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**Significant decadal channel change 58-67 years post-dam accounting for uncertainty in
topographic change detection between contour maps and point cloud models**

Running title: Contour-Map DoD Uncertainty

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Abstract

Construction of digital elevation models (DEMs) and the subtraction of DEMs between different points in time as a method to determine temporal patterns of scour and fill is a highly valuable procedure emerging in geomorphology. These DEMs of Differences (DoDs) must be assessed for error in order to distinguish actual topographic change from uncertainty and surface error. Current methods include: (1) uniformly excluding all values that fall below a minimum threshold; (2) using a spatially variable approach such as the construction of minimum Level of Detection (LoD) grids; or (3) the creation of a fuzzy inference system. Although spatially variable methods for determining error have been more accurate in excluding noise without discarding large amounts of meaningful data, a challenge remains in performing DoDs against preexisting contour-based maps for which no original point data are available. The goals of this study were to (1) develop a method that overcomes the unknown point density of contour (and other historical) data sets and allows for some assessment of DoD uncertainty on the basis of information on topographic variability, (2) perform comprehensive uncertainty analysis testing to understand the opportunities and constraints associated with this new method, and (3) report and interpret the overall pattern and volume of decadal topographic change for a regulated river 67 years post-dam in light of alternate conjectured mechanisms of post-dam longitudinal profile adjustment. The key feature of the new approach is the introduction of a high-density artificial point grid that samples the topographic variability evident in the available historical data set. The testbed used to develop and assess this new DoD method was the ~ 37.5-km lower Yuba River, California. Historical data consisted of 0.6-m contours from a 1999 survey, while a more detailed point cloud was available for the most recent survey in 2006-2008. To evaluate uncertainty in the method, this study applied seven different uncertainty metrics of varying strictness ($t = 1$, $t = 1.96$, uniform 0.3-m exclusion, $t = 1$ plus uniform 0.3 m exclusion, $t = 1$ with LoD minimum at 0.3, $t = 1.96$ plus uniform 0.3-m exclusion, and $t = 1.96$ with LoD minimum at 0.3) and two different DoD adjustment methods (exclusion and subtraction). A stringent approach involving joint use of the contour half-interval and the spatially distributed LoD grid at a 95% confidence limit excluded 44.3% of the study area from spatial assessment of channel change and volumetric change computation. This preferred approach yielded an estimated 2.518 million m^3 of total scour and 2.455 million m^3 of total fill in 7-9 years. After considering

different mapping epochs, the net annual average export was 17,000 m³ (~32,500 tonnes) to the Feather River and a river-valley sediment yield of 2205 tonnes/km²/y. This amount is 36% of the post-dam annual yield of gravel and cobble to the upstream reservoir that blocks sediment conveyance into the study domain, suggesting that the lowland system is still highly dynamic 67 years after the dam was built. The scientific significance of this is that the response of rivers to dams can be far more long-lasting and complex, depending on the suite of cumulative societal impacts to rivers. The ability to account for spatially explicit DoD uncertainty (i.e. data retention when uncertainty is low and data removal when uncertainty is high) when comparing historic contour-based and modern point cloud-based DEMs will allow for more detailed and reliable DoDs and sediment budgets in these cases.

Keywords: channel change; geomorphic change detection; DEM of difference; uncertainty analysis; dam impacts; gravel-bed river; fluvial geomorphology; Yuba River

1. Introduction

Digital elevation model (DEM) differencing (DoD) is an increasingly common method used to quantify channel change, which is valuable for inferring fluvial processes (Wheaton et al., 2010b) and estimating changes in sediment storage for use in a sediment budget (Merz et al., 2006). Both of those analyses are common elements in the assessment of channel response to natural processes as well as human interventions in rivers (e.g. damming, channelization, mining, and rehabilitation). However, DoDs involve diverse sources of uncertainty that influence erosion and deposition calculations and derivative interpretations (Wheaton, 2008). Approaches that elucidate analytical uncertainties help to enrich the understanding of DoD results (Wheaton, 2008; Wheaton et al., 2010b). For example, DoDs can be evaluated to locate and exclude areas of surface “noise” from areas of actual topographic change within a statistically defined level of confidence. In this study, new methods are detailed and compared to make use of historic contour maps in DoD analysis accounting for uncertainty. The need for these new methods stems from the scientific goal of ascertaining spatially explicit downstream morphological response decades after damming to obtain new scientific insights about the longevity and abundance of topographic change.

1.1 Motivating scientific question

Beyond simply computing the pattern of topographic change and a sediment budget of use for local management purposes, a novel scientific question was evident with regard to understanding the half-centennial to centennial mechanism of fluvial change downstream of a dam in the presence of abundant valley-floor alluvium. Geomorphic conceptualizations of dam

impacts on rivers are well developed (e.g., Williams and Wolman, 1984; Brandt, 2000; Lisle and Church, 2002; Grant et al., 2003; Petts and Gurnell, 2005), but in professional practice they tend to be employed for any dammed river regardless of unique local contexts that control geomorphic rates and patterns. Further, the duration of significant changes half a century to a century post-dam is not well documented or conceptualized, but as dams age into this range it is of increasing relevance for river management and rehabilitation, as is the mechanism driving secular geomorphic changes.

In considering river adjustments in the context of landscape evolution, Hack (1960) summarized the concept of dynamic equilibrium in which all sections of a river network (and beyond) adjust to each other. For alluvial rivers, Hack (1960) relied on contemporary observations that indicated the presence of so many mechanisms of fluvial adjustment that equilibrium ought to be restored “very quickly, almost immediately” after a disturbance. Certainly Hack understood that change takes some time, but the question as to how and how fast a system adjusts under different settings is of central importance in geomorphology and river management. In particular, the job of a river manager today entails doing things to rivers, yet might society be better served by patience for natural adjustments to abate in some instances? Studies of longitudinal profile degradation by diffusion modeling have provided variable rates of change in different settings (Begin, 1988). In this study, the testbed river was dammed 67 years prior to the latest surveying data, so the longitudinal pattern of recent decadal topographic change (1999-2008) and the average rates of change might be indicative of the mechanisms at work and how far they have progressed towards a new equilibrium.

Conceptually, there are four possible idealized mechanisms that would yield different longitudinal patterns of topographic change for a dammed river in which abundant alluvium is

107 stored in the valley downstream of the dam. First, the river might have experienced a rapid
108 mechanism of adjustment such that its sediment storage and morphology are no longer changing
109 after 58 years, in which case the longitudinal pattern of vertical change would be uniformly low,
110 close to and centered on zero. Second, if change has been slow enough to be continuing and
111 incision is proportional to discharge (as assumed in most landscape evolution models), then in
112 the absence of additional flow in the testbed river, the pattern of channel change should be
113 roughly uniform along the length of the river segment regardless of time, but systematically
114 indicative of erosion. Third, if excess transport capacity occurs closest to the dam (where slope
115 is highest and sediment supply is lowest) and if that factor is the primary driver of post-dam river
116 corridor adjustment, then after 58 years of adjustment the river should now be changing the least
117 at the upstream end and the most somewhere further downstream, with its material either
118 depositing further downstream or flushing out of the system. Finally, if adjustment is dominated
119 by upstream migration of scour (not necessarily via true knickpoints, since the analysis was
120 river-corridor wide, but perhaps facilitated by them) reflecting a synergy between base level
121 controls, sediment pulses, and damming, then after 58 years the downstream end should have
122 stopped eroding and somewhere upstream should be undergoing the most degradation, with its
123 material either depositing further downstream or flushing out of the system. The clearest answer
124 delineating scour mechanisms associated with excess transport capacity versus upstream-
125 migratory would come from having the most erosion now taking place purely downstream
126 (excess transport capacity) or upstream (upstream-migration). If the erosion is centered in the
127 middle somewhere then it might prove difficult to distinguish between them on the basis of
128 profile data alone. Having access to the full lateral pattern of channel change such as produced
129 in DEM difference yields a useful secondary indicator of channel-change mechanisms to answer

the basic question proposed in this study. Hence the importance of accounting for DoD uncertainty between modern point clouds and historic contour maps.

1.2 Uniform-error thresholding

To answer the scientific question posed in the previous section, it is necessary to have a comprehensive, spatially explicit map of topographic change (and not merely rely on a single longitudinal profile), and that is now well understood to require an uncertainty analysis of the calculated topographic change. Without drawing undue attention to any particular study, DoD estimates can be used with overconfidence and no uncertainty assessment or they can be excessively culled because of the difficulty in distinguishing real change from background noise in a complex spatial pattern across a river corridor. Formerly, determination of data to be excluded was accomplished by applying a uniform error threshold as a measure of uncertainty across an entire surface (Brasington et al., 2000, 2003; Lane et al., 2003; Milan et al., 2007). However, this uniform method of error assessment is biased by: (i) the inclusion of erroneous data in areas of steep slope (e.g., along channel banks), where high surface variability creates a higher uncertainty in the validity of data; and (ii) the exclusion of meaningful data in relatively flat areas, where little variability in the surface results in relatively low uncertainty. Rather than assigning error uniformly, more accurate results may be obtained by spatially varying the threshold of exclusion across a DoD surface. Two different approaches for increasing the accuracy of results by spatially varying the threshold of exclusion have recently been developed by Heritage et al. (2009) and Wheaton et al. (2010a).

1.3 Variance-outcome thresholding

The spatially variable method of uncertainty analysis of DoDs presented by Heritage et al. (2009) and Milan et al. (2011) is based upon using the variability of the surface (i.e. “surface roughness”) as the definitive metric for error assessment regardless of what the origins of the variability may be, and thus it is termed “variance-outcome” thresholding here. In this method, a grid of defined resolution is applied over a raw data point cloud and a standard deviation is calculated within each grid cell. Any cell that contains less than eight survey points is excluded from the analysis, therefore requiring grid resolution to be conditioned to yield adequate coverage (where eight survey points is the minimum threshold for yielding an accurate assessment of standard deviation as suggested by Heritage et al., 2009). Using empirical formulas that reflect the specific survey method and interpolation technique utilized, the standard deviation grid is converted to a survey and interpolation error (SIE) point grid in length units. Milan et al. (2011) provided additional formulas for obtaining error grids. After an SIE grid is constructed for each data set, they are combined to form a level of detection (LoD) grid that accounts for the total uncertainty associated with spatial surface variability present in both DEMs. The combined LoD grid is then subtracted from the raw DoD, resulting in a DoD map that is filtered for uncertainty and error based upon the joint variability of the surfaces.

The primary limitations in the use of this method are: (i) both surfaces have to be in the form of raw data point sets; (ii) point sets have to be sufficiently dense (≥ 8 points per cell) to enable calculation of an accurate standard deviation; (iii) dense point grids are especially difficult to obtain in densely vegetated areas, yet these can be areas of significant topographic change, (iv) a (locally valid) empirical function is necessary for all survey methods used to create the LoD; (v) the empirical functions from Heritage et al (2009) have not been tested for local

form roughness > 1 m; and (vi) any source of uncertainty that is not adequately expressed through surface variability is not accounted for. When deriving a DoD from data gathered via modern surveying methods used with a commitment to yield high-density coverage in all locations, these limitations will not affect the validity of the resulting uncertainty analysis, although this method is not applicable to low density (and variable-density) point cloud data sets or contour-based DEMs.

Spatially variable LoD grids rely on the variability of the surface as a basis for the determination of uncertainty in the creation of DoDs. However, DoDs are highly dependent upon underlying DEM quality, which is determined by a number of factors such as control network quality, surveying methods, and point data quality (DeVries and Wood, 1999; Brasington et al., 2000) as well as sampling strategy and interpolation method (Heritage et al., 2009). When surface variability is high, these additional factors do not generally introduce as much error into the DoD; however, when variability is lessened they can retain a larger influence on the overall error. By applying a spatially variable LoD grid which uses surface roughness as the primary determination of error, uncertainty caused by DEM quality may be underestimated in low variability areas.

1.4 Error-source thresholding

A differing approach to assessing spatially variable uncertainty in DoDs, as presented by Wheaton (2008) and Wheaton et al. (2010a,b), is the creation of a fuzzy inference system (FIS) that addresses each source of error individually and then combines them together, hence it is termed “error-source” thresholding here. An FIS utilizes expert judgment and fuzzy logic to

process individual causes of error and produce variable uncertainty values across a surface. Several key elements contributing to the overall error become inputs to the FIS. Each element is first assessed for its contribution to DEM uncertainty and then its values categorized within a set of descriptions. Once all inputs have been categorized and defined with values, rules are developed to evaluate each possible combination of inputs for its uncertainty. This assessment of uncertainty is applied on a cell-by-cell basis to each DEM to be involved in the calculation of the DoD. The primary limitations in the use of this method are that (i) both surfaces have to be in the form of a raw data point set, or already exist in raster or triangulated irregular network (TIN) form (ii) point sets have to be sufficiently dense (≥ 8 points per cell) to support the calculation approach; (iii) unknown and unquantifiable factors that contribute to surface roughness that cannot be expressed as individual rules are unaccounted for; and (iv) the expert-based rules for assigning uncertainty values and the values themselves require judgment and they require adjustments if they are to be utilized across different experts or locations.

In contrast to the above approaches of using raw point data to analyze DoD uncertainty, a post-hoc analysis of DoDs may be conducted to heuristically check spatial patterns of erosion and deposition for indicators of uncertainty. For example, Wheaton et al. (2010a) developed a spatial coherence analysis in which DoD cell values are assessed for their amount of change relative to the values of neighboring cells. This approach assumed that fluvial processes create continuous patterns of change; for example, having an isolated individual cell of erosion surrounded completely by cells of fill may be unlikely in many settings. Notably, this approach cannot identify and remove systematic survey errors, such as when a surveyor inputs an incorrect rod height for a day's worth of data collection.

To execute the Wheaton et al. (2010a) coherence correction two different approaches are possible. The simple approach is to reclassify the final DoD raster into erosion-only and deposition-only rasters, convert these rasters into polygons, delete out all polygons below a user-selected minimum threshold for erosion or deposition, merge the erosion and deposition polygons to yield a new boundary, and then clip the original DoD to the new boundary that excludes the areas below the thresholds. The advanced approach is to apply a moving window to the DoD that counts the number of cells that are erosional and depositional within each window. If a cell is primarily surrounded by cells of the same category then it is assigned a high spatial coherence index value. Conversely, if a cell is surrounded by cells of the opposite category then it is assigned a low coherence value. The index value is a representation of how likely the cell is to be truly erosional or depositional. Cells may contain values of real change, but are undistinguishable from “noise” based on LoD or FIS assessment. However, if these cells are recognized to be part of an erosion or deposition pattern and assigned a high spatial contiguity probability, then they may still be included in the sediment budget. Additionally, a more precise assessment of uncertainty can be produced through the application of an FIS evaluation or LoD grid to the original DEMs, combined with a spatial coherence analysis of the DoD.

1.5 Problem with historic contour maps

All of the methods described above aid in the analysis of DoDs when both DEMs are derived from raw point data sets (or equivalent rasters or TINs). With the recent development of ultra high-density surveying methods (Lane and Chandler, 2003; Hildale and Raff, 2007), the cost of surveying is declining and the availability of detailed DEMs is growing rapidly (e.g.,

<http://www.opentopography.org>). However, assessment of change over longer time periods requires comparison of these new datasets against traditionally collected, legacy data sets whose original raw data points may no longer be available. For example, it is common for aerial photogrammatic and ground surveys to deliver contour maps of river channels with 0.15-5 m contour intervals. Contour lines can be digitized and converted into a DEM, which suggests an approach is needed for addressing uncertainty in these maps and subsequently derived DoDs.

It is possible that further technological advancements will enable re-analysis of historic datasets (especially aerial imagery) to obtain dense point clouds to replace pre-existing contour-based maps. For river bathymetry, many researchers are progressing on the extraction of water depth from water color or shading in modern and historical aerial photos (e.g. Legleiter et al., 2004; Lane et al., 2010), but so far such data has relatively high inaccuracy compared with modern bathymetric surveying methods. For terrestrial terrain, a rapidly emerging method for extracting dense topographic point clouds from overlapping photosets (called “structure from motion”) may enable new DEMs to be generated from scratch using old surveys with sufficient imagery, georeferencing, and documentation (e.g. Koch and Van Gool, 1998; Jebara et al., 1999). Nevertheless, many geomorphic studies will require comparison of disparate surveys not amenable to these emerging point-cloud methods.

1.6 Study objectives

The overall goal of this study was to blend a methodological study of uncertainty analysis in topographic change detection with a basic scientific study to better understand the occurrence and magnitude of topographic and volumetric change on a dynamic regulated gravel-bed river

more than half a century after damming, which would provide new insight into the persistence of significant river adjustments decades later and the inter-decadal mechanisms of fluvial change. This study investigated topographic change on a 34-km segment of what turned out to be a rapidly changing gravel/cobble-bed river by developing a new method for applying spatially variable uncertainty analysis to a DoD between a new point-based topographic survey and a historic contour-based map for which the original survey point data were unavailable. Without the availability of two high-density point clouds (or equivalently detailed rasters or TINs) of the area under study, creation of sufficiently detailed DEMs for DoD uncertainty correction is unfeasible. When digitizing points along contour lines, high point density is achieved only directly along the contour; whereas areas in between contours rely heavily on interpolation. When contour lines are densely packed such as along the river bank, high point resolution is achieved; but in other areas contours can be spaced many meters apart. Therefore, given the low overall point density that is obtained from digitizing points from the contour lines of historic maps, an LoD grid with an 8-point-per-cell minimum threshold would result in grid-cell resolution that would be far too coarse to be an effective basis for analysis. This study focuses on developing and testing a method of uncertainty analysis that is not restricted by limited information of certain types of original data sets or an unknown point density. This study describes an effective method for the determination of a reasonable amount of uncertainty when comparing modern data against historic contour maps, even though accounting for or eliminating all sources of uncertainty is not possible.

With respect to the testbed river for piloting and evaluating the new topographic change detection method, the novel scientific question addressed in this study involved assessing the longitudinal pattern of dynamism in a gravel/cobble-bed river 58-67 years after damming and

moderate flow regulation, in light of a complex preexisting history of cumulative impacts to its river-valley sediment storage and fluvial landforms. In the case investigated in this study, a preexisting history of hydraulic mining sedimentation, dredger operations, and river training in the river valley raises serious concerns in the dogmatic application of the ideal conceptualization of river response to dams and flow regulation in terms of simple armoring, incision/entrenchment, and narrowing as well as concerns over the push to always do something to rivers and not allow them to recover more on their own. This study reports the findings of channel change at a dynamic gravel/cobble bedded river, which will serve as a useful benchmark for future studies as quantitative topographic change detection emerges as a powerful tool for spatially explicit geomorphic inquiry approaching a near-census of river conditions (Pasternack, 2011).

2. Lower Yuba River testbed

To test the new approach described below, available data sets from repeat topographic/bathymetric surveys of the lower Yuba River (LYR), California were used. The ~ 37.5-km long LYR (Fig. 1) has a complex geomorphic history due to the cumulative impacts of deposition of millions of tons of alluvial valley fill induced by historic hydraulic gold mining on contributing hillsides (Gilbert, 1917; James, 2005), dredger reworking of the ~ 4,000-ha Yuba Goldfields and other areas in the ancestral river migration belt (James et al., 2009), installation of a high concrete arch sediment-barrier dam (Englebright dam at 39°14'23.37" N., 121°16'8.75" W.) in the canyon at the entrance to the LYR in 1941 (Snyder et al., 2004, 2006), and moderate flow regulation from a suite of hydrofacilities throughout the catchment (Yuba County Water Agency, 2009). Daguerre Point dam (DPD), a run-of-the-river dam with negligible available

sediment or water storage, exists 17.76 km upstream from the confluence with the Feather River. It presents a slope break in the river's longitudinal profile and serves as the base level for the upstream region. For the reaches downstream of DPD, base level is established by the incising Feather River, whose levees were initiated after the flood of 1862, but which were raised and improved through the turn of the 20th century to cope with hydraulic mining sediments and promote their passage.

Despite flow regulation, large floods with recurrence intervals $> 15 \cdot Q_{bankful}$ ($> 2123 \text{ m}^3/\text{s}$) occurred in the LYR in 1986, 1997, and 2005. Uncontrolled spills over Englebright dam ($> 127.43 \text{ m}^3/\text{s}$) occur in most years, with the flow needed to go overbank for much of the downstream alluvial channel ($\sim 141.58 \text{ m}^3/\text{s}$) occurring with an ~ 1.25 -year recurrence (Wyrick and Pasternack, 2012). For example, for the decade of channel change spanned by the DoD analysis in this study (1999-2008), overbank flows occurred in seven out of nine years. This is significantly more frequent than for most semi-arid rivers, which may possibly be due to a lack of bank cohesion preventing entrenchment and keeping the channel small relative to the flood regime. Frequent overbank flows, combined with the complete blockage of bedload passage at Englebright dam, result in potentially unprecedented geomorphic change of the vast deposits of hydraulic mining sediment present in the LYR valley (White et al., 2010). On one hand, frequent overbank flows may be indicative of high-intensity erosion potential in the channel. On the other hand, they may be indicative of protective conditions in which water is shunted onto the floodplain causing change there instead of in the channel. Existing literature with more information about the hydrogeomorphic conditions of the LYR include Pasternack (2008, 2010), Moir and Pasternack (2010), Pasternack et al. (2010), Sawyer et al. (2010), White et al. (2010), and Wyrick and Pasternack (2012).

In 2010 a comprehensive substrate survey was done within the entire bankfull channel with a customized visual classification. Participants were trained and tested against pebble-counted samples to insure high quality. The methodological report is available from corresponding author. The resulting mean particle size for the whole river was 97.4 mm. Results stratified by reach and morphological unit are presented in Wyrick and Pasternack (2012). The mean grain size played a role in two aspects of this study- it served as a reference for topographic uncertainty (section 3.2) and it was used to estimate dry density of the alluvium (3.7).

The LYR Accord River Management Team, a group of multidisciplinary technical experts representing licensees, government agencies, and non-governmental organizations undertook this study as an essential component to understand the physical processes that affect the geographic distribution, abundance, and diversity of anadromous salmonids in the river. This study uses high resolution spatial analysis to quantify the extreme magnitude and direction of geomorphic change for an enigmatic gravel-bed river subjected to a complex history of cumulative anthropogenic impacts. Knowledge of channel-change processes in response to societal impacts is being used to help assess specified instream flows and water temperatures (YARMT, 2010) and to guide process-based river rehabilitation (*sensu* Beechie et al., 2010). Yet the opportunities for short-term habitat enhancement may also need to be weighed against their appropriateness in light of the long-term trajectory of river adjustment driven by larger-scale geomorphic and anthropogenic drivers (Sear, 1994).

3. Methods

This study developed a new method for uncertainty analysis of DoDs in which one or both source topographic data sets stem from contour lines, and this study compared several different ways of quantifying uncertainty with the new method. The new method was tested on the LYR, which was thought to have experienced significant erosion and deposition due to its complex geomorphic history associated with intensive anthropogenic impacts (Gilbert, 1917; James, 2005). The two topographic maps used were from surveys conducted in 1999 and 2006-2009. This section describes the source data, the standard DoD calculation, and the newly developed method of DoD uncertainty analysis for use with contour data sets.

3.1. 1999 Contour-based DEM

In 1999 topographic and bathymetric survey data were collected by contractors for the US Army Corp of Engineers (USACE) to yield a map of the LYR. Terrestrial topography was mapped using aerial photogrammetry with a small set of additional, randomly located, ground-based survey points. Wetted channel bathymetry was mapped using a boat-based, single-beam echosounder in cross sections spaced almost evenly ~ 15 m apart over the width of the channel. These data were used at the time to produce 0.6-m contours of the river corridor stored as AutoCAD (AutoDesk, San Rafael, CA) dwg files. Data are available from the USACE to anyone who requests it, consisting of a CD containing terrestrial and bathymetric elevation contours, a set of random ground survey points, and the bathymetric survey points. An effort was made to get all raw data, but as is commonly the case in working with historic data, it was not obtainable. Original contractors are commonly not funded to provide data services in perpetuity and historically data deliverables to project sponsors often specified contours as the

delivery format. To yield a DEM from the available data, points were created at the vertices of line segments along 0.6-m contour lines. This derived point set was then combined with the random ground survey points and the bathymetric points to obtain a topographic point set. The original survey was performed with reference to the outdated NGVD29 vertical datum, and Corpscon v. 6.0 was used to convert elevations to the modern NAVD88 datum. Finally, a Triangulated Irregular Network (TIN) of the 1999 point set was produced in ArcGIS 9.2 with a hard clip at the survey boundary.

3.2. 2006-2009 Point cloud DEM

A topographic map of the LYR was recently produced through a phased effort as funding and need permitted. Ideally, the entire river would have been surveyed in one effort, but the reality of large, complex efforts hinges on resources, available expertise, and variable river conditions. As it turned out, the period between June 2006 and March 2009 was dry with low flows, so it was reasonable to extend mapping over the period to meet project constraints. The data gap areas surveyed in November 2009 were shallow backwater, side-channel, and near-bank areas unlikely to experience significant change during the modest overbank flows of March and May 2009. Subsequent analyses that hinged on the duration between topographic maps from section to section of river accounted for different epochs for the different areas.

In the dry season of 2006, the 6.3-km Timbuctoo Bend reach of the LYR from the Narrows Pool (39°13'20" N., 121°17'40" W.) downstream to the Highway 20 bridge (39°13'13" N., 121°20'7" W.) was mapped. Terrestrial and wadable bathymetric surveying were done by robotic total station, with the prism-pole operator walking an $\sim 3 \times 3 \text{ m}^2$ grid in the wetted channel

and a $\sim 6 \times 6 \text{ m}^2$ grid outside of it. A professional hydrography firm (Environmental Data Solutions, San Rafael, CA) was contracted to collect bathymetric points along longitudinal and cross-channel lines, meeting the class 1 standard ($\pm 0.15 \text{ m}$ vertical accuracy; USACE, 2002). The topographic and bathymetric procedural details used were explained in Sawyer et al. (2010) for a smaller mapping effort done at one site in Timbuctoo Bend in 2005. A strong commitment was made to avoid data gaps in the spatial coverage, with the only small areas occurring in the midst of densely vegetated willow patches and in the center of unboatable, unwadable convergent wave trains. The two surveys were tied together with a common array of benchmarks established with real time kinematics (RTK) GPS. Overlapping in-channel survey areas were used to evaluate the two methods and ensure compatibility of the resulting data sets. The final overall point spacing in this river section (total points divided by total area) was one point every 1.9 m in the baseflow channel and one point every 3.0 m outside of it.

Downstream of Timbuctoo Bend, the terrestrial river corridor widens out enough to shift the methodological decision away from ground-based topographic surveying. Instead, on September 21, 2008 Aero-Metric, Inc. (Seattle, WA) acquired LiDAR data of the river corridor during a constant baseflow typical of the period when hydrofacility maintenance takes place ($24.35 \text{ m}^3/\text{s}$ upstream of Daguerre Point dam and $17.61 \text{ m}^3/\text{s}$ downstream of the diversion at Daguerre Point dam; these are ~ 0.15 of bankfull discharge). The target point spacing was 0.74 m and the final overall point spacing (total points divided by total area) was one point every 0.43 m outside of the baseflow channel. Compared against 8769 ground-based RTK GPS observations of elevation along flat surfaces, 84.7% of LIDAR points were within 0.06 m, another 14.0% were within 0.12 m, and almost all of the remainder of the data were within 0.18 m. All in-water LiDAR points were removed from the data set.

Boat-based bathymetric surveys of the remainder of the LYR were performed by Environmental Data Solutions during 2008 low flow conditions ($\sim 25.5\text{--}42.5\text{ m}^3/\text{s}$) in August and September as well as to a limited degree during 2009 higher flow conditions in March and May ($\sim 200\text{--}370\text{ m}^3/\text{s}$). The vast majority of bathymetric data was from 2008. This time an array with four echosounders stationed across the bow was used to obtain longitudinal swaths of bathymetric points. Unlike for the earlier Timbuctoo Bend survey, it was cost-prohibitive to wade all wetted areas inaccessible by boat, but a set of key data-gap locations was identified based on iterative map production checks and consensus-based expert evaluation by the River Management Team (including a civil engineer, a fluvial geomorphologist, and several aquatic biologists) with additional input from a professional hydrographer and an eco-engineering consulting firm. These data gaps were surveyed using ground-based total station, RTK GPS, and echosounding methods in November 2009 and largely consisted of shallow backwater, side-channel, and near-bank areas unlikely to experience significant change during the higher flows of March and May 2009. Because the majority of the point cloud data in the areas downstream of Timbuctoo bend was surveyed in 2008, with only small areas filled in during 2009, the epoch for differencing between the contour map and point cloud map will be considered as nine years (1999-2008). The final overall point spacing (total points divided by total area) for the river downstream of Timbuctoo Bend was one point every 1.3 m in the baseflow channel.

A comprehensive set of uncertainty analyses was performed over an extended period to ensure that the data sets 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 (97 mm). A thorough QA/QC report (Barker, 2010) is available from the corresponding author upon request. After all QA/QC analyses were performed, a set of TINs were produced for the entire LYR to characterize the 2006-2009 survey.

3.3. DoD gaps

The dense point coverage produced by aerial LiDAR for the 2006-2009 data set allowed for the creation of a TIN with a high resolution of detail and few significant data gaps. However, several small unsurveyed areas (e.g., vegetated side channels and backwaters) existed in the 1999 data set that were determined to have too sparse of coverage for accurate TIN interpolation. Polygons were drawn around these areas and they were excluded from resulting DEMs, DoDs, and subsequent computations. Aggregate-mining operations and their open-pit ponds on the floodplain were also excluded. Boundary polygons for shorelines, data gaps, and ponds for both the 1999 and 2006-2009 data sets were all drawn with reference to the LIDAR intensity imagery from the 2008 flight as well as 2006 and 2009 USDA National Agricultural Imagery Program 1-m resolution color aerial imagery.

3.4. New DoD uncertainty analysis method

To overcome the limited point density resulting from digitizing points along contours, this study explores the application of an artificial point grid to a three-dimensional surface before

DEM subtraction. Initially, each topographic surface begins as a TIN based on the available source data. An $\{x,y\}$ point grid is created with uniform spacing at high resolution, in this case chosen as 0.3-m to be commensurate with the 2006-2009 data set. Point elevations for the grid are then interpolated from the TIN. This point grid is used to create a raster with standard deviation values representing surface variability. To decide what the raster cell size should be for the standard deviation grid, a sensitivity analysis was performed in which different sizes were used and the resulting performance analyzed. Areas with steep slopes were found to be highly sensitive to cell size, therefore looking at those locations carefully when comparing options proved to be the deciding factor in obtaining an accurate representation of topographic change. In this study, the standard deviation of elevations was calculated using 25 points per cell ($1.524 \times 1.524\text{-m}^2$ raster cells because the work had to be natively performed in English units, $5 \times 5 \text{ ft}^2$).

Using empirical functions that are effective at identifying actual topographic change from background ‘noise’ (Heritage et al., 2009), standard deviation values were converted into survey and interpolation error (SIE) values. The selection of these functions was dependent on the specific survey and interpolation technique used. As different survey methods were utilized for the channel and floodplain in both the 1999 and 2006-2009 surveys, shoreline boundaries were drawn based on aerial imagery, and different SIE equations were applied to the floodplain and channel areas. The SIE equation for aerial LIDAR with linear TIN interpolation (Heritage et al., 2009) was applied to both the 1999 and 2006-2009 floodplain areas, as no conversion equation for aerial photogrammetry was available for the 1999 data set. A cross section survey method with a linear TIN interpolation equation (Heritage et al., 2009) was applied to the 1999 in-channel standard deviation points; while a morphology and spot height survey method equation was applied to the 2006-2009 in-channel points (Table 1). The SIE point grids were created for

both DEMs to be involved in the subtraction. These point grids were then combined using the following equation (Lane et al., 2003; Brasington et al., 2003):

$$U_{crit} = t\sqrt{\sigma_{z1}^2 + \sigma_{z2}^2} \quad (1)$$

U_{crit} refers to the critical error threshold for each cell; t is the t -value corresponding to the preferred confidence limit; and (σ_{z1}) and (σ_{z2}) are the SIE point grids for the 1999 and 2006-2009 data sets, respectively. Equation (1) was applied on a cell-by-cell basis to combine the individual SIE point grids of each DEM into an LoD grid formed from U_{crit} values; these LoD grids account for the total uncertainty and surface error present in the DoD that can be distinguished based upon a surface variability analysis.

To obtain results at a 68% and 95% confidence limit, respectively, t -values equal to 1 and 1.96 were used. Uniform exclusions (i.e., ranges of raw DoD values that are not used in subsequent analyses (Fig. 2)) of all data within the half-contour interval of 0.3 m were also performed on the raw DoD and combined with both the 68% and 95% confidence limits. This created a range of levels of uncertainty accounted for, from the most liberal of no accounting for uncertainty to the most conservative of combining a 95% confidence limit LoD grid with an additional uniform error threshold of 0.3 m. Rasters of each of these five uncertainty detection grids were individually compared to the raw DoD on a cell-by-cell basis.

3.5. Exclusion versus subtraction

Uncertainty analysis is an essential aspect of DoD refinement for the evaluation and exclusion of erroneous data caused by surface error (Wheaton, 2008; Heritage et al., 2009). A

balance must be achieved between discarding inaccurate data and retaining meaningful results. Applying an error threshold that is too strict may result in the elimination of relevant data especially in areas where surface variability is minimal. A lenient uncertainty metric may allow error-influenced data to be included in sediment budget calculations. That could yield misleading results. These ideas are well established in the literature. However, the methods for adjusting a raw DoD on the basis of uncertainty analysis remain divergent among different practitioners and have not been thoroughly compared.

With these ideas in mind, two different methods for removing or adjusting uncertain DoD cells were tested for their potential to yield the most reasonable topographic change detection. Using the ‘exclusion method’ DoD cell values that fell below the corresponding cell value in each LoD were assigned ‘no data’ values and excluded from further analysis as being undistinguishable from noise (Fig. 2). Using the ‘subtraction method’ LoD values were subtracted from the raw DoD rather than excluded, consistent with the methodology presented by Milan et al. (2011). Performing a transparent, objective comparison of exclusion versus subtraction for DoD adjustment answers a key methodological issue for the benefit of the geomorphology community.

Two additional tests were also done with the subtraction method, because there are additional permutations of choices for practitioners to choose from. It is vital to make these options transparent and evaluate their trade-offs. In the first, LoD subtraction was combined with 0.3-m uniform exclusion. To achieve this, the LoD raster was subtracted from the raw DoD raster (thus causing more values to enter the 0.3-m range), and then the adjusted DoD values within 0.3 m were excluded. 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. For example using this

method, if a pixel has a raw DoD value of 0.5 and a LoD of 0.1, then its adjusted DoD is 0.4 and it is not excluded, but if the values are 0.35, 0.1, and 0.25, respectively, then it is excluded (i.e. its adjusted DoD goes to zero). In the second test, a new LoD raster was created for each statistical threshold in which all LoD pixel values within 0.3 m were changed to 0.3 m. The resulting reclassified LoD was subtracted from the raw DoD. Returning to the previous example and applying this other method, a pixel with a raw DoD of 0.5 and a LoD of 0.1 has its LoD changed to 0.3, so its adjusted DoD is now 0.2 instead of 0.4 from the first method. For values of 0.35 and 0.1, the adjusted DoD is now 0.05, whereas for exclusion it was zero. As the examples illustrate, this second method of subtraction is more stringent because the majority of the LoD rasters have values within 0.3 m and the small number of pixels that gain back a small amount of change (e.g. 0 to 0.05 in the above example) is trumped by all the rest of the pixels being cut down by a larger LoD. In both the exclusion and subtraction methods, the end results are DoD maps that have been scrutinized at various levels to remove areas where uncertainty and surface error may interfere with calculations of actual topographic change.

3.6 LYR Longitudinal Topographic Analysis

After completing the uncertainty analysis, a subsequent effort was done to refine the boundary of the LYR's alluvial valley floor, which resulted in the exclusion of some additional non-contributory areas over what was assessed in the uncertainty testing. The full map showing the adjusted DoD values within this final mapping area is presented as supplemental information. Comprehensive multi-scalar analysis of the spatial pattern of topographic change (e.g. stratified by reach or morphological unit and comparing in-channel versus overbank areas) is beyond the

scope of this study. To address the motivating scientific question posed in section (1.1), the longitudinal pattern of topographic change needed to be calculated and checked for systematic trends indicative of the overall longitudinal pattern of continued fluvial change 58-67 years after damming. There is no reason to expect systematic mapping errors in either DEM and in fact careful testing found that neither DEM's SIE grid had a statistically significant secular longitudinal trend ($r^2 \sim 0.02-0.03$). Longitudinal occurrence of low and high SIE was correlated between the 1999 and 2006-2009 DEMs (r^2 of 0.71, p-value of <0.001), which is understandable since steep/rough areas in 1999 are likely to still be steep/rough in 2006-2009.

The device used to quantify longitudinal topographic change (and the longitudinal SIE for each DEM) was a polygon shapefile consisting of 6.1-m (20-ft) by valley-wide rectangles stationed up the valley's 34-km centerline. The equally-spaced, adjusted DoD values were averaged within each rectangle and divided by the epoch between surveys (seven years for Timbuctoo Bend results and ten years for everywhere else) to yield comparable rates of change. The longitudinal profile of mean annual vertical change was assessed for an overall trend with a high coefficient of determination. The profile was segregated by the slope break at Daguerre Point dam and each section was checked for a secular trend with a high coefficient of determination. Unless both the overall slope and segregated slopes show a high coefficient of determination and a significant regression slope of similar direction and magnitude, then there is no secular trend.

Recognizing that the river may be divided into different regions, an average of the mean annual vertical change was computed for Timbuctoo Bend (the upstream most area with 983 rectangles), the whole section upstream of Daguerre Point dam (2670 rectangles), and the whole section below Daguerre Point dam (2900 rectangles), and then these values were compared and

assessed for a longitudinal pattern. Given the large number of data points in each group, non-parametric Mann-Whitney U-tests were used to test if any regional differences were statistically significant above the 99.9% confidence level. Results were interpreted with respect to the mechanisms described in section (1.1).

3.7 Volumetric Sediment Budgeting

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 control volume was the 34-km river segment from the onset of the alluvial river corridor at the head of Timbuctoo Bend to the confluence of the Yuba River with the Feather River. There is essentially zero influx of sediment into this reach. The mainstem river has a high concrete dam specifically designed to block sediment. 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. A volumetrically negligible influx of boulders occurs where the perennial channel is against the hillside. In contrast, the valley floor stores on the order of $\sim 10^6$ cubic meters of hydraulic-mining alluvium (Gilbert, 1917; James et al., 2005, 2009). As a result, the sediment budget for this control volume is greatly simplified and consists of net export equaled by a volumetric loss of sediment storage. As an additional division, the control volume was segregated into Timbuctoo Bend, whose corridor is farthest upstream and confined by proximal valley walls (White et al., 2010), the remaining region upstream of Daguerre Point dam, and the rest of the LYR downstream of the dam.

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, the 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. If the sediment came from an upstream cell, then the change would be detected there, but if it entered the control volume as an influx, then there would be no detection at all. This yields an underestimate of the total gross erosion and deposition that occurred for any time step smaller than the surveyed one in the presence of influx (Lindsay and Ashmore, 2002). In this study, there was no influx, so any cell that undergoes a change must leave a signature of that somewhere in the domain. Further, the choice of time step is always arbitrary. As long as it is clear that in this study the time step was seven years (1999-2006) for Timbuctoo Bend and nine years (1999-2008; relatively little data was collected in 2009) for the rest of the river, then it must be understood that “total volumetric change” consists of the sum of the net change of each cell for these epochs.

Second, it is assumed that there are no non-transport mechanisms of volumetric change (i.e. bed “deflation” or “inflation”). Merz et al. (2006) conducted a study in which they placed and contoured $\sim 1000\text{-}220\text{ m}^3$ of loose gravel and cobble to a river and then tracked volumetric change annually. After the first year and in the absence of any significant flows, gravel-placements sites experienced up to 20% volumetric loss, which was termed “deflation”. This is why steamrollers are used to insure compaction in road construction. Sawyer et al. (2009) reported that the density of gravel-placement in rivers may be influenced by repetitive driving over the landforms with front loaders. 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.

Third, it is assumed that gravel/cobble sediment volumes may be converted to sediment masses on the basis of the dry density computed using the Kamura (1963) function, substituting mean particle size for median particle size (based on the availability of the former and not the latter). The Kamura (1963) equation for dry density is

$$125 - 7 D_{50}^{0.21} \quad (2)$$

where D_{50} is median particle size in English units of feet and the resulting density is in English units of lb/ft^3 . Wu and Wang (2006) compared the Kamura equation to four datasets and found that it performed well (computed porosity with 30%). Using the mean grain size of the LYR's substrate (97 mm) in place of D_{50} and converting to SI units yielded a density of 1.912 tonnes/ m^3 (equivalent to g/cm^3). For reference, Merz et al. (2006) computed a dry density of 1.645 tonnes/ m^3 from the average of five quarry-based gravel/cobble dry density bucket measurements. Milhous (2001) observed bulk densities of 1.70 to 2.60 tonnes/ m^3 on the gravel-bed Boulder River in Montana. Sawyer et al. (2009) reported that freshly placed gravel/cobble fluvial landforms have landform-scale densities of 1.434 to 2.12 tonnes/ m^3 . Recognizing that the dry density of gravel and cobble landforms is different for those freshly deposited versus those that are well-seasoned, the choice of 1.912 appears to be reasonably in the middle of reported values, though somewhat uncertain.

4. Results

In this study, seven different uncertainty metrics of varying strictness ($t=1$, $t=1.96$, uniform 0.3 m exclusion, $t=1$ plus uniform 0.3 m exclusion, $t=1$ with LoD minimum at 0.3, $t=1.96$ plus uniform 0.3 m exclusion, and $t=1.96$ with LoD minimum at 0.3) and two different noise-removal methods (exclusion and subtraction) were applied to the lower Yuba River DoD (Figs. 3-5). A raw DoD is also included for comparison. Figures 3-5 were chosen to represent the very diversified results of elevation change along the river; including an area which is highly depositional (Fig. 3), highly erosional (Fig. 4), and both depositional and erosional (Fig. 5). In addition to these areas the full scale DoD for the river is included as an online supplemental.

4.1. Percent uncertain area

The first analysis involved comparing the DoD results for different uncertainty metrics to ascertain the amount of river area that each one classifies as unacceptably uncertain (i.e., the level of detection threshold is not exceeded). Analysis of the raw DoD showed that 43% of the total area experienced a net change between -0.3 and 0.3 m (a change in elevation which did not exceed the half-contour interval), 33% of the area contained values of deposition that exceeded 0.3 m, and 24% contained values of erosion that exceeded 0.3 m. Application of an LoD grid at the 68% confidence limit ($t=1$) excluded only 9% of the total area, while an LoD grid at the 95% confidence limit ($t=1.96$) excluded 16% of the total area (Fig. 6).

In addition to applying the two individual LoD grids, analyses were performed for a uniform exclusion of all data within the contour half-interval of 0.3 m, and combinations of a $t=1$ LoD grid and $t=1.96$ LoD grid plus 0.3-m uniform error thresholds. Note that for considering the

area of unacceptable uncertainty, there is no difference between doing LoD plus 0.3-m uniform exclusion and doing LoD with a 0.3-m uniform minimum; those are only different when computing the adjustment using the subtraction method. Any uncertainty analysis involving a uniform exclusion of within 0.3-m elevation changes resulted in a far higher percentage of data being removed, with 43% of total area discarded for a uniform exclusion only and 44% of area discarded for both the $t=1$ and $t=1.96$ LoD grids plus the contour half-interval uniform exclusion combinations (Fig. 7). By using the LoD grids individually without applying an additional uniform error threshold, 35% more area may be included in further analysis at the $t=1$ raster level, while 28% more area is included at the $t=1.96$ raster level. The $t=1.96$ LoD grid combined with 0.3-m exclusions yielded the most conservative uncertainty detection approach performed for the exclusion-only analysis; however, it excludes little additional area than either of the other two less-conservative metrics involving uniform exclusions because few cells with LoD values higher than 0.3-m exist.

4.2. Adjustment by exclusion

This study contrasted the validity and physical meaning of two different approaches for adjusting DoDs to account for uncertainty: (i) excluding all DoD values that fell below the minimum LoD grid by classifying them as ‘no data’ versus (ii) subtracting the LoD values from the DoD, thus incorporating the uncertainty values directly into the volumetric budget, as presented in the methodology by Milan et al. (2011). Overall, across all of the DoDs and regardless of the uncertainty metric used within the exclusionary approach, the amount of area experiencing depositional change exceeded the area experiencing erosional change (Fig. 8).

Percentages of deposition and scour increased, while areas of within 0.3 m of change decreased at the same rate from the raw DoD to the $t=1$ and $t=1.96$ LoD grids. Ratios of areas of deposition and scour remained constant across the three uniform exclusions analyses. Generally, deposition values tended to be smaller, with the majority within 0 to 0.5 m; while higher values of erosion were present in larger percentages over a wider range (Fig. 9). Although uniform exclusions of all changes within 0.3 m decreased volumes of both deposition and scour — as more depositional values existed within the 0 to 0.3 m range — a greater number of depositional cells were discarded, creating a total volumetric change that was erosional. Contrarily, the raw DoD, $t=1$, and $t=1.96$ LoD grids each produced depositional sediment budgets (Table 2). Little variation to the overall volumetric budget occurred between the $t=1$ and $t=1.96$ LoD grids, but large changes did occur when a uniform error threshold was added because of the distribution of values. Given the vast net amounts of scour and fill volumes involved and the close proximity of their values, net volumetric change amounted to 2.4-3.4% of scour or fill volume individually based on uniform and LoD exclusion. Although the mean vertical change only deviated by 0.03 m across all uncertainty detection metrics, the median change exceeded the mean in all cases, indicating a slight left-skew in the overall value distribution.

4.3. Adjustment by subtraction

When the LoD grids were subtracted from the DoD rather than excluded, the resulting topographic changes showed large differences in overall net change amongst themselves and between equivalent tests using the exclusion method (Table 3). Given that raw DoD depositional values tended to be smaller than erosional values, subtraction therefore affected depositional

changes much more than erosional ones. On average, net volumetric scour was decreased by 15%, while net volumetric fill was decreased by 20%. This ultimately caused the net change in volume to grossly shift toward an erosional net sediment budget, with the largest change observed in the uniform subtraction of 0.3 m causing a 328% increase in net change. Having a high net erosional change is exactly what one would expect to have for a reach with zero upstream sediment input because of a high dam. In the tests where LoDs were set to have a minimum value within 0.3 m, the results turned out very similar to those for the uniform 0.3-m subtraction because the vast majority of the raw DoD raster is within 0.3 m. The net change was a little smaller than for the uniform subtraction because this alternative approach removed all of the erosional cells whose LoD was > 0.3 m. Thus, the LoD with a 0.3-m minimum is a stricter uncertainty test, but it results in a smaller net change.

Through use of the subtraction method, the mean change was decreased, while the median change was increased when compared to the statistical data gathered for the exclusion method. This causes an even greater left-skew of the data, which is due to the shift to an increased erosional net volumetric budget described above. The shift toward a more erosional net change occurred across all uncertainty detection metrics when using the subtraction method and was not heightened by using a $t=1$ versus a $t=1.96$ LoD grid, even though the absolute value of the volumetric budgets for the 0.3-m threshold subtractions were far higher. Because of a higher strictness in the $t=1.96$ LoD grid, the absolute value being subtracted from the cells when using this grid is greater, causing greater changes in the DoDs produced by the subtraction method when compared to those made using the exclusion method (Fig. 10). When using uniform or LoD subtraction, net volumetric change ranged from 1% to 20% of scour or fill volumes individually. When net volumetric change was divided by surface area, net incision

depth for both subtraction and exclusion was only -0.04 to 0.01 m across all uncertainty calculations. Overall, the large raw numbers of scour and fill volumes are mitigated by the large surface area (~14.7 million m²) included in the study, resulting in sediment budget calculations that are reasonably well balanced for the whole river.

4.4. Selection of most realistic uncertainty approach

In the absence of any means to know the true pattern of topographic change in the river, common-sense physical reasoning was used to eliminate many uncertainty estimates. This is a common problem in geomorphology, such as applying numerous methods for estimating bankfull discharge and then reasoning out which to select for management use (Williams, 1978; Johnson and Heil, 1996). In this instance the strongest performance indicator for rejecting an estimate was the occurrence of net deposition, which is physically impossible for a gravel/cobble river segment downstream of a dam that blocks all gravel, cobble, and boulder influx as well as almost all sand influx. Further, the river experienced a flood with a peak ~22 times bankfull discharge between surveys as well as many small and moderate overbank floods, indicating ample transport capacity to export sediment out of the river. Only estimates that yield net erosion are reasonable in this context.

On the basis of this performance indicator, subtraction outperformed exclusion as a whole. First, the raw DoD was net depositional (Table 2). Blindly moving forward with geomorphic interpretation of channel change and sediment volume estimation without any accounting of uncertainty would be wrong. Second, the two out of five exclusion estimates that did not include the 0.3-m uniform exclusion were net depositional (Table 2). In contrast, only

the less conservative of the two subtraction estimates that did not include the 0.3-m uniform exclusion was net depositional, and even then it was less than one-third the amount of deposition as the corresponding exclusion estimate (Table 3).

The more difficult choice in identifying the most realistic uncertainty analysis involved selecting among the subtraction-based options. Using spatially distributed statistical thresholds alone was judged to be too generous because the vast majority of LoD values were below the half-contour interval. On the other hand, using a uniform subtraction of the half-contour interval was judged to be too severe because the spatially diverse pattern of simplicity and complexity in the historic contour lines had real topographic information at the sub half-interval level that is worth considering. The method in which the LoD was adjusted to have a 0.3-m minimum must by definition be at least as severe as the uniform subtraction and a bit more so because some cells had statistical thresholds > 0.3 m. The final decision was to select the subtraction method with the $t=1.96$ LoD grid plus 0.3-m exclusion as a compromise to represent the existence of the 0.3-m half-contour interval, but also allow for some <0.3 -m variation to be included. One could use the subtraction methods with higher and lower net changes to bound metrics of topographic change, such as volumetric fluxes. The final selection of an adjusted DoD for spatial topographic-change analysis and volumetric fluxes computation was to use the subtraction method with $t=1.96$ LoD plus 0.3-m exclusion. Final cut and fill estimates for the adjusted DoD and considering the smaller valley floor area after more detailed boundary mapping are provided in Table 3.

4.5. LYR longitudinal topographic change

The longitudinal profile of topographic change is indicative of a downstream-to-upstream temporal sequence of erosion (Fig. 11), with the regime of the last decade involving strongest net erosion at the upstream end and net deposition downstream of DPD. Looking at the complete adjusted DoD map of topographic change and the volumetric totals reported in Table 3, it is evident that the river did not rapidly and completely respond to damming; the river is still undergoing significant longitudinal sediment redistribution and landform change 58-67 years later. On the other hand, the river is not just getting started with its adjustments, but has already changed dramatically from its original state at the time the dam was closed, particularly downstream of DPD. The complete longitudinal change profile had a negligible linear relation with least-regression slope of 0.3 mm of additional vertical change per km upstream (r^2 of 0.2). There are complicated variations in topographic change along the river that cannot be understood at this spatial scale, but may be interpreted by considering reach-scale and morphological-unit scale controls in the full supplemental map, such as flow-convergence routing (Sawyer et al., 2010; White et al., 2010) which is beyond the scope of this study.

When separated into segments above and below Daguerre Point dam, the longitudinal profiles of vertical change had negligible slope (0.2 mm per km) and no trend at all ($r^2 \sim 0.01$ -0.03), indicating the absence of a secular trend for the whole length of the river. At first glance this might indicate a mechanism of uniform incision. However, the average change above and below Daguerre Point dam was -5.0 cm/yr (i.e. net erosion) and 2.7 cm/yr (i.e. net deposition), respectively. Segregating the upstream area into within and below Timbuctoo Bend, the rates of net incision were -8.1 and -3.2 cm/yr, respectively. Nonparametric Mann-Whitney U-tests confirmed that the differences in vertical change between Timbuctoo Bend, remainder above DPD, and below DPD were all statistically significant above the 99.9% level. Thus, although

there is no simple linear trend in longitudinal topographic change, there are secular regional differences in which the upstream-most region is undergoing the most erosion by far, the next region is undergoing some erosion, and the overall downstream region is experiencing deposition. This overall secular pattern is consistent with an upstream migratory mechanism of change, likely facilitated by knickpoints, and in fact several true knickpoints are present in Timbuctoo Bend (Wyrick and Pasternack, 2007). There is no reason to expect adjustments to slow down any time in the next few decades (Pasternack, 2008).

4.6. LYR volumetric sediment budget

The results of volumetric budget calculations for the LYR are uninfluenced by events above Englebright dam, as there is no transfer of bedload or topographically relevant suspended sediment over the dam to the LYR (Fig. 12). Based on Snyder et al. (2004), Englebright dam traps 47,100 m³/y considering only gravel and cobble. Using results for sedimentary volume change gathered based on the subtraction method, clearly the Timbuctoo Bend reach of the river has a large influence on the sediment supply for the rest of the LYR. Specifically, the seven-year average sediment outflux from Timbuctoo Bend alone was found to be 44,800 m³/y, even though it represents only 7.6% of the area of the entire LYR. This outflux is 95% of the entire watershed supply of gravel and cobble to Englebright dam, so that is very large for such a small area. Sand and mud make up a negligible amount of the sedimentary volume in Timbuctoo Bend (Pasternack, 2008). In the next section of river above Daguerre Point dam, an additional average 54,400 m³/y was eroded, despite the presence of the small dam. Of the combined upstream outflux, 83% is stored in the remaining LYR and just 17%, or 17,000 m³/y (on average) exports

to the Feather River. Using the dry density of 1.912 tonnes/m^3 , computed with eq (2), the corresponding mass export is estimated to be 32,500 tonnes/y. The uncertain bounds for mass flux corresponding to dry densities of 1.645 and 2.6 tonnes/m^3 is 28,000 to 44,200 tonnes/y.

5. Discussion

5.1 DoD uncertainty outcomes

Although topographic variations between contour lines is very difficult to detect when digitizing points from historical contour-based maps, this study shows that meaningful topographic changes can be detected, adjusted DoD produced, and volumetric sediment fluxes computed despite uncertain information. Through comparison of many different uncertainty detection metrics, variations in the methods can be scrutinized so that the most appropriate method can be chosen for any individual study. The inherent uncertainty present within DoDs makes application of an error evaluation essential; however, the conservativeness of the detection method must also be taken into account. A strict approach such as subtracting a 95% confidence-limit, spatially-explicit LoD grid with an additional contour half-interval exclusion provided the most realistic assessment of actual topographic change in this study. This also results in the exclusion of the greatest amount of information, some of which may be the result of viable elevation change, especially for depositional areas (similar concepts as reported by others, such as Brasington et al. (2003)).

841 However, when analyzing data from contour-based maps in which the contour interval is
842 0.6 m, the question remains as to whether topographic changes within the contour or half-contour
843 interval can be reliably distinguished. During the course of this study, uniform exclusions of the
844 half-contour interval were analyzed on the basis that given linear TIN interpolation between
845 digitized contour-line points, the greatest deviation between the actual elevation and
846 interpolation elevation would be 0.3 m. Although application of an LoD without uniform
847 exclusion of the contour half-interval resulted in the inclusion of elevation changes within 0.3 m,
848 based upon the resolution of the original data set. Inclusion of these areas of change were
849 deemed inaccurate because they are dominated by broad, low-level deposition and result in either
850 net deposition in a river where that is impossible or minimal net erosion.

851 The results of this study indicate an overall tendency for depositional changes to be
852 smaller in magnitude but larger in overall area coverage, while erosional changes are highly
853 focused and larger in magnitude. This is consistent with previously published studies (Wheaton,
854 2008, Wheaton et al., 2010a,b). As a result, deposition as a geomorphic process is more difficult
855 to quantify with confidence than erosion. When changes to the topographic surface are very
856 small in magnitude they can go unnoticed because it is difficult to determine if these are actually
857 areas of change. A large number of these small changes can significantly affect sediment budget
858 calculations. Furthermore, since the erosional changes do not follow this pattern, but rather are
859 more likely to be larger in magnitude (even if they are smaller in overall area coverage), they are
860 more likely to be detected and counted in the sediment budget. This discrepancy in detection can
861 also impact the confidence in the assessment of net volumetric change. In this study, the
862 presence of a high dam blocking sediment input to the LYR and guaranteeing a net erosional
863 system provides a strong aid in critiquing the different uncertainty metrics and adjustment

calculation approaches. The key finding was that uniform exclusions of the contour half-interval are necessary when building DoDs from contour maps, but that building that threshold into the LoD explicitly was excessive compared to using it as the basis of an exclusion after the LoD was subtracted from the raw DoD.

Despite the benefits of a more conservative analysis provided by a uniform exclusion error assessment, applications of uniform error thresholds are unable to adequately capture the varying error that occurs along the surface of a terrain. In choosing this metric, slight geomorphic changes along relatively flat areas will not be detected, but that is difficult to avoid when forced to rely on contour maps. Over large areas, these subtle changes could ultimately add up to significant alterations in overall sediment budgets. The combination of an LoD grid subtraction with a uniform error exclusion provided the benefit of accounting for possible uncertainty being present in areas of change that exceed the contour half-interval value, especially in areas with steep slopes.

Although the method of uncertainty analysis presented here allows for contour-based maps to be included in DoD and sediment budget calculations, it does contain limitations in its application. Since a 0.3-m point grid is applied universally across all aspects of the surface, the same number of points is distributed across flat areas where distance between contours is large and across steep areas where contours are more densely packed. The farther apart contour lines are located from one another, the greater the error in TIN interpolation algorithms; however in using this method, these relatively flat areas contain cells with very low standard deviation and SIE values, nonreflective of the larger possible interpolation error. On the other hand, if contours are spaced so far apart because the surface is truly that flat, then the very low standard deviations and SIE values would be justified and appropriate. Ultimately, this relates to the

inability of spatially distributed LoD grids to distinguish sources of uncertainty that are not adequately expressed through surface variability, especially in contour-based data sources. One approach to rectify this in the future might be to adjust the point density comparable grids in proportion to slope or surface roughness at roughly the channel-width scale. However, compared to the spatially distributed LoD approach presented by Milan et al. (2011) and the FIS analysis presented by Wheaton (2008), this method does not require data to be in the form of raw survey points (or an equivalent form reducible to the survey points, such as a raster or TIN-based format) or contain a high point density value to get good results, both of which are characteristics that are often unavailable in historic contour-based maps.

The key device employed in this study that is different from the past ones is that a matching high-density grid of elevations is made for both surveys, such that it contains any and all information available in those surveys, and then these grids are assessed for their variability and errors. This aid has been found to be highly useful for also analyzing point-based datasets where point density is highly variable. Inevitably geomorphologists and river managers will want to compare future topographic surveys against historical contour-based ones, no matter what the uncertainty or risk (e.g. Lane et al., 2010), so the method demonstrated in this study provides an opportunity to evaluate uncertainty in such cases where contours are available. Using several different uncertainty metrics and comparing results against real-world constraints, we determined that an aggressive removal of questionable changes ($t=1.96$ plus uniform 0.3-m exclusion) was the best for this study.

5.2 LYR River Corridor Changes

Looking beyond the methodological issues, this study presents significant findings about remarkable topographic change on a dynamic regulated gravel-bed river 58-67 years after it was dammed. Since Englebright dam was closed, the LYR has been adjusting by evacuating hydraulic mining sediment at a high rate. The longitudinal profile of topographic change indicates that it has occurred at the broadest scale by upstream-migration, analogous to the patterns previously investigated using diffusion-based geomorphic mimicry (Begin, 1988). The focus of maximum migration-based erosion (now in Timbuctoo Bend) migrated ~30 km, but the time frame is somewhat uncertain. The supply of hydraulic mining sediment diminished throughout the late 19th and early 20th centuries, but upstream-migration likely accelerated when Englebright dam was built in 1941. If all migration occurred after the dam was closed, then the maximum migration rate of the peak scour region is 0.45 km/y, whereas if the full period (127 y) is used since hydraulic mining was enjoined in 1882, then the minimum migration rate of the peak scour region is 0.24 km/y. These numbers substantiate Hack's (1960) conjecture of adjustment that is "very quickly, almost immediately" in geologic terms, especially when considering that the profile in this study is not a mere thalweg profile, but a corridor-wide average profile. Still, the rate may not be viewed as fast enough in the domain of river management.

In contrast to previous anecdotal evaluations and measurements with only a few cross-sections (Adler, 1980; Beak Consultants, Inc., 1989), this study found that the LYR is still changing a lot internally and exporting a moderate load of ~32,500 tonnes/y to the Feather River at present. The observed annual export amounts to an equivalent of 36% of the watershed's average annual supply to Englebright dam since 1941. The flux from the North Yuba to Englebright dam has been cut off since 1971 because of New Bullards Bar Reservoir built on

that tributary; so in terms of the comparable 1999-2008 period, the LYR annual outflux is significantly higher than just 36% of the 1999-2008 annual watershed yield when North Yuba yield is excluded from consideration.

Given that the area of the DoD analysis was $\sim 14.74 \text{ km}^2$, the estimated annual mass flux out of the LYR of 32,500 tonnes/y corresponds with a river valley sediment yield of 2205 tonnes/ km^2/y . Using the sediment yield empirical relation that Dendy and Bolton (1976) derived from a study of deposition in ~ 800 reservoirs distributed throughout the United States, the corresponding Yuba watershed sediment yield is estimated as 434 tonnes/ km^2/y (ignoring historic mining influences). The occurrence of 5.1 times higher sediment yield for a river valley bottom compared with a watershed is significant. The expectation is that for a comparable size of area, a watershed has diverse processes (e.g., many types of mass wasting, freeze-thaw erosion, gullyng, sheet and rill erosion, and channel erosion processes) at its disposal thanks to steeper slopes (and colder temperatures) compared to a valley bottom with a comparatively uniform low slope where the erosion mechanisms are limited to the channel subset, including incision, avulsion, lateral migration, bank erosion, and knickpoint migration. However, in reality the cumulative impacts of historical hydraulic mining sedimentation, dredger mining, river training, and damming appear to yield a more dynamic regime in which these channel erosion mechanisms are excessively active. Therefore, care is needed when applying existing concepts of the geomorphic response of rivers to dams and flow regulation (e.g., Williams and Wolman, 1984; Brandt, 2000; Lisle and Church, 2002; Grant et al., 2003) to a river that was subjected to a complex preexisting history of cumulative anthropogenic impacts. Some analyses and interpretations of the LYR have made that mistake, without due consideration of its unique history.

Based on volumetric calculations, 45 % (nearly half) of LYR export derives from 5.8-km long Timbuctoo Bend and rest comes from the next 10.5 km of channel down to DPD. Previous mechanistic investigations in Timbuctoo Bend including monitoring and modeling have provided insights into the causes of erosion in that reach (Pasternack, 2008; Sawyer et al., 2010). Together with inspection of the DoD, the key processes are flood-induced overbank scour and channel-bed incision, lateral migration through the non-cohesive banks, channel avulsion, and low flow knickpoint migration at riffle crests. Additionally, a region of significant scour between the confluence with Dry Creek and DPD exists (Fig. 11). Normally, the backwater zone of a river upstream of a dam is thought of as a depositional area; but for small run-of-the-river dams like DPD whose sediment storage capacity is full, it is likely that pulses of sediment move through the river corridor, with alternating periods of deposition and erosion. It is conjectured that the 1997 flood could have deposited a lot of material above Daguerre Point dam and then erosion during the period from 1998-2008 could have exported that slug past the dam. Finally, downstream of Daguerre Point dam the primary mechanisms of erosion appear to be overbank scour, channel downcutting, and lateral migration. However, that region is net depositional with the most deposition occurring overbank in vegetated patches.

6. Conclusions

The creation of DoDs for the detection of topographic change and for estimation of volume-based sediment storage changes and fluxes is an important advancement in geomorphology; however, inherent fallacies in DoDs require a careful evaluation of uncertainty to be applied before final calculation of sediment budgets. Previous limitations in the

977 construction of spatially distributed uncertainty detection metrics prevented this process from
978 being applicable to contour maps. The method presented in this study provides a modification
979 on an existing uncertainty analysis approach in order to make it applicable to situations in which
980 the original point data are limited or unknown. Seven different uncertainty detection metrics
981 were applied and analyzed during the course of this study, utilizing both uniform error thresholds
982 and spatially distributed LoD grids. This study also compared two different methods for
983 adjusting DoDs, either by exclusion or subtraction. Although more area may be included by
984 using solely a spatially distributed LoD grid, more conservative results may be obtained by
985 combining a LoD grid with a uniform error threshold at the contour half-interval level. As our
986 ability to produce highly detailed DEMs from high density survey methods increases, valuable
987 information can be acquired regarding fluvial processes and geomorphic change if these new
988 DEMs can be compared to historic contour-based maps.

989 Assessment of topographic change and volumetric change-based sediment fluxes for the
990 LYR with inclusion of comprehensive uncertainty analysis is crucial to understanding historic
991 change on the river and assessing the effect of this change on the linked aquatic-riparian
992 ecosystem. For the case of the lower Yuba River, a vast amount of sediment is both eroded and
993 deposited throughout the river valley in a complex spatial pattern, with a relatively small net
994 outflux (1.3% of total scour and fill). However, compared to rivers in the region, that net outflux
995 is quite large. It is explained by the natural response of the regulated river to the historical
996 sequence of extreme valley filling followed by sediment supply starvation and river training.
997 The river is 'readjusting' itself by upstream migration back to the pre-mining base level at the
998 centennial timescale and is far more dynamic 67 years after damming than might be conceived of
999 without full consideration of the complex history of cumulative anthropogenic impacts. Whether

it gets there or not and the geomorphic pathway it takes depends on yet-to-be-determined river and dam management actions.

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Equations used for the conversion of standard deviation point grids to survey and interpolation error (SIE) point grids (Heritage et al., 2009). The input, 'x' is the standard deviation value in meters which is used as the basis for assessing surface variability; the output, 'y' is the resulting SIE value in meters.

Area	Survey method description	Equation
1999 and 2009 Floodplain areas	Aerial LiDAR and triangulation with linear interpolation	$y = 0.4432x + 0.0434$
1999 In-channel area	Cross section and triangulation with linear interpolation	$y = 0.4274x + 0.0808$
2009 In-channel area	Morphology and spot height survey and triangulation with linear Interpolation	$y = 0.4109x + 0.0911$

The LYR topographic change results using LoD exclusion and removing different levels of uncertainty

Metric	Mean change (m)	Median change (m)	Total scour (m ³)	Total fill (m ³)	Net change (m ³)	Net volume change/area (m)
Raw DoD	0.008	0.032	-4,237,272	4,357,018	119,746	0.008
Uniform exclusion of 0.3 m	-0.016	0.114	-3,908,081	3,776,501	-131,580	-0.016
t=1 LoD grid	0.009	0.045	-4,202,082	4,322,411	120,330	0.009
t=1 LoD grid plus 0.3- m exclusion	-0.015	0.114	-3,897,508	3,771,012	-126,496	-0.015
t=1.96 LoD grid	0.008	0.055	-4,142,390	4,243,897	101,507	0.008
t=1.96 LoD grid plus 0.3-m exclusion	-0.016	0.115	-3,887,384	3,758,810	-128,574	-0.016

The LYR topographic change results using LoD subtraction and removing different levels of uncertainty

Metric	Mean change (m)	Median change (m)	Total scour (m ³)	Total fill (m ³)	Net change (m ³)***	Net volume change/area (m)
Uniform subtraction of 0.3 m	-0.038	0.000	-2,863,134	2,300,506	-562,628	-0.038
t=1 LoD grid	0.002	0.056	-3,847,362	3,883,644	36,282	0.002
t=1 LoD grid with 0.3- m minimum in LoD	-0.038	0.000	-2,854,247	2,297,173	-557,074	-0.038
t=1 LoD grid plus 0.3-m exclusion	-0.029	0.369	-3,553,573	3,336,461	-217,112	-0.029
t=1.96 LoD grid	-0.002	0.009	-3,520,826	3,485,880	-34,945	-0.002
t=1.96 LoD grid with 0.3-m minimum in LoD	-0.037	0.000	-2,822,775	2,276,519	-546,256	-0.037
t=1.96 LoD grid plus 0.3-m exclusion*	-0.043	0.364	-3,256,314	2,973,133	-283,181	-0.043
t=1.96 LoD grid plus 0.3-m exclusion; less area**	-0.040	1.249	-2,518,500	2,455,028	-63,472	-0.012

*Deemed best performer.

**Further clipping of the river corridor to exclude non-contributory areas.

***Cannot convert to annual rate by simple division, due to different survey epochs for different areas.

Figure Captions

Fig. 1. Map of the lower Yuba River in its regional and national contexts with key local place names and boxes showing the locations of subsequent figures.

Fig. 2. Generic illustration of the concepts of exclusion and subtraction and the potentially significant difference depending on which one is used in DoD uncertainty analysis. These DoD and LoD data are arbitrary and not from the Yuba testbed.

Fig. 3. Examples of DoDs resulting from various uncertainty analyses of a section of the LYR downstream of Daguerre Point dam that shows widespread floodplain deposition and lateral channel migration. Each image displays the areas excluded under each metric, with white areas indicating regions where change was excluded.

Fig. 4. Examples of DoDs resulting from various uncertainty analyses of a section of the LYR between the confluence with Dry Creek and Daguerre Point dam that is predominantly erosional. Each image displays the areas excluded under each metric, with white areas indicating regions where change was excluded.

Fig. 5. Examples of DoDs resulting from various uncertainty analyses of a section of the LYR just upstream of the Highway 20 bridge constriction that shows channel and floodplain incision as well as medial bar formation. Each image displays the areas excluded under each metric, with white areas indicating regions where change was excluded.

Fig. 6. Illustration showing the percentage of the raw DoD falling within each category of geomorphic change in the two spatially distributed LoD grids.

1179 Fig. 7. Bar chart displaying the percentage of total area excluded with each uncertainty detection
1180 metric used with the exclusion method.

1181 Fig. 8. Illustration showing the divisions within each metric for the exclusion method. Rounded
1182 to the nearest percentage, no changes can be detected between metrics involving uniform
1183 exclusions.

1184 Fig. 9. Histograms showing the distribution of elevation change values across the five different
1185 DoDs with uncertainty analysis applied using the exclusion method and one raw DoD.

1186 Fig. 10. Elevation differences between exclusion and subtraction rasters for the same area as
1187 shown in Fig. 2. Values were calculated by subtracting the subtraction raster from the
1188 exclusion raster for each uncertainty detection metric.

1189 Fig. 11. Longitudinal profile of mean vertical change in 6.1-m intervals with different colored
1190 thin lines for different regions. Brown is Timbuctoo Bend, blue is remaining region
1191 upstream of DPD, and black is downstream of DPD. Thick black line shows the trend of
1192 statistically different regional averages.

1193 Fig. 12. The LYR volumetric sediment budget.

0 0.25 0.5 1 1.5 2 km

(A)

t=1 LoD Grid

(B)

t=1.96 LoD Grid

Uncertainty detection metric

LYR DoD: areal divisions

t = 1.96 LoD grid subtraction with 0.3 m exclusion

LYR DoD: area 1

t = 1.96 LoD grid subtraction with 0.3 m exclusion

LYR DoD: area 2

t = 1.96 LoD grid subtraction with 0.3 m exclusion

LYR DoD: area 3

t = 1.96 LoD grid subtraction with 0.3 m exclusion

LYR DoD: area 4

t = 1.96 LoD grid subtraction with 0.3 m exclusion

LYR DoD: area 5

t = 1.96 LoD grid subtraction with 0.3 m exclusion