Title

TOPOGRAPHIC CHANGE DETECTION AND SEDIMENT BUDGETING AT SEGMENT, REACH, AND MORPHOLOGICAL UNIT SCALES AFTER A FLOOD OF 20 TIMES BANKFULL DISCHARGE

Authors

Pasternack, Gregory
Wyrick, Joshua

Publication Date

2016

TOPOGRAPHIC CHANGE DETECTION AND SEDIMENT BUDGETING AT SEGMENT, REACH, AND MORPHOLOGICAL UNIT SCALES AFTER A FLOOD OF 20 TIMES BANKFULL DISCHARGE

GREGORY PASTERNACK
Department of Land, Air, and Water Resources, 233 Veihmeyer Hall, 1 Shields Ave, University of California
Davis, CA, 95616, USA

JOSHUA WYRICK
Lafayette College, 740 High Street
Easton, PA, 18042, USA

Regulated rivers generally incise, but how that happens spatially and what the consequences are at different spatial scales is poorly understood. In this study, spatial segregation was applied to a raster map of topographic change from 1999 to 2008 on the lower Yuba River in California to see how a flood of 20 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. 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 controlled by the ratio of slope to bankfull Froude number, a ratio indicative of lateral migration.

1 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. Although landform change can be naturally driven by tectonic and climatic processes, there is a dominant role for land use and the damming of rivers in the industrial era of human civilization. Studies of these problems in the 20th century largely relied on either intensive studies of small sites with limited extrapolative capability, rapid reconnaissance of qualitatively evaluated metrics, or statistical analysis of a small sampling of cross-sections, with locations distributed based on expert judgment depending 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. Processing such vast and complex raw datasets has proven a challenge unto itself, but it is essential to move forward envisioning what a new paradigm of science and management would look like making use of such data [1],[2]; how do we use the data to answer classic scientific questions and what new understanding can we make with an appreciation of spatial complexity? The term ‘near-census’ is used herein 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. 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 future technology will eventually resolve.

The overall goal of this study was to apply near-census data and analyses to quantify how topographic changes in a regulated gravel-cobble river are spatially organized at the segment (10^2-10^3 channel widths, W), reach (10-100 W), and morphological-unit (0.1-10 W) scales. At the segment scale, a regulated river is going to exhibit a net export of sediment as it evacuates valley-scale sediment storage, but does the channel necessarily disconnect from its the floodplain? At the reach scale, are there differences in the amounts of sediment scour and deposition between reaches, and if so what hydrogeomorphic controls explain them? At the morphological-unit scale, does an incising regulated river lose differentiation between unit types or do local factors promote renewal of units even as the river loses elevation? These questions are best answered by collecting near-census data over a long river segment and aggregating the data up to insure a comprehensive outcome mindful of spatial heterogeneity. Repeat surveys are needed to explore changes through time.

2 METHODS

The Yuba River drains 3480 km^2 of the western Sierra Nevada range in north-central California, USA, with a high dam (Englebright) delineating the start of the final 37.1-km river segment ending at the Feather River confluence. After a short bedrock canyon, the 34-km alluvial lower Yuba River (LYR) segment has a single-thread channel (~20 emergent bars/islands at bankfull flow) with low sinuosity, high width-to-depth ratio, mean bed slope of 0.185%, mean bed surface sediment size of 97 mm, and slight to no entrenchment. The width of the alluvial valley widens after the first 5.8 km constrained by hillsides and then narrows again for the last 10 km due to artificial channelization. Although the LYR receives almost no sediment influx due to upstream dams, it has a vast abundance of sediment in storage from historic hydraulic blasting of hillsides rich with gold.

Data used in this study consisted of (i) two topographic digital elevation models (DEMs) [3], (ii) two-dimensional (2D) hydrodynamic model results [2] (e.g., wetted area polygons from simulations of bankfull discharge (141.6 m^3/s) and a discharge yielding a depth of twice bankfull depth (1195 m^3/s), and (iii) polygons delineating different landform features at three spatial scales of interest [1]. Details of these data are beyond the scope herein, so readers should refer to the cited references. DEMs of the alluvial LYR were produced for 1999 and again in 2008 (though one reach, Timbuctoo Bend, was mapped in summer 2006 and this was accounted for in all annualized computations), which spanned a range of dry, normal, and wet years, including a flood of > 20 times bankfull discharge that occurred in December 2005-January 2006. Topographic change detection was done between the two maps to produce a DEM of difference (DoD), including spatially explicit levels of detection to account for survey and mapping uncertainties [3]. Aerial photography from 1999 was used to map the wetted area of the initial topography at a flow close to bankfull flow at 0.3-m resolution. A polygon of the alluvial valley was also made. The alluvial LYR was delineated into six geomorphic reaches and a polygon of each was mapped on the basis of several factors: confluences with two major tributaries (Deer and Dry Creeks) contributing significant water and 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. Finally, river corridor alluvial landforms at a scale of 0.1-10 channel widths, referred to herein as morphological units (MUs), were mapped for the whole LYR for the ending year (2006 or 2008) on the basis of multiple meter-scale geospatial datasets, including but not limited to topography and simulated 2D hydraulics over a wide range of flows. There were 31 in-channel and overbank landform types present.

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. Because there were only six reaches, correlation and regression analyses were performed with great care to see if any reach-scale landform variables explained the differences in topographic change metrics.

3 RESULTS

At the segment scale, there were nearly equal areas and volumes of scour and fill (Fig. 1), with a small net export of 17,000 m^3/yr. The upstream 16.3 km had net scour, while the downstream 17.8 km had net fill. When change was stratified by occurrence in or out of the 1999 bankfull channel, both regions experienced substantial areas of scour and fill, but a higher volume of fill than scour occurred in the channel, while the opposite was true overbank. In terms of net depth of change (volume/area), the channel filled 5.8 cm per decade, while the overbank region scoured -3.8 cm per decade. This indicates that as the channel migrated and avulsed to the 2008 location, it tended to fill in its old channel and scour through the banks and cut new pathways over floodplains.

Comparing between 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). Most reaches were dominated by scour or fill, but the downstream-most reach had essentially the same area and volume of scour and fill. Even though a reach may have been dominated by scour or fill on an area or volume basis, there was little correlation between that and the mean scour rate in scour areas or the mean fill rate in fill areas. For example, the reach with the second highest volume of gross erosion also has the highest mean fill rate in fill areas. The best correlations and regressions found to explain topographic change metrics between reaches related to the entrenchment ratio and the ratio of bed slope (S) to bankfull Froude number (Fr_b) (Fig. 2). These results have to be viewed cautiously due to the small number of reaches, though the value for each reach is highly certain due to the extremely large number of

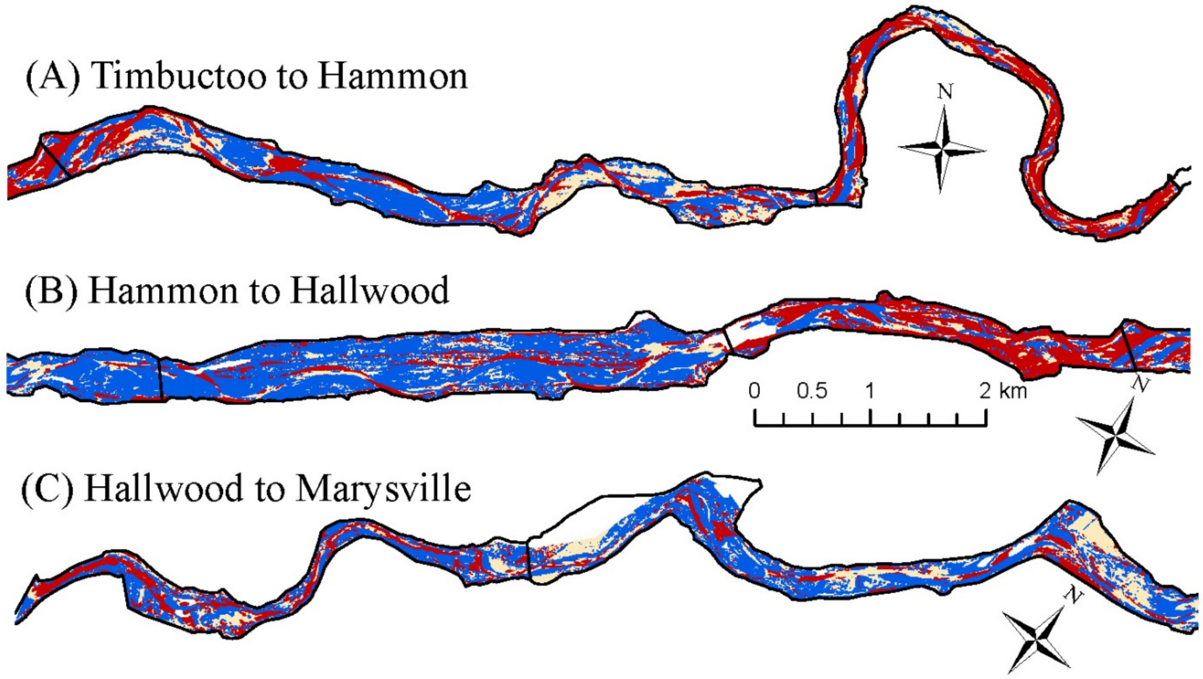

Figure 1. Patterns of scour (red), fill (blue), no change (cream), and no data (white) in river reaches (black).

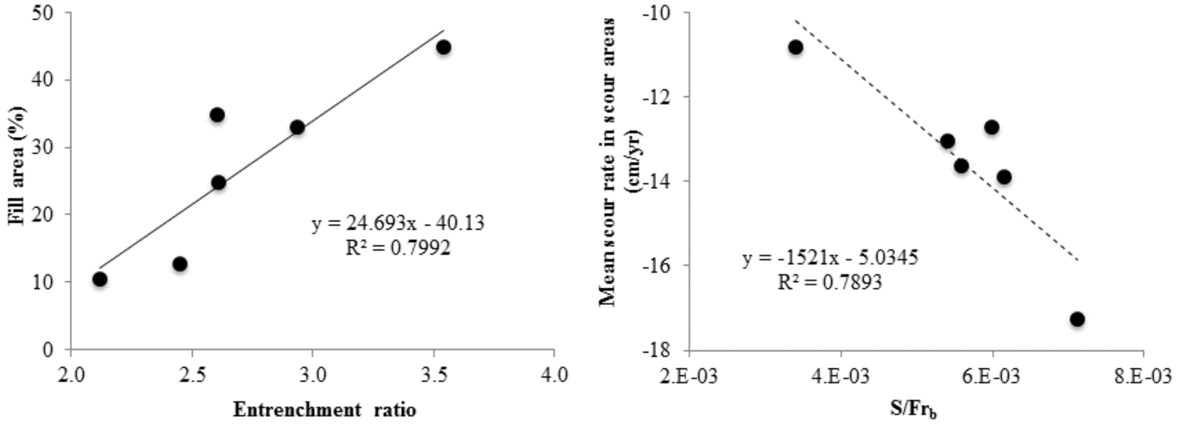

Figure 2. Reach-scale regressions between geomorphic controls and topographic change metrics. Dashed line indicates low confidence due to few reaches and poor distribution of points along S/Fr_b axis.

points used to compute it. 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, and thus the higher the value, the less entrenched the channel is. Computing the entrenchment ratio and Fr_b for each reach required using 2D hydraulic model outputs. This study found that reaches whose channels are particularly well connected to their floodplains (i.e., high entrenchment ratio), have the greatest potential to redistribute sediment between the two, and thus yield high relative percent fill and scour areas compared to those that are less well connected. The reach with the best connectivity happens to have a large side channel on its floodplain that only connects when discharge exceeds double bankfull discharge, and thus it has a lot of area for topographic change to take place.

Morphological units had to be mapped for the 2006/2008 DEM, not the 1999 DEM, so the segregated topographic changes indicate changes that created the units, not how pre-existing units changed. The types of MUs vary dramatically in their relative areas in the river corridor, so the majority of the differences between areas and volumes of change simply reflect that. The fair basis for comparing MUs is mean elevational change for each type. Erosion preferentially aided the differentiation of cutbank, pool, chute, and run units (in decreasing order). Interestingly, area that became riffles were also net scoured, but the net elevation change was only 35% of that for pool, indicating maintenance of riffle-pool relief. Often riffles are viewed as produced by deposition during floods in response to reversal in mean Shields stress between narrow-deep pools and wide-high riffles and/or as a result of local turbulence-drive scour of forced pools with deposition downstream on riffles, but in this case both riffles and pools are scouring, just at different rates. In contrast to in-channel features produced by scour, fill preferentially aided the differentiation of point bars and islands.

4 DISCUSSION

As revealed through spatial analysis of detectable topographic changes over a 7-9 year period that included a large flood, the LYR is a regulated river effectively evacuating sediment from its valley through a complex mélange of geomorphic processes. The changes that were observed were governed by multiple spatial scales of controlling factors. At the segment scale, the river is in the process of redistributing sediment from its upper three reaches to its lower three reaches. In doing so, the pre-existing channel throughout the segment is preferentially filling in, while overbank areas are scouring. There are several reasons why floods are so effective at the segment scale in evacuating sediment from the full width of the valley. First, the active valley available today is not the full historical valley width, but a width confined by natural and artificial lateral boundaries. Because the top alluvial reach is confined by natural hillsides, floods effectively fill the valley and scour it down. Avulsion and lateral migration are only responsible for locally intense scour in that reach. Further downstream, artificial berms of hydraulic mining sediment have created a wider valley, but at only a fraction of historic width. Apparently the width is sufficiently small compared to the magnitude of floods for sediment evacuation to proceed valley wide. Second, even though flows are regulated, only one of the three major subcatchments has a large water supply reservoir, so the LYR still receives significant flooding during intense winter rainstorms and from rain-on-snow events. Third, the hydraulic mining sediment stored in the valley is highly non-cohesive in most places, so high channel banks are not sustainable. As a result, the channel is relatively wide and banks gently slope onto the floodplain. Finally, the gravel-cobble-mantled overbank regions are only lightly vegetated, so there is little root cohesion to prevent erosive processes there. The sum of these factors produces an ability to change the topography of all valley landforms, contrary to the common expectation for regulated rivers, which are often thought of as disconnecting between channel and floodplain.

Usually when articles discuss “reach scale” patterns and processes, it is on the basis of either very coarse watershed DEMs (10-100 m resolution) or on the basis of averaging a small number of surveyed cross-sections. The notion that such methods accurately represent reach-scale geomorphology is now an open question [2]. Near-census data and upscaling provide an alternative to those methods for the first time, and when used here did find some new insights. Significant differences in channel and valley landforms exist between reaches on the LYR, and as a result systematic differences in topographic change metrics were found. At the reach scale, valley landform metrics such as the entrenchment ratio explain aerial differences. Meanwhile, channel metrics indicative of the relative roles of lateral migration versus downcutting explain the intensity of scour and fill where those are located. Ultimately however, the majority of causal explanation for topographic change does not lie at the reach scale, but at the scale of more localized topographic controls that steer nonuniform hydrualics to drive specific scour and deposition processes. Segment and reach landforms set the context for these dynamics. Overall, topographic change was found to reflect a variety of patterns and processes at different spatial scales and the use of landform segregation of change data proved useful at revealing how a large flood impacts a dynamic gravel-cobble regulated river.

REFERENCES

[1] Wyrick, JR., Senter AE. And Pasternack GB., “Revealing the natural complexity of fluvial morphology through 2D hydrodynamic delineation of river landforms”, *Geomorphology*, Vol. 210, (2014), pp. 14-22.

[2] Gonzalez RL. and Pasternack GB., “Re-envisioning cross-sectional hydraulic geometry as spatially explicit hydraulic topography”, *Geomorphology*, Vol. 246, (2015), pp. 394-406.

[3] Carley J K., Pasternack GB. Wyrick JR. Barker JR. Bratovich PM. Massa DA. Reedy GD. and Johnson TR., “Significant decadal channel change 58-67 years post-dam accounting for uncertainty in topographic change detection between contour maps and point cloud models”, *Geomorphology*, Vol. 179, (2012), pp. 71-88.