Historical Geomorphic and Land Use / Land Cover Reconstructions

for the Lower Yuba River Based on Remote Sensing

A Proposal to the Yuba County Water Agency (YCWA)
Sept. 20, 2010
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OVERVIEW

The proposed project will produce an extensive digital, georectified historical and geomorphic database for the Lower Yuba River (LYR) and floodplain from Englebright Dam to the Feather River confluence. The data and imagery will include planimetrically corrected historical maps and aerial photographs for the period from 1906 (map) to 1999. A large number of aerial photographs dating from 1936 to 1998 will be scanned and georectified. A complete set of detailed topographic maps from 1906 field surveys (CDC, 1906) will be georegistered with the aerial photographs. The 1906 contours will be digitized and interpolated to produce a set of 1906 digital elevation models (DEMs) and allied topographic visualization products.

A representative series of historical DEMs and 3D models with visualizations will be generated from the aerial photos at nine locations for six selected time periods. Ancillary data, such as digital soils maps, will be merged with the dataset into a digital spatial database. Historic geomorphic and vegetation maps will be produced at a scale of approximately 1:20,000 (as allowed by data quality and registration accuracies) using the rectified historical imagery for six historical periods (1906, 1947-52, 1958, 1975-78, 1986-88, and 1998). The aerial photographs will be manually interpreted and classified to produce geomorphic maps showing contemporary positions of channel margins, gravel bars, terrace scarps, levees, high-water channels, and areas of substantial anthropogenic geomorphic disturbance (dredge spoils, land fills, bridges, dams, agricultural leveling, levees, etc.). Mapping will include digitization of channel margins (low-flow water lines) vectorized into shape files for each period. Finally, the imagery will be interpreted and classified to produce a generalized vegetation map for each of the six periods.

BACKGROUND

Knowledge of historical changes in the lower Yuba River is more important to river managers than for most rivers owing to the extreme geomorphic changes the Yuba experienced in the late nineteenth and early twentieth centuries and the vast sedimentary deposits remaining along the river. Approximately 1.1 x 10^9 m^3 of hydraulic mining sediment (HMS) was produced in the Foothills in watersheds of the region (Feather, Yuba, Bear, and North Fork American) and more of this sediment was produced in the Yuba Basin than any of the other rivers (Gilbert, 1917; James, 1999; 2004; 2005). The ubiquity of HMS deposits in the lower Yuba is well established owing to its distinctive lithology (James, 1991a) and geochemical fingerprint that includes high total mercury concentrations (Hunerlach et al., 2004; James et al., 2009). Reworking of HMS deposits has been accompanied by rapid and pervasive geomorphic changes to channels and floodplains in the region (James, 1989; 1991b; 1994) especially along the lower Yuba (James et al., 2009; in review; Ghoshal et al., 2010). In addition to the obvious relevance to river management, ecologic habitats, and water quality concerns, these changes are of particular scientific interest to geomorphologists on a theoretical basis owing to the importance of the lower Yuba to classic concepts of river response to sedimentation formulated by the great Earth scientist, G. K. Gilbert (1917). Sediment wave theory and the importance of distinguishing between sediment flux and river-bed morphology have been described in detail elsewhere (James 1989; 1991b; 1999; 2006; 2010). The river is also of geomorphic interest because the extreme changes occurred rapidly and recently so many scientific observations are available.

The lower Yuba River is bordered by historical-aged sediment deposits that are dominantly composed of HMS reworked from the mines above. In the upper reaches (Englebright to Parks Bar) these deposits are composed of cobbles and gravel including high terraces of limited lateral extent but volumetrically substantial due to their height above the modern channel. At the extreme, our sediment samples from the tailings fan at Rose Bar–created by the Blue Point hydraulic mine—have mercury concentrations up to 7.2 ppm. The Rose Bar fan deposits can be traced downstream to terraces on both sides of the river where Hg concentrations decline but remain high (James et al., 2009). These terraces have retreated in historical time delivering Hg-rich sediment downstream potentially to the Feather and Sacramento Rivers. The historical analysis of this project will determine erosion rates of the Rose Bar fan and the downstream terraces during the 20th century, and the magnitude of flood events that are required to activate this erosion.

The Yuba Gold Fields in the middle of the study area include large ridges of loose gravel at the angle of repose deposited by dredging. Along the main channel, these gravels are freely delivered to the river during floods contributing coarse bed material that potentially armors the channel downstream. The historical component of these spoils also has high mercury concentrations (Hunerlach et al., 2004). Historical analysis of this project will examine rates of erosion of dredge spoils, especially along main channels, and estimate the magnitude of flood events that activate this erosion.

The lower study area is dominated by a wide (up to 4.1 km) zone between the levees that may be referred to as a "floodplain" from a flood hazard perspective or a historical "terrace" (abandoned floodplain) from a geomorphic perspective. This surface is thickly mantled by HMS from when it was alluviated during the late 19th century (James et al., 2009). A series of high-water channels across this terrace surface represent former main-channel positions when the river was at a higher position. Our historical reconstructions will bracket these lateral channel changes in time as well as the timing of vertical channel incision into the high surface, which abandoned the former floodplain.

Concepts of River Recovery from Episodic Sedimentation

Alluvium deposited following human disturbances; i.e., *legacy sediment* (aka *post-settlement alluvium*), is ubiquitous on many floodplains (Happ, 1945; Knox, 1977; 1987). Legacy sediment may result from episodic sediment production induced by land clearance, mining, or other activities. Extensive deposits of legacy sediment indicate the passage of a bed wave or aggradation-degradation episode (James, 2010). The geomorphic recovery of rivers from episodic sedimentation is of broad concern to river managers who need to comprehend the long-term dynamics of river systems as they readjust to lower sediment regimens. These morphologic adjustments are intimately tied to changes in sediment storage and transport and may be associated with identifiable phases of degradation or recovery.

Most studies of temporal variability in sediment transport focus on fine scales of time and space (Simons et al., 1965) following individual flood events (Costa, 1974; Fuller, 2007; 2008). Some studies have examined episodic sedimentation events at a massive spatial scale over a short period of time (Montgomery et al., 1999; Major et al., 2000; Gran and Montgomery, 2004; Major, 2004). The classic study at a broad scale is G.K. Gilbert's (1917) treatise on hydraulic mining sediment that focused on responses of the Yuba River over the first sixty years; 30 years of mining followed by 30 years of recovery. It has been shown that high sediment transport rates and channel morphologic responses occurred well into the late recovery phase in the Yuba and Bear Rivers (James 1989; 1991; 1997; 2010; James et al., 2009; 2010; Singer et al., 2008; Ghoshal et al., 2010), in contrast to interpretations deduced from the classic sediment-wave theory commonly cited at this scale (Gilbert, 1917). A few studies have documented large sedimentation events from their onset into the recovery phases (Madej & Osaki, 2009), but much remains to be learned about how systems recover from massive sedimentation events of the scale experienced in the Yuba Basin. Observations of geomorphic recovery at this scale may be used to anticipate responses to future sedimentation events induced by climatic and anthropogenic changes. Sedimentation events at this scale may leave extensive valley bottom deposits of legacy sediment as high terraces when channels incise.

Recovery of fluvial systems from episodic sedimentation depends on sediment reworking in channels and floodplains, which depends, in turn, on the geometry and erodibility of sediment storage, storage residence times, and the magnitude-frequency of floods that remobilize sediment. Most sediment-routing methods are based on transport capacity within channels, assuming an unlimited sediment supply. Fine-grained sediment is often supply limited (Gomez et al., 1993; Magilligan et al., 1998), however, and depends on erosion upstream. Over decadel time scales, sediment supplies from lateral channel migration may also play an important role. The frequency of sediment recruitment from degrading alluvial storage reservoirs varies greatly but can be generally conceptualized by decreasing transport capacity in two phases (Lisle and Church, 2002). In the first phase of degradation, abundant sediment allows changes in storage in response to changes in supply. In the second phase, however, bed armoring and form roughness determine spatial patterns of transport and storage. From the perspective of landscape sensitivity (Brunsden & Thornes, 1977; Huggett, 1988; Allison & Thomas, 1993), channels are much more subject to change during Phase I of degradation than Phase II. In many rivers, such as the Lower

Yuba, the transition from Phase I to Phase II may be artificially induced by engineering works such as wing dams or other bank protection structures. Alternatively, however, recovery may be retarded or reversed if large volumes of sediment are introduced. For example, dredge spoils from the Yuba Gold Fields provided abundant bed material in the middle reaches of the lower Yuba River that may have slowed the transition in reaches immediately downstream. Thus, the conceptual model of Lisle and Church (2002) may vary greatly in time and space for a particular river based on natural or anthropogenic heterogeneity.

To evaluate conceptual models of channel recovery from episodic sedimentation, a distinction should be made between sediment flux and channel incision or other geomorphic changes. Confusion emanates from interpretations of Gilbert's (1917) classical sediment wave model that was described as a sediment flux (analogous to a water wave), but was documented by low-flow stage elevation data (bed incision). Much confusion has resulted from a failure to distinguish between these two processes when considering channel recovery from massive sedimentation events. Sediment flux and bed incision are not necessarily in phase but may respond to different conditions following a major sedimentation event. Generally, bed incision is more rapid than the removal of sediment stored on floodplains and may define a symmetrical wave with regard to time, while sediment flux may remain elevated long after channel incision (Figure 1).

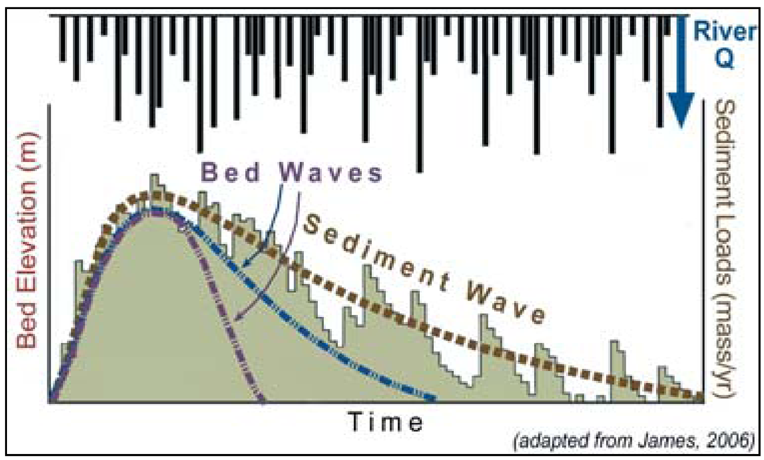


Figure 1. Conceptual model showing difference between a symmetrical bed wave (Gilbert 1917), skewed bed wave (left scale), and strongly skewed time series of sediment flux (right scale). Skewness reflects long-term storage and remobilization of laterally stored sediment. The prolonged period of high sediment flux is stochastic in response to destabilization by large floods (James, 2006; 2010).

OBJECTIVES

The proposed study will focus on the later period of recovery of the lower Yuba River from aggradation. Although the 1906 map data push historical reconstructions back well into phase one of the channel recovery period, most of the data developed by this study will be from the 1940s and later, after major channel avulsions had ceased. We have documented up to 12.9 m of vertical channel incision into the former floodplain from 1906 to 1999, but it is not clear when this vertical incision occurred. The incision is important in that it left broad terraces with reduced lateral connectivity, and presumably lowered water tables across the broad terraces. Episodic bank erosion and deposition of alluvial splays continues at some locations within the lower modern floodplain that is inset between high terrace scarps.

Two research questions will guide this research and provide a conceptual framework for data development and analysis. These mesoscale perspectives over decadal time should improve understanding of on-going channel processes.

1) Are there systematic changes in geomorphic sensitivity over an extended period of post-aggradational recovery? The hypothesis to be tested is that the magnitude of erosion attributable to a given magnitude flood decreased through time; i.e., a given flood becomes less geomorphically effective through time and larger floods are now necessary to cause change. Long-term impacts of specific flood events in remobilizing sediment by documenting the decadal timing of bank and terrace erosion following flood years. Erosion and deposition attributable to flooding does not necessarily occur during floods but may be sustained by subsequent moderate flood events following bank destabilization. Thus, interpretations of geomorphic change will consider time lags following large floods. Measurements will not include in-channel bathymetry (that cannot be determined from aerial photographs) but will focus on lateral channel changes and changes to emergent bars. Erosional responses to floods will be evaluated with regard to discharge magnitude as recorded at the USGS stream gauge near Marysville. Measurements of volumetric change via high-resolution topography will be used to develop reach-scale sediment budgets.

2) Have broad-scale processes of floodplain morphogenesis in the Lower Yuba varied spatially with specific events, structures, or processes identifiable in the historical record? Idiosyncrasies are often dismissed in river science, because they are difficult to model or apply to general principles. Similarly, historical data is often neglected because it is difficult to quantify. Nevertheless, local river behavior is often best explained by local conditions that require historical knowledge. Examples of potentially significant historical channel changes in the Lower Yuba include:

- Progradation of Rose Bar tailings fan by reworking of hydraulic mining sediment from the Blue Point Mine.
- Construction, sedimentation, and failure of the Barrier Dam, ca. 1906.
- Dredging of the Yuba Gold Fields and construction of high cobbles ridges at the angle of repose adjacent to the main channel.
- Construction of levees near Marysville that narrow the floodway from 4 to 0.6 km width.
- Construction of wing dams along the lower channel (dates unknown)

We will test the hypothesis that these structures or events have had measureable effects on sediment storage and channel morphologic responses downstream; or, in the case of the Barrier Dam and Marysville levees, also in backwater areas upstream. Testing will include photogrammetric and cartometric data analysis coupled with historical evidence of the perturbations that will be summarized in a written report. Examples of historical data include, California Debris Commission licensing of the Blue Point Mine to ascertain timing of 20th c. sediment deliveries and records of Barrier Dam (Gilbert, 1917).

This project will collect, digitally scan, rectify, and assimilate most of the historical aerial photographs available from 1936 to 1998 for the lower Yuba River into a GIS database. We have collected a large amount of aerial photographic and historical map data over the years, and some of it has been processed. We will continue that processing while collecting a great deal more digitized aerial photograph to fill in missing areas and time periods and improve data quality with some of our scans that lack high density oversize images. The project will generate a spatially distributed GIS database of historical data for the LYR and a series of specific data products based on those data. The emphasis will be on a historical aerial photo data set with high spatial and temporal resolutions, topographic data derived from it, and geomorphic and vegetation mapping at a periodicity of approximately one decade. The project will document rates of erosion by producing planimetric maps of channel changes along the entire river and volumetric maps at selected reaches where topographic data will be generated for six periods: 1906, 1947-52, 1958, 1975-78, 1986-88, and 1998.

SCOPE

The study area will extend along the Lower Yuba River (LYR) from Englebright Dam downstream to the confluence with the Feather River. In the lateral dimension it will include all of the area between the levees in the lower river and will extend in the upper portions of the study area, where there are no levees, to the colluvial valley margin; that is, where historical alluvium (largely hydraulic mining sediment terraces) are in contact with pre-historical surfaces.

Two types of spatial coverage will be included in the project. Most of the products will be produced for the entire LYR study area. This includes aerial photo rectifications, delineation of wetted channel boundaries, geomorphic mapping, and vegetation mapping. Topographic data and the associated by-produces (DEMs, contour maps, 3D models, etc.), however, will be produced only at nine selected sites as explained under Item 5, Topographic Data and 3D Models. Temporal coverage will also vary. The first set of products (rectified aerial photographs) will be produced for all times available. The CDC maps (Item 2) are for 1906, while the other products (topographic data and geomorphic and vegetation maps) will be produced for six specific time periods. .

Although we have a growing library of digital data for the lower Yuba, it will greatly assist us and improve the quality of the products produced by this project if additional spatial data are made available to us. For example, LiDAR data will improve georectifications.

METHODS AND DATA – ENTIRE STUDY AREA

1. Scanning and Rectifying Historical Aerial Photographs

We have scanned a large number of aerial photographs over the years (Appendix A), but large gaps remain in our collection (Appendix B). A large number (>100) of digitally scanned aerial photographs will be obtained by purchase or scanning at a density of at least 600 dpi on an oversize scanner (necessary to capture all four fiducial marks on a standard 9x9 air photo). All of the images will be rectified to a common base map using ground control points derived from either a high quality DOQQ or better data if available. (For example, if recent LiDAR data are available for our use, this may provide the best base map.) We will locate at least twenty ground control points for each photograph (usually more than twenty where identifiable features make it possible), spread evenly across the photograph. Aerial photographs will be rectified to the NAD83 State Plane CA Zone II, feet coordinate system and datum. *ERDAS Imagine 10* will be used to perform the rectifications.

Our experience with historical rectifications in this region indicates that precision and confidence will vary through time and space. Early aerial photos are harder to georectify if they lack distinctive cultural features to use as ground control points. Owing to sparsity of GCPs in the upper reaches (Rose Bar through Timbuctoo Bend), georectifications in that area are less precise than downstream. Downstream below the Yuba Gold Fields, the area is relatively flat and, by the time of the earliest aerial photographs, several farm roads are present that can be used for rectifications. We will report the root mean square error (RMSE) and number of ground control points used in each rectification.

2. Digital Coverage of 1906 CDC Topographic Maps and Other Historical Maps

A set of high-resolution topographic maps of the lower Yuba River from the California Debris Commission (1906) have been scanned, edge-matched, and rectified (Figure 2). They will be registered to the NAD83 State Plane CA Zone II, feet coordinate system. The 1906 CDC maps were made from field instrumental surveys at a horizontal map scale of 1:9,600 and a contour interval of 0.6 m (2 ft). They contain bathymetric contours of the Yuba River channel-bed. The map set consists of 13 sheets with six topographic map sheets that will be processed by this project, and seven sheets of channel cross-sections and a longitudinal profile. Contours have been digitized using *ArcGIS 10* for portions of these maps (Ghoshal et al., 2010; James et al., in press) and that task will be completed for all of the map sheets as part of this project.

Six 1906 3x3-m square-gridded DEMs will be generated from the digitized contours by non-linear TIN interpolation method using Erdas Imagine 10 and the sheets will be mosaiced to form a single DEM of the entire lower Yuba River from Englebright Dam to Marysville. Yuba River low-water channel margins, bars, paleochannel margins, and terraces will be digitized from the five sheets of the rectified 1906 CDC maps, and a shape file will be generated representing the position of the Yuba River channel in 1906. A 1906 contour map of the floodplain will also be generated from the topographic (TIN) data and presented as a shape file. Elevation data will be referenced to the NAVD88 vertical datum. The 1906 CDC map was originally surveyed to the U.S. Engineering Datum (USED) as was printed on the first map sheet near Marysville:

> "Elevations are expressed in feet and tenths and are referred to U.S.E.D. datum plane, which is 3.60 ft. below mean sea level, the datum plane of the U.S. Geological Survey, and are based on a benchmark of that survey at Oroville"

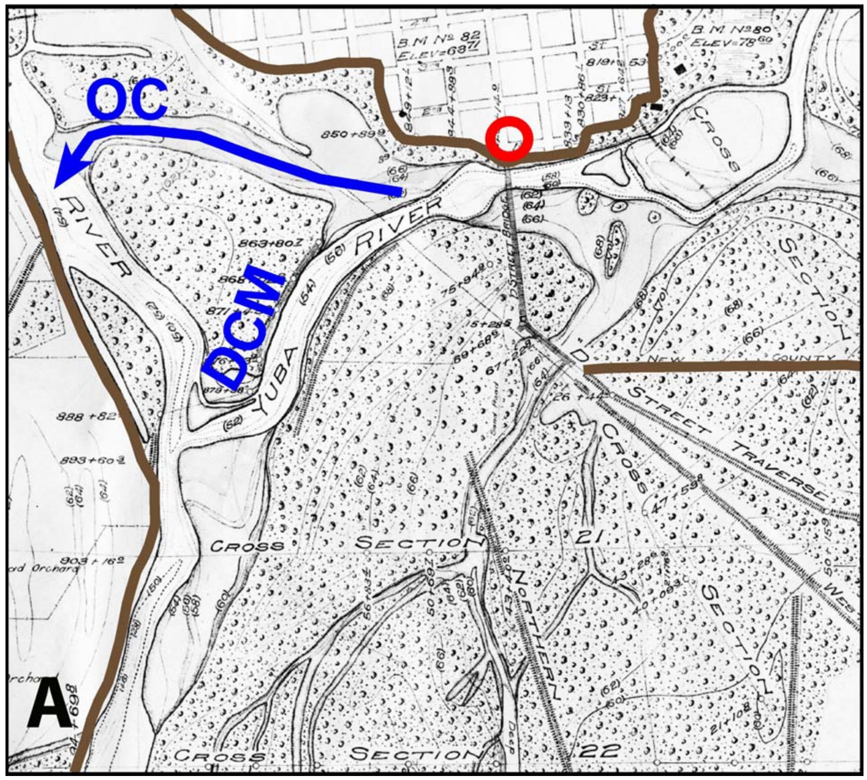


Figure 2. Excerpt from 1906 CDC topographic map of the confluence with Feather River that has been scanned, rectified, and partially annotated. (OC=Old Channel, DCM=Dredged channel mouth, red circle is old Marysville Gauge site.) Source: James, 2010.

Adjustment of the USED to NGVD should vary across a range of 22 cm, from 0.76 to 0.98 m (2.48 to 3.2 ft), and is commonly done using 0.91 m (3.0 ft) unless other information is known (CDWR, 2007). Geodetic control of this datum may not be accurate, however, because attempts to validate vertical registrations have revealed systematic bias. We will employ empirical calibrations to establish vertical control of the 1906 CDC data by comparing elevations at stable location from the 1906 CDC with elevations from the same points on recent data referenced to the NAVD88 vertical datum; e.g., LiDAR data provided by YCWA. An example of calibrations based on cross sections from 1906 and 1999 photogrammetrically derived data indicated that 1906 cross-sections were 1.2 m higher than the 1999 cross sections (Figure 3). A similar, 1.097 m, correction was found necessary on Feather River data derived from another set of CDC maps (Megison, 2008). It is possible that the geodetic control is accurate and that the 1.2 m vertical lowering from 1906 to 1999 is real and attributable to geographically extensive sediment compaction or groundwater subsidence. We cannot determine this from the data available, however, and prefer to vertically register apparently stable surfaces. This procedure allows us to measure morphological change of the channel, floodplain, and terrace system through time, and disregard broad regional vertical adjustments (if any).

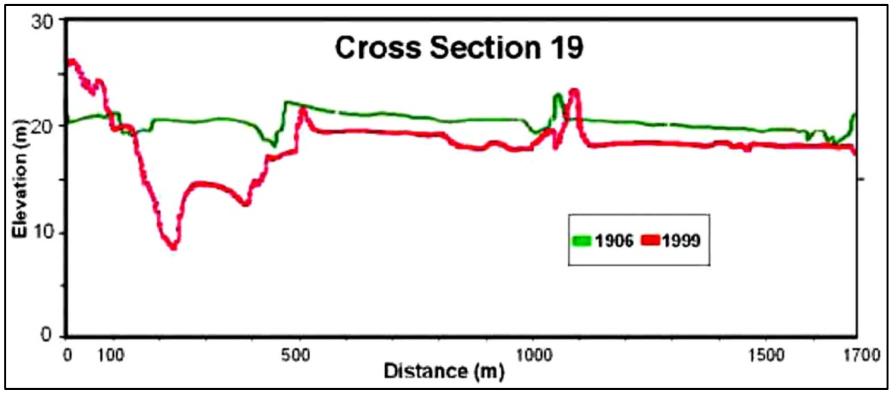


Figure 3. Cross section from CDC (1906) map is 1.2 m higher than a cross section from 1999 photogrammetric data for surfaces beyond the levee where surface is assumed to be stable. A −1.2 m vertical correction was made to the Yuba River CDC DEM before differencing. (Source: Ghoshal et al., 2010)

Additional historical maps will be located and geo-registered as best as possible. Early maps, prior to 1906, are not likely to be of sufficient precision and accuracy to allow cartometric analysis, but they can produce important constraints on the timing of various channel positions (James et al., in press). Later historical maps, such as a geomorphic map of the channel produced in 1986 (Beak, 1989); and possible survey maps for the flood control system will be sought and brought into the historical GIS dataset when this is practical.

3. Geomorphic Maps

Geomorphic maps will be generated showing contemporary channels, emergent bars, chutes, floodplains, high-water channels, terrace scarps, natural levees, and anthropogenic features including artificial levees, dredge spoils, dams, landfills, etc. Emergent bars are defined here simply as the subaerial portions of bars exposed during low flows at the time of air-photo acquisition. Subaqueous features are largely indistinguishable on historical B&W aerial photographs and will be masked out from the topographic analysis. Exposed bar surface features can be difficult to distinguish due to over-exposure of exposed coarse sediment, so emergent bars will simply be classified and attributed as point, medial, or lateral bars based on their planimetric configuration. Riffles will be mapped as transverse or diagonal (e.g., Pasternack, 2008). (We are open to refinements to this classification scheme in consultation with YCWA and RMT scientists, but will be limited in what can be discerned from historical imagery.) It is not possible to determine bed material textures from existing aerial photographs. The modern channel is largely dominated by cobbles from Rose bar down through the Yuba Gold Fields and a mix of cobbles and gravel from there to Marysville where the gravel-sand transition occurs in the area dominated by backwater during large floods. We are very interested in changes in sediment textures through time because it could be indicative of the transition between Phases I and II of channel degradation, but the aerial photographic data may not provide this information.

Geomorphic maps will be derived for the same six periods as data allow, using the rectified aerial photographs, historical maps, 3D models, and ancillary data such as digital soil maps and vegetation maps. We will also draw upon our extensive field experience and collection of >1000 recent hand-held oblique photographs of channels and floodplains along the LYR. Wetted channel margins and other features will be digitized from the rectified aerial photographs by on-screen tracing using ESRI *ArcGIS 10* software to generate shape files for vector maps of the wetted channel perimeter for each of the five or more periods of focus. Changes in lateral channel positions can be measured by overlaying the channel-margin vectors from all the years to lateral changes between periods and over the entire period of 100 years. These maps allow the identification of former channel positions and the assessment of lateral channel changes through time (Figure 4). Areas of channel erosion and deposition determined from shifts in the position of the wetted perimeter between each sequence of imagery will be computed and tabulated.

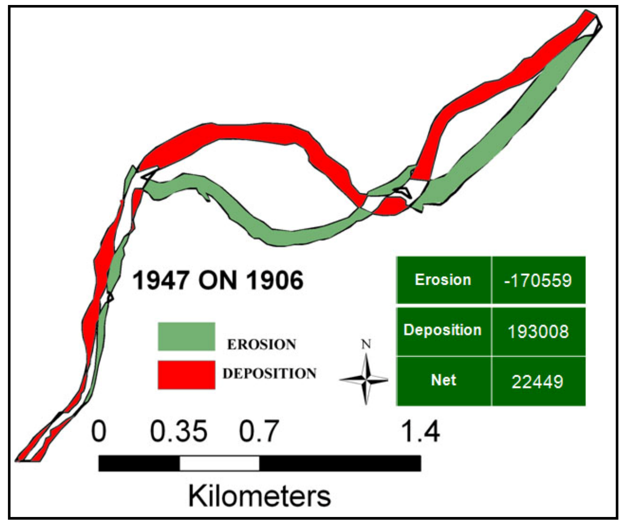


Figure 4. Channel positions on the lower Yuba in 1906 from CDC map and in 1947 from aerial photograph. Source: Ghoshal et al., 2010.

4. Classification and Mapping of Riparian and Floodplain Vegetation

Historical floodplain and terrace vegetation maps will be generated for five of the time periods (all but 1906) along the entire Lower Yuba River. We will use image processing and GIS techniques with the historical aerial photographic data in combination with historic 30-m Landsat TM data. Historic aerial photographs and Landsat multispectral imagery will be used to map vegetation for pre-1980 and post 1980 periods, respectively. Landsat data are available online for free from the USGS (http://landsat.usgs.gov/Landsat_Search_and_Download.php; cf. EarthExplorer, http://earthexplorer.usgs.gov). Recent vegetation maps and the on-going riparian vegetation analysis being conducted by the RMT based on LiDAR and NAIP imagery will be used to extrapolate vegetation maps back in time. Earlier Landsat MSS data have spatial resolutions too coarse (60 m) for this purpose. Maps will also be derived from older, pre-Landsat TM aerial photographs based on a very simple land-use/land-cover classification primarily to a level I classification to show locations of trees, shrubs, and orchards as a single class. By this means we will attempt to map as much of the floodplain as possible (data availability allowing) for five time periods (1947-52, 1958, 1975-78, 1986-88, and 1998). We will also attempt to locate and incorporate other vegetation maps, such as a map cited by Beak et al., (1989) as "U.S. Army Corps Engineers 1976", but not listed in the references of that report.

The vegetation mapping will be completed in phases; first to develop high-resolution merged images from the aerial photography and multispectral imagery. These images will be classified using pixel-based supervised classification to generate vegetation polygons. Finally, a decision-tree model (Rule Set) will be developed and the segmented image will be classified using an object-based classification system. An accuracy assessment will be performed. We expect the quality and level of classification of the vegetation maps to decline with the age of air photos. More recent imagery can be more confidently link to the current vegetation maps but earlier vegetation maps will be less accurate.

METHODS AND DATA – NINE STUDY REACHES

5. Topographic Data and 3D Model Generation at Nine Sites

Detailed 3D stereographic mapping for the historical data and associated topographic analysis will be conducted at nine representative locations spread along the lower Yuba: Rose Bar, Timbuctoo Bend, Parks Bar, Barrier Dam, Daguerre Point Dam, 1st Bend (below Simpson-Dantoni Road), 2nd Bend (near the landfill), Marysville above Simpson Road, and the confluence. These representations will be made for six time periods as data availability allows. Some of the six time periods may lack imagery at some of the nine sites, so we will not likely be able to produce detailed topographic analyses for all of the 54 potential space-time intervals (N=6x9). With the exception of the 1906 map, topographic reconstructions will not include low-flow channel bathymetry because sub-aqueous topography cannot be accurately mapped using conventional aerial photography. The purpose of developing detailed 3D topographic models is to allow volumetric computations of erosion and sedimentation at a decadel time scale. These computations will be spatially distributed, allowing identification of specific geomorphic processes, such as deposition on natural levees or erosion by lateral planation or bar incision.

Historic high resolution topographic maps and DEMs will be generated using soft-copy photogrammetry analysis in areas of overlap on stereo photo pairs. We will use standard digital techniques to construct DEMs from stereo photographs (Dornbusch et al., 2008). Ackermann (1996) and Hapke and Richmond (2000) describe soft-copy photogrammetry methods for extracting a DEM from aerial photographs and explain different applications to quantify 3D terrain alterations. Gagnon et al. (1993) discuss the accuracy of DEMs extracted using soft-copy photogrammetry and compare these accuracies with traditional survey techniques. Leica Photogrammetric Suite and Stereo Analyst module in Erdas Imagine 10 software will be used to extract DEMs from the stereo photos of the study area. The methodology is adopted from the user's guide of Leica Photogrammetric Suite (ERDAS, 2008). The input data needed for DEM extraction are:

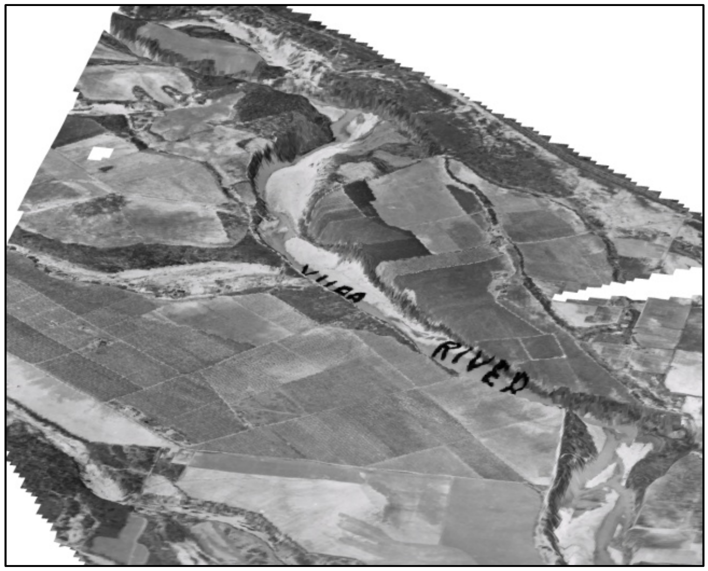
- A stereo pair of aerial photographs with at least 60% overlap.

- Ground control points (GCP) with X,Y,Z coordinates from GPS surveys, DOQQs or LiDAR data. We have a series of GCPs collected in the field for some of the study area and will augment these with the latest and best DOQQ and LiDAR data available. We will also collaborate with the RMT to obtain additional GCPs and to keep the topographic data in the same coordinate system.
- A camera calibration report (CCR) that includes camera focal length (CFL), the principal point, locations of fiducial marks, and lens distortion parameters. We have been and will continue to gather CCRs for the aerial photography in our collection. These metadata will be included as an appendix in our detailed report.

After loading two or more overlapping images into the Leica Photogrammetric Suite (LPS), thousands of x,y,z points will automatically be generated by triangulation using automatic terrain extraction. These points will be converted to bare earth points by masking with the vegetation map to remove points over vegetation canopy and removing points over cultural features such as bridges or buildings. The LPS uses a non-linear TIN interpolation procedure to generate DEMs. TIN interpolators have often been found to be superior to inverse distance weighting or kriging for this purpose (e.g., Heritage et al., 2009). Pixel sizes of DEMs will be set to a standard 3x3 m. Pixel resolution depends upon the scanning resolution and scale of the air photos (Jensen 2007). The photographs will be scanned accordingly so that an optimum resolution of 3x3 m can be achieved during DEM extraction. A systematic error analysis and accuracy assessment for the process will be calculated and reported for each DEM extraction along with the number of GCPs and the root mean square error (RMSE); (e.g., Hodgson and Breshnahan, 2004; James et al., in press).

Once DEMs have been generated it is relatively easy to generate 3D visualizations in *ArcGIS 3D Analyzer* and *Arcscene.* Visualizations of selected surfaces at specific periods during the evolution of the system will be generated to provide easily manipulated reference tools. For example, we will generate a series of historical perspective models from the DEMs with the aerial photographs draped over them (e.g., Figure 5).

Figure 5. Perspective view of 1947 aerial photograph of lower Yuba River draped over a 1906-1999 DEM of difference (DoD) derived by subtracting a 1906 DEM from a 1906 DEM. This visualization shows that most vertical channel incision was complete and that former channels (now highwater channels) were abandoned at this site by 1906. From: James et al. in review.



DELIVERABLES

All final data and a GIS database with shape files and indices based on ArcGIS software (ESRI Corporation) will be delivered to YCWA for incorporation into their relicensing effort and river management effort no later than August 10, 2011. The products to be delivered will include:

1. An extensive set of aerial photographs from most available sources from Englebright Dam to the Feather River confluence, co-registered to a common base map for the period 1936 to 1998. A large number of rectified aerial photographs will be provided in a format specified by YCWA (e.g., geotifs or ERDAS Imagine image files). Metadata such as accuracy assessments will be included in our detailed final report.
2. A complete digital coverage of the 1906 California Debris Commission topographic maps, including rectified scans, shape files of digitized two-foot contours and wetted channel boundaries, and DEMs generated from the contours.
3. Geomorphic maps of floodplains and channels based on aerial photographs, soils, and visual interpretations/remote sensing classifications. These maps will show active and abandoned historical channels, past and present levee positions, etc. This product will include a set of GIS shape files with the channel wetted perimeter for each of the periods of study. The database will also include a GIS shape file with soil polygons derived from USDA SURGO data edited to interpret soil geomorphology and to identify historical alluvium.
4. Classification and mapping of riparian vegetation for selected years based on remote sensing analyses of the scanned photographs. This will consist of a series of raster-based panels covering the entire area of the river for which imagery can be acquired, for at least five time periods.
5. Topographic generated by soft-copy photogrammetry at nine sites for six time periods. DEMs, TINs, and contour maps will be generated and provided in file formats readable by

YCWA. A set of 3D models, such as aerial photographs draped over DEMs, will be generated in a format readable by ArcGIS as well as static renderings (e.g., jpgs) for easy viewing.

6. A comprehensive written and illustrated report of our findings will be produced with an emphasis on the remote sensing, spatial analysis, geomorphic interpretations, and historical documentations of channel changes.

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Appendix A. Data Sources of Yuba Aerial Photos that have been scanned

	Rose Bar	Tim buc2	Parks Bar	1ST Bend	Landfill 2d bend	Marysvl 3rd Bend	Confl Fr/YR
1936						SA	SA
1937	SA	SA	SA			SA	SA
1947	SA/GS	SA/GS	SA/GS	SA	SA		
1952	SA/D	SA/D	SA/D	YC	YC	YC	YC
1956							DWR-F
1958	D	D	D	D	D	D	D
1967				DWR-F		D	D
1975	DWR	DWR	DWR	DWR	DWR	DWR	DWR
1986	DWR	DWR	DWR	DWR	DWR	D	D
1987	DWR	DWR				DWR	DWR
1989				DWR	DWR	DWR	DWR
1997						DWR	DWR
1998	DWR	DWR	DWR			DWR	DWR

Sources	
D	Davis library
SA	CA State Archive
YC	Yuba County
GS	USGS
DWR	DWR
DWR-F	DWR FERC
DOQ	DOQQ- USDA

Appendix B. Lower Yuba aerial photos available that we do not have but will acquire.

	Rose Bar	Tim buc2	Parks Bar	1ST BEND	Landfill 2d bend	Marysvl 3RD BEND	Confl Fr/YR
1941	CXW#	CXW#	CXW#	CXW#	CXW#	CXW#	CXW#
1947	GS-CW	GS-CW	GS-CW	GS-CW	GS-CW	GS-CW	GS-CW
1964	FSA	FSA	FSA	FSA	FSA	FSA	FSA
1970	FSA	FSA	FSA	FSA	FSA	FSA	FSA
1973	AR573001495	AR573001495	AR573001495	AR573001495	AR573001495	AR573001495	AR573001495
1975	ABM-9	ABM-9	ABM-9	ABM-9	ABM-9	ABM-9	ABM-9
1978	GS-VEQG*	GS-VEQG*	GS-VEQG*	GS-VEQG*	GS-VEQG*	GS-VEQG*	GS-VEQG*
	78-037**#	78-037**#	78-037**#	78-037**#	78-037**#	78-037**#	78-037**#
1979	79-083**	79-083**	79-083**	79-083**	79-083**	79-083**	79-083**
1981	FSA-USDA	FSA-USDA	FSA-USDA	FSA-USDA	FSA-USDA	FSA-USDA	FSA-USDA
1984	NHAP1	NHAP1	NHAP1	NHAP1	NHAP1	NHAP1	NHAP1
1986	WR-ASL	WR-ASL	WR-ASL	WR-ASL	WR-ASL	WR-ASL	WR-ASL
1987	NAPP1	NAPP1	NAPP1	NAPP1	NAPP1	NAPP1	NAPP1
1987	GS-VFLLC	GS-VFLLC	GS-VFLLC	GS-VFLLC	GS-VFLLC		
1989	WR-AVU(L)	WR-AVU(L)	WR-AVU(L)	WR-AVU(L)	WR-AVU(L)	WR-AVU(L)	WR-AVU(L)
1993	NAPP2	NAPP2	NAPP2	NAPP2	NAPP2	NAPP2	NAPP2
1998	NDOP	NDOP	NDOP	NDOP	NDOP	NDOP	NDOP
1998	NAPP3	NAPP3	NAPP3	NAPP3	NAPP3	NAPP3	NAPP3
1998	BFK/BMT(L)	BFK/BMT(L)	BFK/BMT(L)	BFK/BMT(L)	BFK/BMT(L)	BFK/BMT(L)	BFK/BMT(L)

Sources			
		USDA:	FSA = Farm Service Agency
	USDA		NAIP = Nat. Agriculture Imagery Prog
	USGS		NAPP = Nat. Aerial Photography Prog
	NASA		NHAP = Nat. High Altitude Prog
	DWR (L: large scale)		NDOP = Nat. Digital Ortho Prog
	U.C.Berkeley	USGS	GS-CW= Aerial Photo: 2/22/1947
Also (not shown)	US Forest Service		GS-VFLLC= 7/27/1987-9/30/1987
	USACE		HRO= High Resolution Orthoimagery
			NAPP & NHAP available at
	Whittier College		USGS & USDA