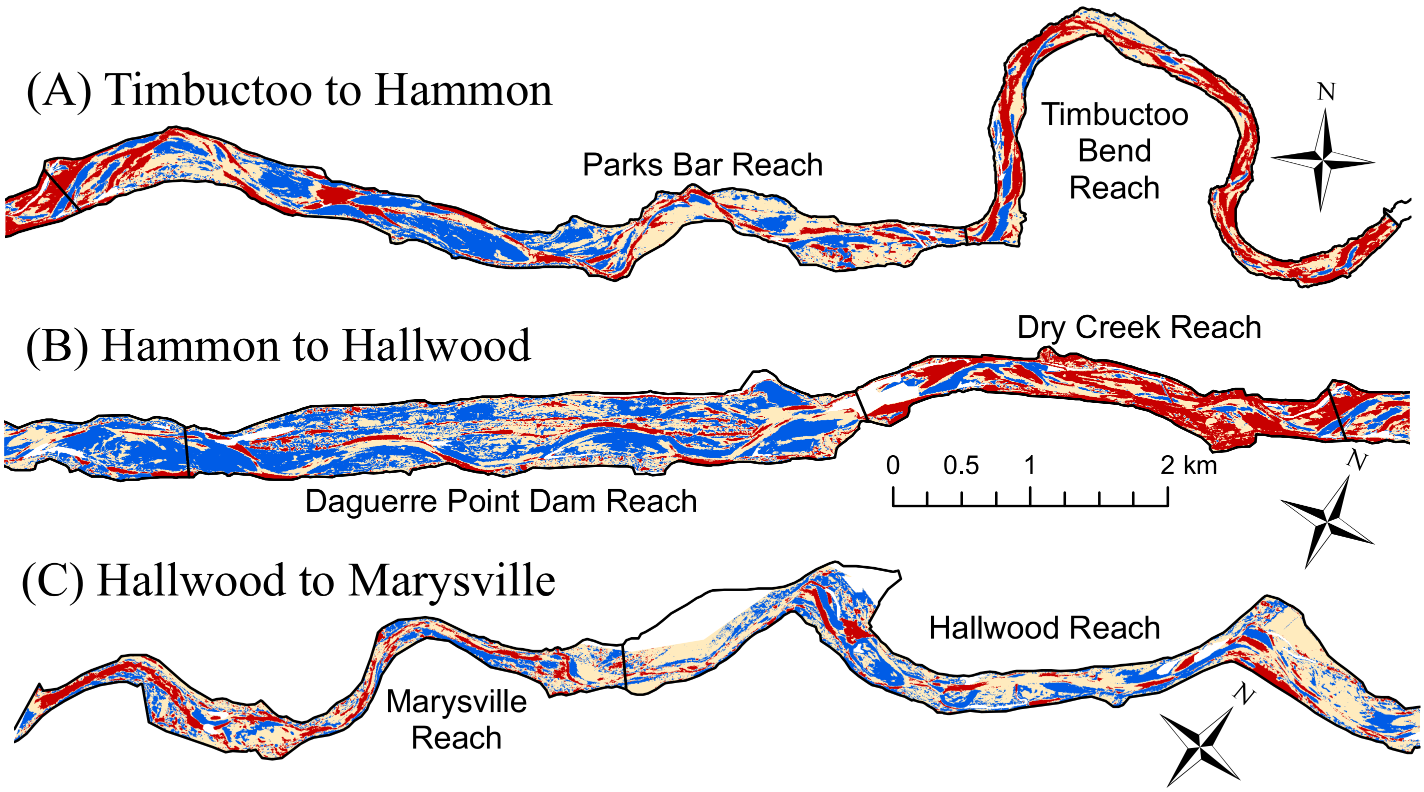
e. Produce a Level of Detection (LoD) grid that combines the two SIE rasters into a single error raster using the t-value for 95 % confidence (1.96) and the statistical equation for error propagation given by:

$$LoD = t\sqrt{(SIE_{time1})^2 + (SIE_{time2})^2}$$

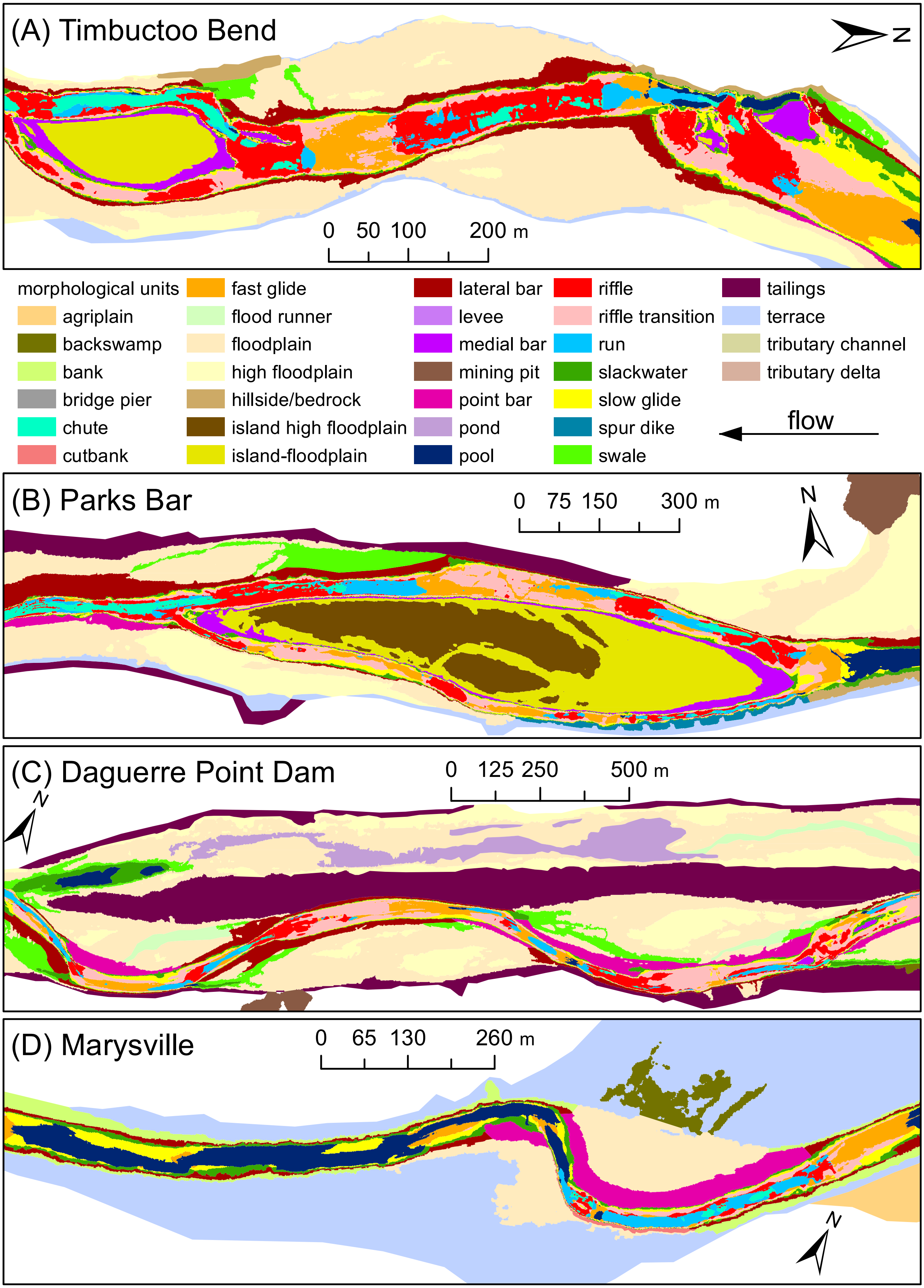
f. Create the raw DoD raster with a 1.5 x 1.5 m cell size.

g. Create separate deposition and erosion rasters using the "Con" function in the ArcGIS raster calculator.

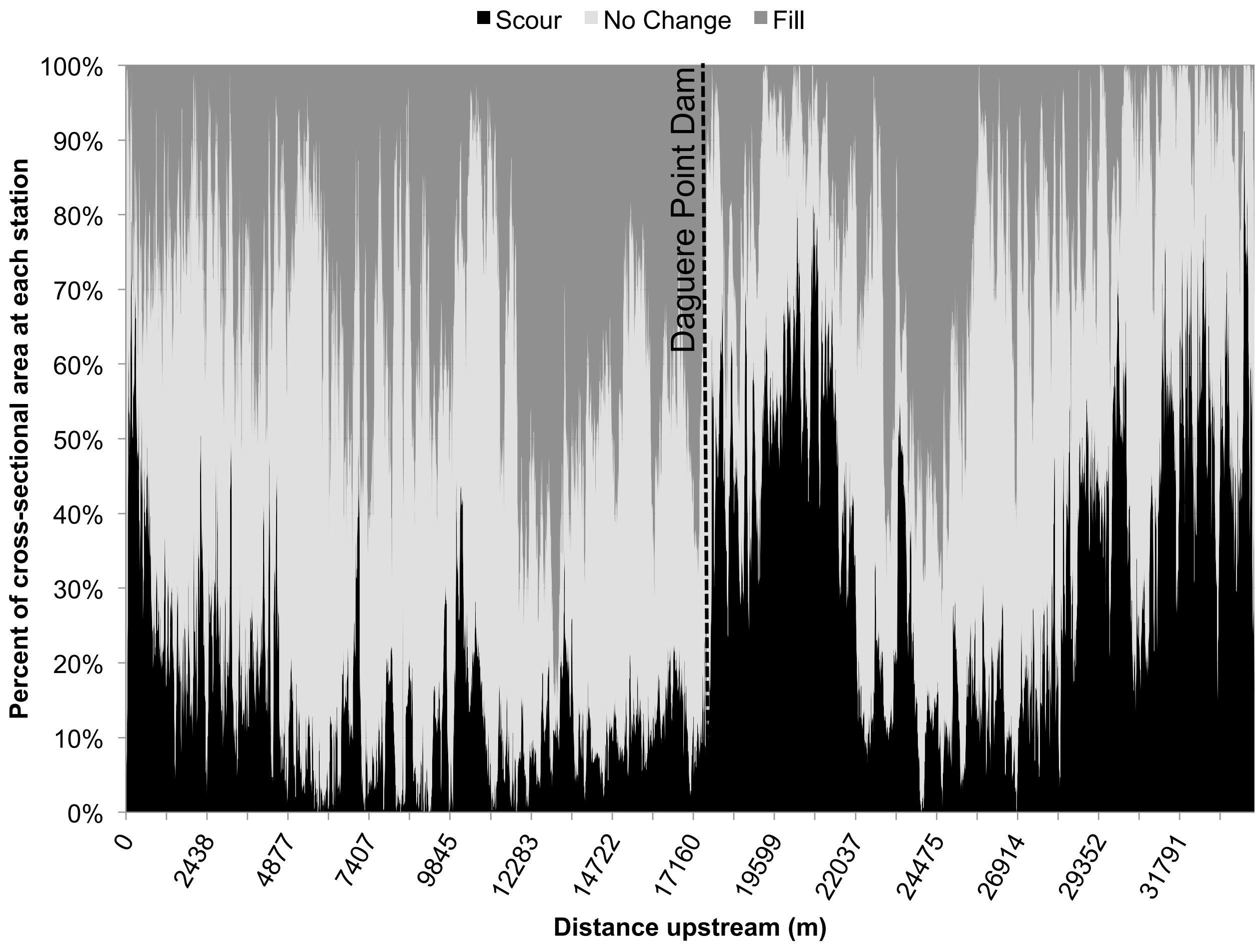
h. Remove the LoD from each raster by subtracting it from the deposition-only raw DoD and adding it to the erosion-only raw DoD.



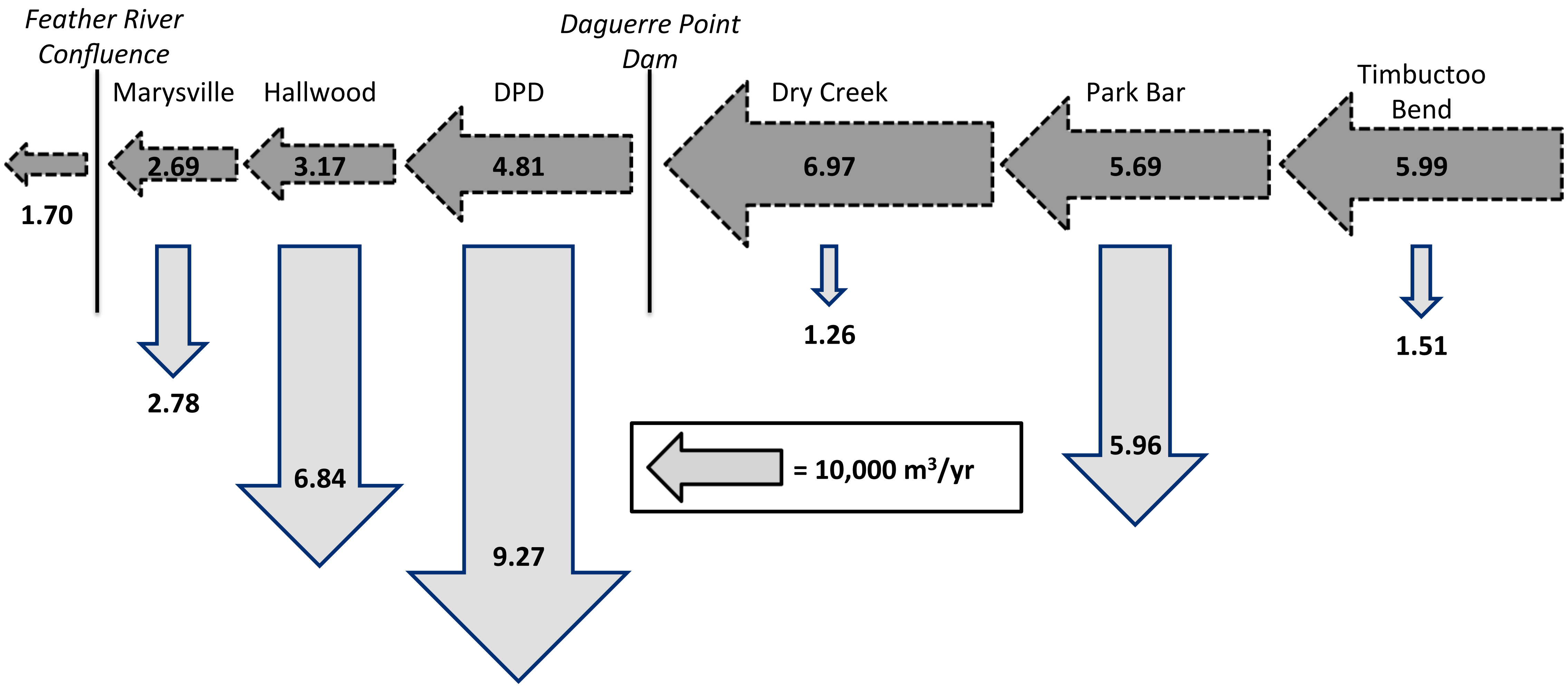
(A) Timbuctoo to Hammon
Parks Bar Reach
Timbuctoo Bend Reach
N
(B) Hammon to Hallwood
Dry Creek Reach
Daguerre Point Dam Reach
0 0.5 1 2 km
N
(C) Hallwood to Marysville
Hallwood Reach
Marysville Reach
N



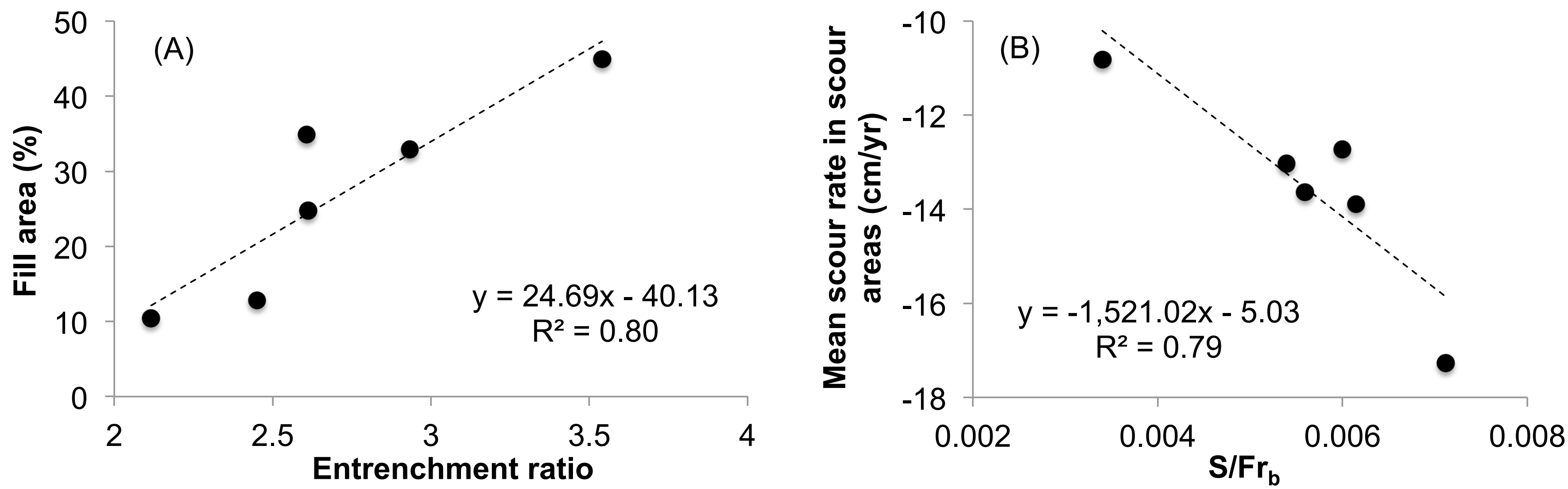
(A) Timbuctoo Bend
N
0 50 100 200 m
morphological units
agriplain
backswamp
bank
bridge pier
chute
cutbank
fast glide
flood runner
floodplain
high floodplain
hillside/bedrock
island high floodplain
island-floodplain
lateral bar
levee
medial bar
mining pit
point bar
pond
pool
riffle
riffle transition
run
slackwater
slow glide
spur dike
swale
tailings
terrace
tributary channel
tributary delta
flow
(B) Parks Bar
0 75 150 300 m
N
(C) Daguerre Point Dam
0 125 250 500 m
N
(D) Marysville
0 65 130 260 m
N

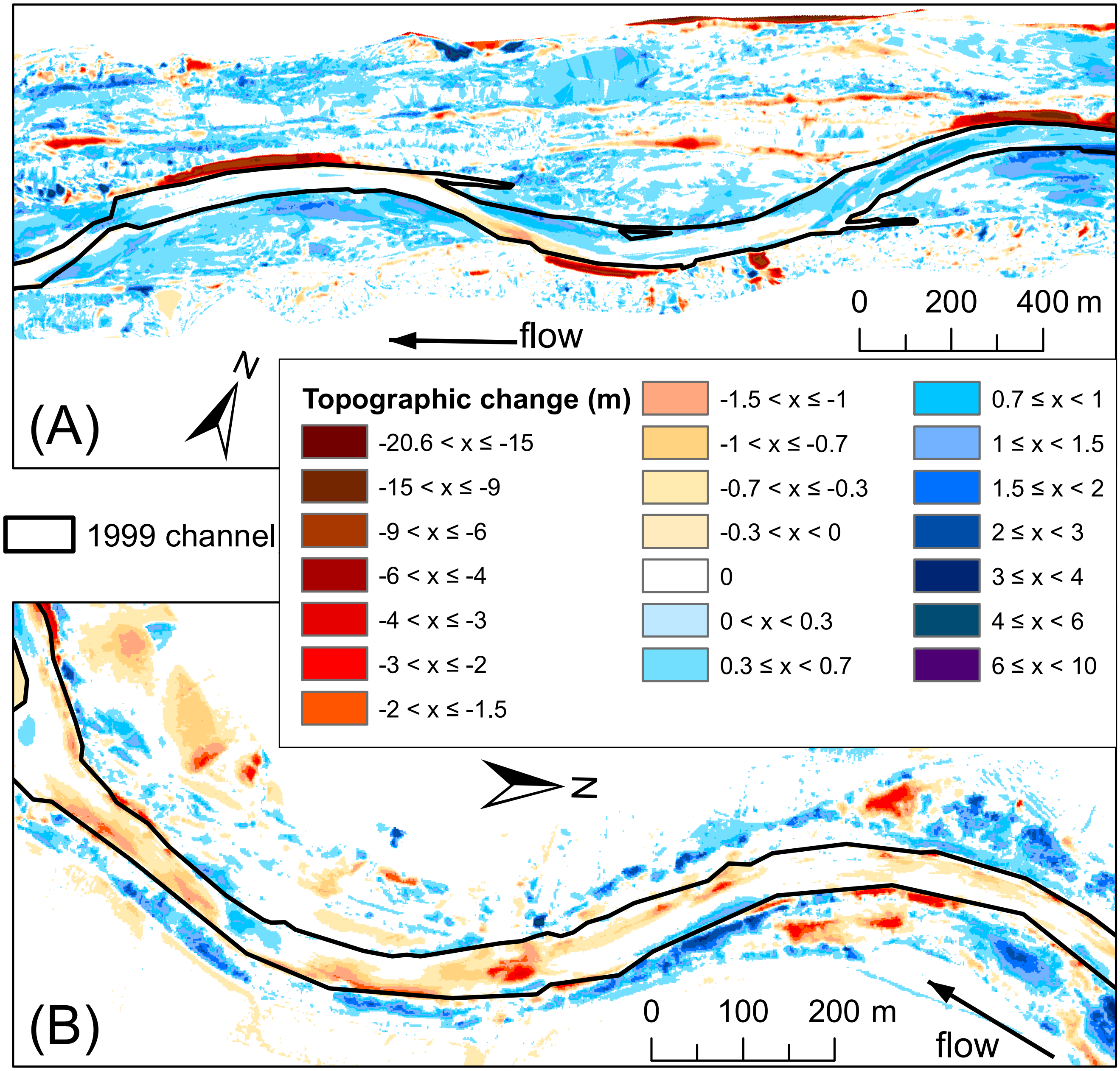


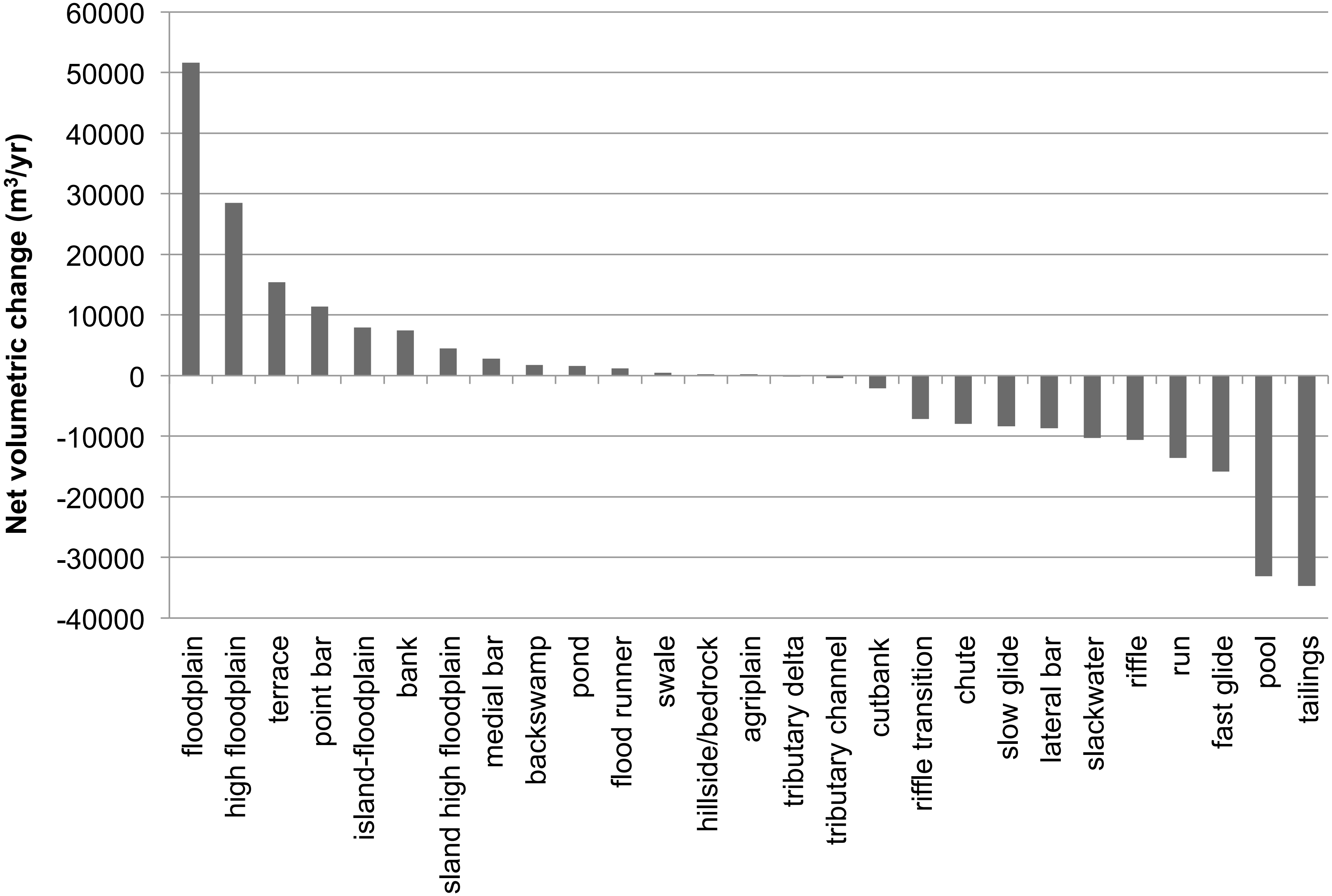
Scour
No Change
Fill
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of cross-sectional area at each station
Daguere Point Dam
0
2438
4877
7407
9845
12283
14722
17160
19599
22037
24475
26914
29352
31791
Distance upstream (m)

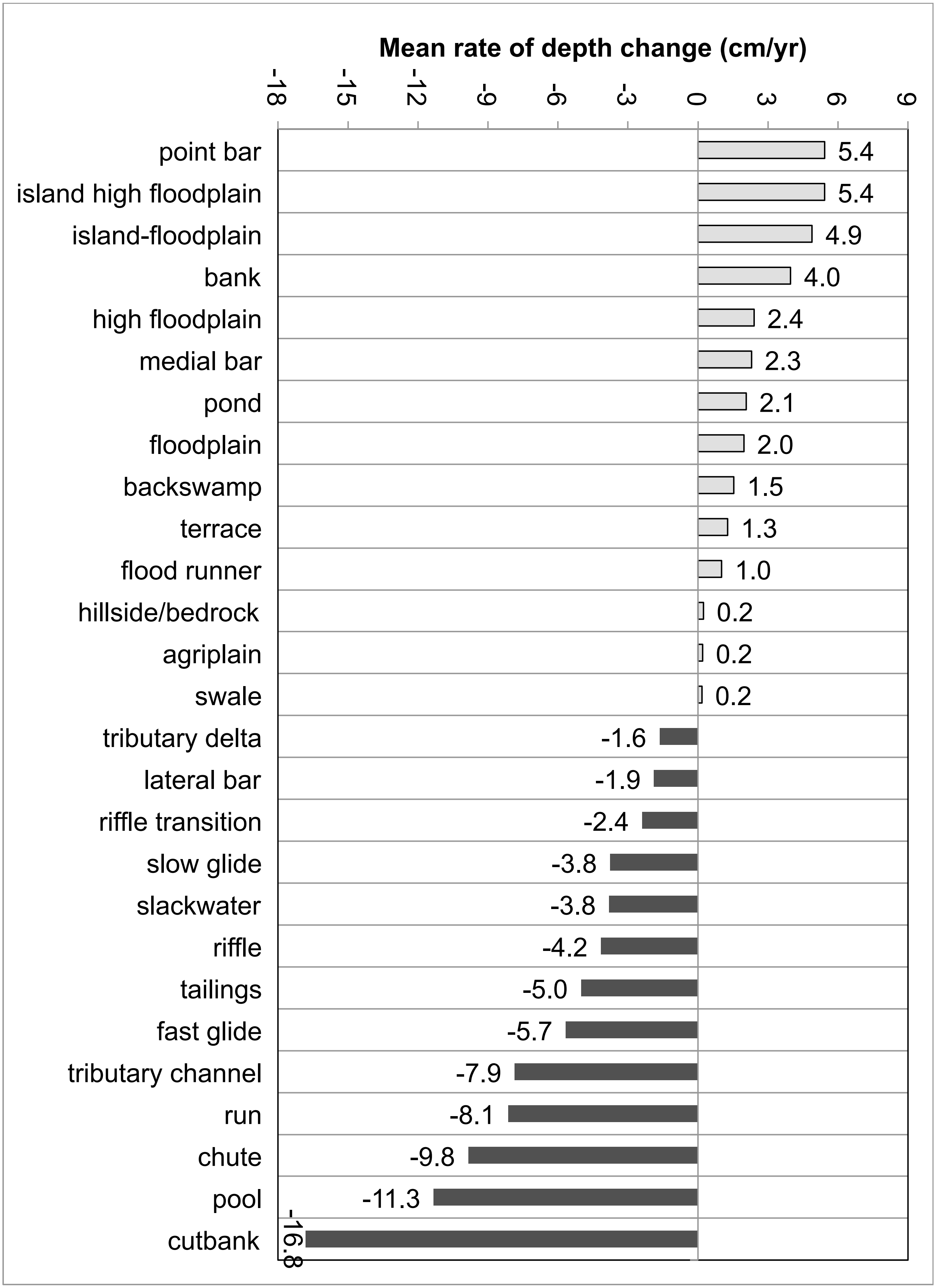


Feather River Confluence
Marysville
Hallwood
DPD
Daguerre Point Dam
Dry Creek
Park Bar
Timbuctoo Bend
1.70
2.69
3.17
4.81
6.97
5.69
5.99
2.78
6.84
9.27
1.26
5.96
1.51
= 10,000 m³/yr


(A)
Fill area (%)
Entrenchment ratio
y = 24.69x - 40.13
R² = 0.80
(B)
Mean scour rate in scour areas (cm/yr)
S/Frb
y = -1,521.02x - 5.03
R² = 0.79


(A)
flow
N
0
200
400 m
Topographic change (m)
-20.6 < x ≤ -15
-15 < x ≤ -9
-9 < x ≤ -6
-6 < x ≤ -4
-4 < x ≤ -3
-3 < x ≤ -2
-2 < x ≤ -1.5
-1.5 < x ≤ -1
-1 < x ≤ -0.7
-0.7 < x ≤ -0.3
-0.3 < x < 0
0
0 < x < 0.3
0.3 ≤ x < 0.7
0.7 ≤ x < 1
1 ≤ x < 1.5
1.5 ≤ x < 2
2 ≤ x < 3
3 ≤ x < 4
4 ≤ x < 6
6 ≤ x < 10
1999 channel
N
(B)
0
100
200 m
flow


Net volumetric change (m3/yr)
60000
50000
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
floodplain
high floodplain
terrace
point bar
island-floodplain
bank
island high floodplain
medial bar
backswamp
pond
flood runner
swale
hillside/bedrock
agriplain
tributary delta
tributary channel
cutbank
riffle transition
chute
slow glide
lateral bar
slackwater
riffle
run
fast glide
pool
tailings



Mean rate of depth change (cm/yr)
-18
-15
-12
-9
-6
-3
0
3
6
9
point bar
5.4
island high floodplain
5.4
island-floodplain
4.9
bank
4.0
high floodplain
2.4
medial bar
2.3
pond
2.1
floodplain
2.0
backswamp
1.5
terrace
1.3
flood runner
1.0
hillside/bedrock
0.2
agriplain
0.2
swale
0.2
tributary delta
-1.6
lateral bar
-1.9
riffle transition
-2.4
slow glide
-3.8
slackwater
-3.8
riffle
-4.2
tailings
-5.0
fast glide
-5.7
tributary channel
-7.9
run
-8.1
chute
-9.8
pool
-11.3
cutbank
-16.8