

**ATTACHMENT 1  
TO  
CHANNEL MORPHOLOGY DOWNSTREAM OF  
ENGLEBRIGHT DAM STUDY PROPOSAL  
EXISTING INFORMATION SUMMARY**



(red painted tracers for sediment transport study in the lower Yuba River)

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## Introduction

Geomorphology is the study of the landforms on the surface of the earth. Geomorphic analysis involves mapping the shape of landforms to describe their spatial patterns, observing landforms over time to record their changes, exploring the drivers and mechanisms of landform change, and evaluating the responses of biological, chemical, and hydrological processes to geomorphic change. Beyond understanding natural conditions and dynamics, geomorphology is essential in planning societal use of the landscape and in figuring out the impacts of societal activity on the environment and through it the externalities that come back and harm society and economics.

Traditionally it has been thought that rivers possess the capability of adjusting their attributes to accommodate flow and sediment transport regimes so that sediment in- and out-fluxes are balanced and landform conditions are “stable”. However, in reality geomorphic drivers and boundary conditions are much more independently dynamic and fast changing than classically envisioned, such that landforms may always be in a state of adjustment in response to external drivers and internal free oscillations that is normal and appropriate. Rather than thinking of landforms as “stable”, it is more appropriate to think of them and the ecosystem functions they are associated with as resilient in the face of change. Knowledge of historic, pre-human baseline conditions or regional reference conditions is limited and may not be as useful in understanding natural geomorphic and ecosystem services as once envisioned. In light of this natural complexity, a geomorphic assessment of conditions after a large dam or other facility is built and operated may not be as simple as documenting geomorphic instability and attributing that to human impacts relative to the presumed stable baseline conditions.

Rather than compare human-impacted conditions to theoretical baseline or reference conditions, a more effective approach is to deduce the geomorphic processes in a system under different regimes and evaluate the implications for resiliency of ecosystem services. Through a mechanistic understanding of environmental systems, it may be possible to rationally rehabilitate an ecosystem to achieve resiliency in cases where it has been lost or is desirable to instill, even if it was not historically present.

The goal of this report is to thoroughly document the studies that have been done that provide insight about the fluvial geomorphology of the lower Yuba River (LYR) and its relation to the resiliency of ecosystem services. A description of the geomorphology of the river requires consideration of A) geomorphic drivers, B) landforms and boundary conditions, C) hydrogeomorphic dynamics, D) physical habitat and ecological dynamics, and E) river management actions. As the report details, a lot of research has been performed already and more is being done presently as a result of the Yuba Accord. Rather than describe the existing information chronologically or by considering each study completely one at a time, the approach taken is to focus on each essential geomorphic topic and draw from across all relevant knowledge sources to address each issue. Sources referenced in the body of the report are listed with full citations at the end of this report. Throughout the report, an effort is made to assess the adequacy of existing information and identify data gaps that limit the ability to assess dam impacts on fluvial geomorphology.

## **A. Geomorphic Drivers**

The chain of geomorphic processes in a river corridor begin with driving forces that cause landforms to change. Slow geologic forces such as tectonics and sedimentary subsidence establish the context of a river basin and explain its long-term landform evolution as a result of erosion and deposition over thousands to millions of years. Faunt (2009) investigated both natural and anthropogenically induced subsidence in the Central Valley and did not report any concerns for the LYR region.

Glacial processes are nonexistent in the LYR. Similarly, freeze-and-thaw erosion of riverbanks is not an important process in the LYR, because air temperature rarely dips below the freezing point. Given a lack of sand- and mud- sized sediments, wind processes are likely to be geomorphically unimportant. Kinetic erosion by rainsplash and chemical weathering do play a role in the breakdown of hillside bedrock and soils, but do not influence the coarse-grained floodplain and channel.

### *A1. Surficial Inflow of Water and Associated Materials*

The most significant driving force for geomorphic change in the LYR corridor is flowing water. Water is a powerful force for landform change in and of itself, but it also carries with it sediment that is even more powerful in its geomorphic impacts. Diverse chemical and biological materials also move with the flow. Hydrological analysis of the LYR flow regime is critical to understanding the river's behavior and conditions, and thus has been performed by many investigators.

Traditional U.S. Geological Survey (USGS) gaging stations are used to record water levels and estimate flow rate; records are publically available on the internet at no cost. Gaging stations operated by local and state organizations are also present, but data is more difficult to obtain. Additional water level recorders have been placed into the LYR on a temporary basis in support of several individual projects.

The LYR is gaged at two locations and three of its tributaries are gaged. The gages are

The Yuba River USGS gaging station #11418000 is near Smartville, CA. This gage is located in the EDR. Its stage-discharge relation is dynamic due to its location upstream from an alluvial cross-channel bar, requiring regular re-calibration. The record is from 10/1/1941 to present.

The Yuba River USGS gaging station #11421000 is near Marysville, CA. This gage is located downstream of Daguerre Point Dam and agricultural water diversions, so its values are often lower than those recorded at the Smartville gage. Also, it is located relatively far upstream of the confluence with the Feather River, because flow fluctuations in the Feather River cause significant water level variations in the lowermost LYR, precluding the ability to create an independent stage-discharge relation for the LYR near its mouth. The record is from 10/1/1943 to present.

The Deer Creek USGS gaging station #11418500 is at the Mooney Flat Road bridge over Deer Creek near Smartville, CA. It is located in a bedrock channel. The record is from 10/1/1935 to present.

The Shubert subcatchment at the University of California Sierra Foothills Research and Extension Center flows into the LYR in the Narrows and has been gaged for over 60 years. It has a small amount of flow, but its long record has been used to study the influence of different land management practices on runoff generation and water quality, particularly with respect to cattle grazing.

Dry Creek is gaged at Collins Lake, but the data is not publically available on the internet. Typical controlled releases are ~2 cfs. Uncontrolled winter floods occur and appear to transport sediment and alter Dry Creek's morphology, but the fluvial geomorphology has not been documented as of yet.

No other minor tributaries (e.g. Big Ravine and Blue Point mine) have gages.

Overall, the LYR is well gaged, providing the baseline data necessary to evaluate hydrological drivers of geomorphic processes. A basic hydrological analysis including monthly flow distribution was performed by DWR and USACE (2003).

#### A1a. Yuba River Development Project

YCWA (2009) presented the hydrology of the Yuba River watershed. They reported on measured tributary inflows, estimated ungaged flow accretions, and accumulated flows.

#### A1b. Flow Release Schedules

Flow release schedules are presently established by the Yuba Accord and are available on the River Management Team (RMT) web site ([www.yubaaccordrmt.com](http://www.yubaaccordrmt.com)).

#### A1c. Flood Analyses

DWR and USACE (2003) report the largest floods at the gages affecting the LYR.

Moir and Pasternack (2008) and Pasternack (2008) performed flood frequency analysis for the pre-Englebright (before 1942), Englebright-to-New Bullards Bar (NBB) (1942-1971), and NBB-to-present (1971-2004) time series using the Smartville gaging station data. They found the present-day statistical bankful discharge to be 5,620 cfs and that for pre-NBB to be 11,600 cfs. The 2-, 5-, 10-, and 50-yr return interval discharges for 1971–2004 were 10,600, 37,000, 51,200, and 142,00 cfs, respectively.

MEI (2008) performed flood frequency analysis using the Marysville gaging station data (actual span of years used were not reported, but might have included all years irrespective of

dam regimes). The 2-, 5-, and 10-year recurrence interval peak flows were found to be 17,100, 48,000 and 80,500 cfs, respectively.

Pasternack (2008) performed an analysis of flood types using the Flood Regime Characterization computer code for MATLAB 7 written by Eric Booth (UC Davis Hydrologic Sciences M.S. student) in 2006. This code analyzes the magnitude and duration of flood events from a daily discharge time series to create classes of flood types. This classification process is facilitated by expert-based input of significant hydrologic and geomorphic thresholds. Once flood types are created, then water year types are created by clustering similar water years together based on the number of days each flood type occurs during each water year. The frequency of each water year type throughout the record is also calculated.

MBK (2006) provided a list of reports about flooding and drainage issues in Yuba County. It also summarized the findings about flood control infrastructure. They state that a serious threat exists along the LYR due to the ever-present possibility of levee failure and that the dams in the system can only provide protection for floods up to the ~70-year event.

NBB and Englebright Dams regulate flows into the LYR, but they do not hinder large floods, because the South and Middle Yuba Rivers have no large dams to abate winter floods driven by large rainstorms or rain-on-snow events. For example, the present LYR flow regime includes channel-changing floods that occur every ~9 years (e.g. 1986, 1997, and 2005/2006). For example, in 1997 there was a flood that produced a peak mean daily discharge of ~154,000 cfs. On New Years Eve at the end of 2005, there was a flood with a peak mean daily discharge of ~95,600 cfs. On top of each of these flows over Englebright Dam, one also has to factor in the significant contributions of Deer Creek and Dry Creek, which help to sustain the duration of the peak flood. For example, the combined hourly peak discharge for the 2005/2006 New Years Flood at the highway 20 bridge was ~109,000 cfs. Large floods that occur on the LYR pose a hazard to Marysville and Yuba City, because levees protecting those cities have historically been prone to failure.

#### A1d. Indicators of Hydrologic Alteration (IHA)

Indicators of Hydrologic Alteration (IHA) is a widely used method to measure the variation of the flow with respect to the natural flow regime or pre-impact hydrograph. IHA defines 32 hydrologic parameters among the five components of the flow regime for the evaluation of changes between natural and manufactured flows. The Range of Variability Approach (RVA) provides flow targets based on the statistics of the natural flow regime (Richter et al., 1997). An IHA analysis was performed by Dr. Marisa Escobar at UC Davis to compare the flow regime pre- and post NBB (NBB), and some of the results were documented in Escobar and Pasternack (2010), but no comprehensive IHA report was written. Pasternack (2008) also presents some metrics of hydrologic changes before and after Englebright Dam.

IHA analysis of LYR median monthly flows showed a decline in spring-snowmelt flows after NBB was built. During the pre-Englebright era, median monthly discharge peaked during the

snowmelt season in April at ~6300-6700 cfs. After Englebright was built that dropped to ~4600 cfs. After NBB was built it dropped down to a peak of ~2500 cfs. Similarly, for the month of May, monthly flows decreased on average from ~5,200 cfs before to 2,000 cfs after NBB. Therefore, like other regulated rivers, the LYR has a degraded monthly flow distribution in which there are the lowest flows during the late summer to early fall and then highest flows during the winter, but the lowest of the low flows are not as low as they used be and the flood peaks are curtailed.

#### A1e. Climate Change Effects on Unimpaired Flow

There is a very high level of uncertainty about what climate conditions will be like for the northern Sierras in 2050 and beyond. Several studies have been done in which the future climate has been assumed to be one in which conditions are identical to the current climatic regime, except that the mean air temperature is shifted up 1-8 °C. Using that approach, the expected outcome is dramatically less snow water equivalence and snow cover, resulting in an inadequate water supply for California.

The UC Davis Hydrology Program conducted a climate-change analysis of flows in the North Yuba above NBB, whose flow is unregulated. The study included analysis of past effects and projections of future impacts. Mean daily discharge from 1938-2009 was checked for three indicators of climate change effects: calendar day of peak snowmelt discharge, fraction of annual runoff April through July, and the center of mass of snowmelt runoff. All of these metrics showed no statistically significant impacts of climate change on the North Yuba system as of yet. However, a coupled model of regional climate change at 4-km resolution (WRF dynamical downscaling) and distributed hydrodynamic modeling (RHESys) of the North Yuba catchment predicts a significant increase in snow storage and increase in water supply for 2048-2053. This was contrary to previous studies that assume no change in precipitation and significant warming. In fact, the best projections now suggests that the Yuba catchment will have a significant increase in precipitation, snow, and water supply in 2050.

#### A1f. Geomorphic Significance of Specific Flow Ranges

Based on multiple lines of observational evidence and hydrological flood frequency data analysis, Pasternack (2008) reported the following flow thresholds for geomorphic processes in Timbuctoo Bend:

- A preferential riffle-scouring discharge range of flow <11,000 cfs
- A modern bankfull discharge of ~5,600 cfs,
- A 1942-1971 bankfull discharge of ~11,600 cfs,
- A preferential run-scouring discharge range of ~9,000-25,000 cfs,
- A floodplain-filling discharge of ~20,000 cfs,
- A preferential pool-scouring discharge range of >45,000 cfs.

The above thresholds may not apply to the rest of the lower Yuba River. The existence of such thresholds in other LYR reaches is presently under investigation.

## *A2. Groundwater and Hyporheic Flows*

California DWR has long-term groundwater monitoring wells throughout the region spanning 1947-present. DWR and USACE (2003) shows that two sites are right along the river just downstream of the Yuba Goldfields, but none are in the river corridor upstream of that. According to that report, groundwater pumping for agriculture has varied over the decades and is now lower than in the past due to surface water deliveries. Also, more water appears at Marysville than is present in the river as it passed over Daguerre Point Dam, indicative of extra inflows from groundwater recharge or from Yuba Goldfields surface outflows.

The Yuba Goldfields are an ~10,000 acre, highly disturbed assemblage of landforms in the LYR corridor that resulted from historic industrial gold mining. The industrial operations involved reprocessing gold out of hydraulic mining debris that deposited on the valley floor. The landforms consist of towering lines of coarse sediment with intervening deep lines of ponds. The LYR and the Yuba Goldfields are hydrologically connected by groundwater and hyporheic fluxes as well as by direct surface water connection during floods. River water has been observed to flow into the Yuba Goldfields during high flows and flow out during low flows. YCWA (2009) estimated that there is 500 TAF of storage of flood waters in the Yuba Goldfields.

USACE (2002) performed MODFLOW groundwater simulations that predict hydraulic head throughout the Marysville region.

YCWA (2007) included groundwater impact analysis, primarily related to diversion flow and agricultural recharge in the vicinity of the LYR.

Three Rivers (2009) performed an assessment of groundwater in the area south of the LYR in support of levee strengthening work.

Faunt (2009) reported on groundwater status and usage for the entire Central Valley, including information about the region containing the Yuba River.

No hyporheic flow studies have been performed on the LYR, but there is ample visual evidence of water flowing through the substrate in large quantities. For example, at the upstream end of all surficially disconnected backwaters there is a visible inflow of water straight out of the gravel. The inflow is strong enough to create observable velocities.

## *A3. Sediment Sources and Influx*

In an unregulated catchment, sediment flux plays an important role in geomorphic change. Once a river is impounded, sediment transport and delivery is disrupted and the rate of geomorphic dynamics is often reduced. Knowledge about the pre-dam influx of sediment can be useful in understanding baseline conditions. However, the LYR is somewhat unique in that it stored a vast amount of sediment in its river corridor prior to damming as a result of historic hydraulic

gold mining. Consequently, sediment transport remains vigorous in the LYR even though sediment influx is small. In this context, information about pre-dam sediment influx provides insight into severity of historic impairment due to gold mining.

Gilbert (1917) characterized the quantity and texture of sediment coming from hydraulic mining in the Yuba River catchment.

USGS Upper Yuba River Studies Program investigation of sediment behind the dam (Snyder et al., 2004a,b). Used drilling down the length of the reservoir to explore the stratigraphy of the thick deposit. Applied two different extrapolation schemes to estimate the volume and mass of each size fraction of sediment in each reach of the reservoir.

Snyder et al. (2006) analyzed the hydrologic history of the Englebright-Lake catchment in the 20<sup>th</sup> century and related that to variations in lake levels and the lake's depositional history. Englebright Dam is a 100% barrier to the flux of sand, gravel, cobble, and boulders. Turbid water carrying silt and clay sized particles goes over Englebright Dam during floods.

Curtis et al., (2005) developed a conceptual model of sediment processes for the Yuba River watershed. They used GIS to estimate the spatial pattern of hillside susceptibility to erosion.

Pasternack (2008) re-analyzed the Snyder et al. (2004a,b) data to isolate the gravel/cobble loading to have an upper bound on unregulated gravel/cobble influx to the LYR.

James et al. (2009). "The immense deposit in the lower Yuba River alone represents 24% of the hydraulic mining sediment produced from 1853 to 1884". [That is ~253 million cubic meters of sediment.] "Most mines in the Yuba Basin dumped sediment into extremely steep, narrow canyons, where it was quickly and efficiently delivered downstream to alluvial fans and basins in the valley."

Boulder generation on hillsides abutting channel are rolling down into the river is important for cover, but unknown.

#### *A5. Sources and Influx of Chemicals and Biological Materials*

Large amounts of mercury were imported and used to process gold-bearing rocks in the Yuba catchment, introducing a serious toxic compound into the system. Studies have been done to assess the scope of the problem, including the risk of methylation, which makes inorganic mercury bioavailable.

Beak Consultants, Inc (1989) evaluated the LYR's water quality (dissolve oxygen, pH, dissolved solids, hardness, alkalinity, nutrients, ammonia, inorganic trace elements, select organic compounds, and turbidity, and found that it was "quite good" and within the acceptable range for salmonids. They did consistently detect mercury in sediments and fish tissue samples.



May et al. (2000) documented significant bioaccumulation of methylmercury in fish in Lake Englebright.

Hunerlach et al. (2004) characterized total mercury and methylmercury in sediments trapped behind Daguerre Point Dam. Higher concentrations of total mercury were found with finer sediment sizes, but total mercury concentrations were relatively low, as were methylmercury concentrations. They also assayed trace elements other than mercury using ICP-Mass Spectrometry (ICP-MS) and major elements (Ca, Mg, Na, K, Si, Fe, and Mn) by ICP-Atomic Emission Spectroscopy (ICP-AES).

Alpers et al. (2006) reported geochemical data for mercury, methylmercury, and other constituents in the sediment under Englebright Lake. Related those to sediment particle size distributions.

James et al. (2009) reported geochemical data for total mercury in sedimentary strata associated with hydraulic mining debris near Marysville, CA.

#### *A6. Role of Tributaries*

The influx of sediment, wood and other materials from tributaries (Deer Creek, Dry Creek, Big Ravine and Blue Point Mine) is likely very small in comparison to the amount of sediment stored in the LYR channel and floodplain. Deer Creek and Dry Creek contributions are largely blocked by dams and flow regulation on those streams. Tributary contributions are not a function of main stem Yuba flows or operations, but may be potentially important to understand from the perspective of sand contribution to the LYR.

### **B. Landforms and Boundary Conditions**

As dictated by the mathematics of differential equations, the ability of driving forces to cause geomorphic change is strongly mediated by the characteristics of the landform itself, including surface composition, internal structure, morphology, and vegetation. These characteristics are termed “boundary conditions” in math and engineering. Their status is often influenced by dams, but on the LYR one has to consider the significant role of pre-dam hydraulic gold mining in dictating boundary-condition status.

#### *B1. Aerial Photography and Remote Sensing*

Satellites and airplanes serve as excellent platforms for collecting digital imagery of river corridors to study changes over time. Satellites have lower resolution, but return more frequently. Putting the two sources together can provide a strong assessment of river conditions before and after diverse human impacts.

Landsat satellites that take digital images of the Earth’s surface have operated since 1972. Landsats 1, 2, and 3 flew over the LYR every 18 days and collected images with 80-m resolution using a multispectral scanner. Landsats 4-7 have an upgraded thematic mapper system with a

30-m resolution and a 16-day return cycle. These images provide the potential to study LYR morphology and vegetation at a high temporal frequency for 36 years. However, the spatial resolution is relatively low compared with airplane-based photography, which is commonly 1-m resolution.

Airplane-based photography of the LYR occurred in 1937, 1947, 1952, 1958, 1984, 1986, 1991, 1995, 1996, 1997, 1999, 2002, and annually since 2004. Historical imagery has largely not been georectified. Most imagery since 1999 is georectified. The National Agricultural Imagery Program has 1-m resolution imagery from 2009 that represents the highest quality georectified imagery available for the present condition.

The RMT had airborne LIDAR flown for the LYR from highway 20 bridge to the mouth of the LYR in autumn 2008. The LIDAR intensity returns provide an image of the river corridor and the raw returns have ~2' spacing.

Jason White at UC Davis georectified all available historical imagery of Timbuctoo Bend (provided by Geography Prof. Allen James of University of South Carolina, originally of the Yuba region) and those images are available. White (2008) and White et al. (in press) report the findings from analyzing those images to answer specific questions about riffle-pool location and persistence in Timbuctoo Bend.

## *B2. Geology, Physical Geography, and Channel Classification*

The studies documented in this subsection provide overviews of the landforms and boundary conditions of the LYR.

The California Geologic Survey released a new Geologic Map of California in 2010. According to the map, the river segment from Highway 20 bridge to Marysville consists of "Q" Quaternary deposits. The segment from Englebright Lake down to highway 20 bridge consists of "MzV" Mesozoic metavolcanic rocks, though the river bed itself is composed of recent alluvial sediments. A more detailed characterization of soils, seismicity, and geology is presented in Yuba County (1993).

Gilbert (1917) and James et al. (2009) provided detailed geographic and geomorphic descriptions of physical conditions in the LYR.

Beak Consultants, Inc (1989) qualitatively divided the LYR into four reaches on the basis of "major changes in stream character (gradient, channel morphology and substrate) and significant alterations in stream discharge". The reaches were 1) The Narrows Study Reach, extending 11,400 ft from Englebright Dam to the downstream terminus of The Narrows, a steep-walled canyon; 2) Garcia Gravel Pit Study Reach, extending 56,400 ft downstream from The Narrows to Daguerre Point Dam; 3) Daguerre Point Dam Study Reach, extending 41,400 ft downstream from the dam to the upstream terminus of the Feather River backwater, and, 4) Simpson Lane Study Reach, extending 18,500 ft from the upstream terminus of the Feather River backwater to the confluence of the Yuba and Feather rivers.

White (2006) used Timbuctoo Bend landform and flow characteristics to describe the LYR according to several river classification schemes.

Pasternack et al. (2010) reported on the 100-year history of channel conditions in the EDR with an emphasis on the status of Sinoro Bar at the junction with Deer Creek.

The general physical geography of the LYR is heavily influenced by the legacy of hydraulic gold mining. The river is still best classified as a wandering gravel-bed river, typical of what is seen in front of retreating glaciers. The degree of wandering is constrained by the large training berms and the presence of the Yuba Goldfields.

### *B3. Topography*

A topographic map is a representation of the elevation pattern of a land surface. Because topography is one of the most fundamental variables controlling ecosystem processes on Earth, it is essential to have a good topographic map to manage the landscape. In the case of rivers, topographic maps are particularly important, because the speed and direction of water flow and sediment transport is directed by landform configuration. In turn, flow and sediment help define instream habitat conditions and they can cause landform change. Repeated topographic mapping can be used to characterize how rivers change through time. Both habitat conditions and channel dynamics are important considerations in river management, particularly in regulated rivers that are actively managed to balance multiple needs and interests.

CDC (1906) included a longitudinal profile of the river bed and information about drilled boreholes to determine mining sediment thickness and depth to bedrock. They found that there was 23 m of fill (75') in the channel at The Narrows. The sediment thickness thinned to 4.8 m at Marysville. Depth to bedrock at DPD was 15.9 m. there was no floodplain sediment fill determination.

Gilbert (1917) described topographic mapping in the reach downstream of Parks Bar before "Barrier no. 1" was built and after it was destroyed by a flood. Mapping consisted of contour-based surveying during low flows and cross-sections spaced ~500' apart during high flows. The whereabouts of these maps is unknown.

Gilbert (1917) described four maps of Timbuctoo Bend made in 1898, 1905, 1906, and 1908. The river's wetted area for each of these maps is shown in Figure 8 of his report, but not the actual maps. The whereabouts of these maps is unknown.

1999 USACE topographic map. Bathymetric cross-sections every 100-300'. Terrestrial points primarily from photogrammetry and secondarily from LIDAR. No mapping of river bed from Englebright Dam down through Narrows. Some sizable data gaps, particularly where there were islands, backwaters, and side channels. The 1999 map of the river channel and floodplain is no longer valid after the floods of 2005 and 2006. The 1999 map was

produced in the 1929 NGVD datum, but a version of the map using the 1988 NAVD datum has been produced by Prof. Pasternack at UC Davis.

Childs et al. (2003) produced a bathymetric/topographic map of Englebright Lake.

2006-2009 UCD/USFWS/RMT map. Combination of boat-based, ground-based, and LIDAR mapping was used to create a much higher spatial resolution than the 1999 map. Point spacing on the floodplain was finer than 1 point every 2 feet. In the channel the spacing was more variable, but still on the order of 1 point every 5-20'. The EDR was mapped too, but the Narrows is still not mapped as of spring 2010. No sizable data gaps exist downstream of the Narrows- all islands, backwaters, and side channels mapped. A report explaining the data collection and map production procedures is available from the RMT.

In summary, a high-quality, high-resolution topographic map exists for the LYR in its present configuration. The map is suitable for a wide range of hydraulic, sediment transport, geomorphic, and habitat analyses. The sequence of topographic maps from 1999 to 2009 enables analysis of channel change.

#### *B4. Sedimentology and Substrate*

The LYR is largely alluvial and has a loose sedimentary river bed. Surficial sediment composition and structure influence sediment transport and site selection by organisms for different life stages.

Beak Consultants, Inc (1989) stated that spawning gravels in the LYR are abundant and in excellent condition, especially from the Narrows Pool all the way down to the Marysville gaging station. There was no evidence of bed “armoring” in which the surface of the riverbed becomes covered with a nearly impenetrable layer of very coarse cobbles and small boulders. The absence of armoring is evidence of geomorphic maintenance of morphological units and their substrates, which implies dynamic channel changes.

Beak Consultants, Inc (1989) used a visual classification system to characterize LYR substrates at 31 transects with at least 20 points to represent the proportional occurrence of habitat types in each reach.

The U.S. Fish and Wildlife Service Instream Flow Branch performed substrate mapping of 18 study sites (9 salmonid spawning and 9 salmonid rearing sites). At each site, cross-section based visual classification of surface substrates was done. In addition, a faster approach was tested in which surface substrates were visually mapped onto map sheets for areas rather than along cross-sections. Comparison of the two methods found that the facies maps worked equally well as the cross-section approach. No pebble counts.

USACE (1997) reported gravel and cobble particle size distributions for the LYR based on Wolman Pebble Counts performed by Ayres and Associates.

Hunerlach et al. (2004) characterized sediment particle size distributions in sediments trapped behind Daguerre Point Dam. Sand/gravel fraction samples were separated into 10 size fractions using screens with the following sieve sizes: 75, 50, 25, 4.75, 2.36, 1.18, 0.60, 0.30, 0.15 and 0.075 mm. Sandy, silty, and clay-silt fraction samples were conventionally sieved in the 0.063-2 mm range and then all particles <0.063 mm were assayed using a SediGraph 5100 particle-size analyzer with 14 size fractions ranging from 0.00025-0.063.

MEI (2008) performed two Wolman pebble counts of active bar surface sediments in the vicinity of the point of the Brown's Valley diversion intake (one upstream and one downstream of it. The median sizes were 23-28 mm.

Pasternack (2008) and Moir and Pasternack (2010) reported diverse pebble count data for Timbuctoo Bend and the Englebright Dam Reach. In 2004-2006 pebble counts were made on different morphological units at the Timbuctoo Bend Apex Riffle. For this 2004 set of pebble counts at the TBAR site, the median particle size was 62.1 mm. Pebble counts were also done relative to different Chinook salmon spawning periods, including pre-spawning fresh bed conditions, red tailspills, and post-spawning altered beds. The median grain size of fish-mobilized sediment varied from 29.2-79.9 mm (mean = 49.2 mm).

In 2007a longitudinal survey of bed material grain size distributions was done along the edge of the channel adjacent to each riffle crest and pool through Timbuctoo Bend. For the EDR, so little alluvial sediment is present that pebble counts were done wherever possible. Fulton (2008) reported a comparison of substrate conditions between Timbuctoo Bend and the EDR. The EDR did not have any river-rounded gravels and cobbles.

USACE (2007) described the plans for a pilot gravel injection of 500 short tons (361 yds<sup>3</sup>) of gravel and cobble into the Narrows 2 pool to rectify the lack of suitable substrate for spring-run Chinook spawning. The injection took place on November 29, 2007. A residual of 34 yds<sup>3</sup> was left mixed into the aggregate in the parking area and hillside, with the remaining 327 yds<sup>3</sup> being placed into the river.

Pasternack (2009) conducted two reconnaissance trips through the EDR in spring and summer 2009 to photographically document the substrates in that reach. No pre-existing river-rounded gravels or cobbles were observed. Accumulations of small angular rocks were pinpointed and photographed. The gravel injected in 2007 was present. Sediment-budget analysis reveals that 252 yds<sup>3</sup> was still in the Narrows 2 pool. The other 75 yds<sup>3</sup> had moved a short distance downstream. Nothing had moved past the Narrows 1 facility, presumably because its outflow jet perpendicular to the channel creates a significant hydraulic barrier to bedload transport.

In spring 2010 the RMT approved a protocol for mapping the substrate and cover for the entire LYR systematically. The approach uses a new visual classification system for substrate with size divisions that are much easier to consistently identify in practice, because they were determined by properties of the statistical distribution of particle sizes in a gravel-

bed river. Specifically, the mean bed material size for the river is ~60 mm, yet visual classifications often require users to differentiate sizes smaller or larger than 64 mm- right at the peak of the statistical distribution. Also, the new divisions are mindful of important limits on the sizes that different salmonids normally move during spawning. Prior to initiating the survey, field crews were tested twice on the method using 17 samples with various size mixtures of sediment taken from the LYR (and subsequently returned there). Test results showed that crew members performed well at identifying the presence or absence of size classes as well as determining the percent of material in each size class to the nearest 10%. As a result, beginning in July 2010, crews have been using real-time differential GPS units to field-map polygons of the surficial bed material down to polygon sizes >10 m<sup>2</sup>. The coverage is for the wetted area of ~5000 cfs, as predicted using the 2009 topographic map and the associated SRH models for the whole river.

Before Englebright Dam was built, the hydraulic mining deposits that filled the entire valley were composed of a mixture of all sizes of non-cohesive alluvial sediments. That mixture is still preserved in alluvial terraces on the hillsides that exist as remnant deposits and under the river bed. However, once those materials wash in to the river or are exhumed as the river incises down, silt and sand sized particles wash away, leaving local patches of gravel and cobble on the bed surface, with the exact size distribution tied to the hydraulics and landform shape of each morphological unit present. On the fall limb of floods, sand from terrace cutbanks and minor tributary inflows settles onto the gravel/cobble surface. On the floodplain, the surface is largely gravel and cobble as well, but riparian vegetation captures large piles of fine gravel and sand.

#### *B5. Vegetation*

Beak Consultants, Inc (1989) mapped riparian plant communities and urban development along the LYR from color aerial photographs (scale 1 in = 500 ft). The linear extent of these features along the river was determined by planimetry, and then qualitatively compared to historic vegetation maps (U.S. Army Corps Engineers 1976) to assess changes that may have occurred during the past decade. The plant communities along the river were found to be a combination of remnant Central Valley riparian forests, foothill oak/pine woodlands, agricultural grasslands, and orchards. Native riparian forest (mainly Fremont cottonwood, white alder and willow) was found to line the river channel. Gravel and sandbars were dominated by cottonwood where any vegetation was present at all. Blue oak/digger pine woodland occurred in the upper portion of the study area along the stream course. No meaningful comparison could be made between the vegetation mapping results of this study and those of the U.S. Army Corps of Engineers for the early 1970's due to differences in criteria used to distinguish community types.

Sawyer (2007) applied a methodology for characterizing the hydraulic roughness of willows on the banks of the LYR. She found that the best Manning's n value for use with willows is n=0.057.

The RMT is developing a vegetation map of the LYR downstream of the highway 20 bridge using the results of a LIDAR airborne mapping survey in autumn 2008. For the reaches

upstream of that, they will perform image classification on 2009 NAIP digital color imagery. Ground-based verification of the image classification is planned. These efforts are expected to be complete by December 2010.

Because much of the LYR floodplain is composed of coarse sediment, it does not have a topsoil that can hold nutrients and water sufficiently to sustain much vegetation. Willows line the present bankful channel and exist along lines on the floodplain at former channel bank locations that have been abandoned by channel dynamics. Cottonwoods and other riparian species are present around partially connected former channels that are presently “backwaters”. The hillsides are oak woodland.

#### *B6. Streamwood and boulders*

The RMT is planning to map the present distribution of streamwood and boulders stored in the river in July and August 2010.

#### *B7. Civil Engineering Structures*

Structures have been built into the LYR to serve several societal purposes in and around the river. These structures can impact channel form and flows.

##### *B7a. Levees and Training Berms*

James et al. (2009) provided historical analysis of levees and their impacts in the LYR.

##### *B7b. Bridges*

The Highway 20 bridge is the only bridge over the LYR upstream of Marysville. It is high above the water, but it does have piers into the river bed. Four bridges exist in Marysville at Simpson Lane, A Street, Route 70 (E Street), and a railroad line.

##### *B7c. Dams*

Gilbert (1917) description of “Barrier no. 1” a short distance downstream of Parks Bar. This concrete dam was destroyed by a flood in March, 1907.

SWRI (2003) presented an overview of the history and 2003 status of biological conditions in the LYR as part of a biological assessment of a proposed flow bypass structure being built at Englebright Dam.

Pasternack et al. (2010) reported on the relative roles of Englebright Dam and instream gold mining in influencing current conditions in the EDR.

By design, dams in the Yuba watershed capture a lot of the flow that comes during spring snowmelt, help attenuate winter flood peaks, and trap sediment that would otherwise fill lowland river valleys. Most also block fish passage. Flow releases from NBB provide cold water that helps support anadromous salmonid freshwater life stages.

#### B7d. Diversions

Beak Consultants, Inc (1989) described existing and proposed water rights and diversions.

DWR and USACE (2003) described diversions and how much overall is removed at Daguerre Point Dam.

SWRI (2003) describes diversions in the Yuba watershed.

YCWA (2007) provides extensive description and modeling of diversions from the LYR.

### C. Hydrogeomorphic Dynamics

Water and sediment transport drive landform change on the LYR. Direct observation of these changes is difficult and expensive, especially in a large gravel-bed river. During the 20<sup>th</sup> century significant changes and improvements to the understanding of coordinate systems and datums make comparisons of topographic surveys from different eras highly uncertain. Determining the underlying causes of observed changes requires computer simulation of individual events.

#### *C1. Channel and Floodplain Hydraulic Models*

Several different hydrodynamic models have been used to study LYR hydraulics. The *ID analytical method* involves predicting open channel processes at cross-sections by coupling some combination of a mass-conservation equation, empirical hydraulic-geometry equations, empirical flow-resistance equation, and an empirical or semi-empirical sediment-transport equation. An example computer program that has been used on the LYR for implementing this scheme is *WinXSPRO*. A similar analytical routine is incorporated as one of several hydraulic estimation approaches in *PHABSIM*, but this has not been used on the LYR.

A variant of the analytical method is based on the geomorphic concept of “hydraulic geometry” relations and is known as IFG4. This method involves observing stage for each transect and velocity at each point along a transect at 1-3 discharges (preferably with three corresponding to high, middle, and low flows) (there is also a no-velocity observation approach for unwardable areas). Next, the least-squares regression fit is computed for the logarithm of stage against that of discharge for each transect. Similarly, the least-squares regression fit is computed for log-velocity against log-discharge for each point (aka “vertical”) along each transect. These regressions are then used to interpolate stages and velocities at the points for unobserved discharges.



Numerical approaches to hydraulic estimation employ computers to approximate solutions of 1D, 2D, or 3D equations of motion where the solution procedures are dependant on adjacent nodes or cross-sections. 1D numerical models use a standard step method to iteratively solve the energy equation for steady gradually varied flow from one cross section to the next to calculate water surface profiles. An example computer program that has been used on the LYR for implementing this scheme is HEC-RAS. This model is freely available from the U.S. Army Corps. of Engineers, but it is also incorporated in to several commercial packages. It is a widely used gold standard for 1D numerical modeling in the U.S. PHABSIM also incorporates a 1D numerical modeling scheme.

2D (depth-averaged) numerical models solve vertically integrated conservation of momentum and mass equations using a finite element, finite difference, or finite volume computation method to acquire local water depth and depth-averaged 2D velocity vectors at each node in a computational mesh. These models further add the ability to consider full lateral and longitudinal variability down to the sub-meter scale, including effects of alternate bars, transverse bars, islands, and boulder complexes, but require highly detailed topographic maps of channels and floodplains. 2D models are more realistically linked to flow, sediment transport, and biological variables measured in the field at the same spatial scale. 2D models have been used to study a variety of hydrogeomorphic processes and they are used in regulated river rehabilitation emphasizing spawning habitat rehabilitation by gravel placement. Four different 2D numerical models have been used on the LYR, including FLO-2D, RIVER2D, FESWMS, and SRH-2D. FLO-2D is a high-end commercial package commonly used for floodplain flood assessment. RIVER2D is a free suite of programs used heavily by fisheries biologists to evaluate physical aquatic habitat. FESWMS is a free model produced by the Federal Highway Administration to look at local hydraulics around structures, but it has also been used to study hydrogeomorphic processes and physical aquatic habitat. SRH-2D is a relatively new model that spans many of the capabilities of FLO-2D, RIVER2D, and FESWMS and is more computationally efficient and numerically stable, so it can be used to simulate long river segments in very high resolution.

Associated with each modeling study is a suite of direct observations of depths, water surface elevations, and velocities in the LYR. These observations are compared to model results to characterize the level of uncertainty in the models.

#### Cla. IFG4 Hydraulic Estimation

Beak Consultants, Inc (1989) used the IFG4 method to characterize the hydraulics of the LYR. They designated 31 transects with at least 20 points to represent the proportional occurrence of habitat types in each reach. At each wadable point, depth, velocity, and substrate was observed. Depth measurements were made with a top-setting wading rod and velocities made with various point-scale current meters. Substrates were assessed based on a visual classification system. The one-velocity and no-velocity approaches to calibrating IFG4 was used.

#### C1b. Numerical LYR Models For Flood Management Studies.

USACE (2002) made HEC-RAS and FLO-2D hydraulic models of the channel and floodplain with coarse 400'x400' cells (i.e. 400' internodal spacing) for use in studying terrestrial flooding during large floods. HEC-RAS was run first to get the boundary conditions necessary to drive FLO-2D. FLO-2D was then used to assess how water gets onto and off the Yuba Goldfields.

#### C1c. RIVER2D Models Of 18 Sites On The LYR.

The U.S. Fish and Wildlife Service Instream Flow Branch (Gard, 2007, 2008) performed 2D hydraulic modeling of 18 sites for flows of 400-4500 cfs (the full range of controllable flows). Ten sites were riffles thought to be preferred for spawning, and these were assessed for physical microhabitat for spawning and rearing life stages. Eight sites were in other mesohabitats and were only assessed for rearing life stages. Modeled velocities were compared to observed velocities. Model results were not analyzed to evaluate hydraulic and geomorphic processes, but could be used for that purpose.

#### C1d. FESWMS Model Of Two Sites On The LYR

Professor Greg Pasternack from UC Davis was sponsored by the U.S. Fish and Wildlife Service to perform 2D hydrodynamic modeling of two different sites on the LYR over a range of discharges with FESWMS. FESWMS was implemented within the Surface Water Modeling System (SMS) 8.1 graphical user interface. One site was the Timbuctoo Bend Apex Riffle (TBAR) whose topography was independently mapped in 2004 and 2005 (before and after the May 2005 flood peak of 42930 cfs). The 2004 TBAR topography was modeled at flows of 400, 622, 827, 1200, 135, 1800, 2250, 2700, 4500, 5620, 11600, and 42930 cfs. The reason these uneven integer values were modeled (which also holds for the subsequent uneven integer values described below) was due to the availability of actual observations of downstream water surface elevations to drive the models at these flows rather than relying on a 1D numerical model or 1D analytical approach to estimate exit conditions, as was done by USACE (2002). A different computational mesh was made for each discharge and the meshes all had an intermodal spacing of ~1 m. For the 2005 TBAR topography, discharges of 650, 747, 855, 1101, 1223, 3347, 9547, 23140, 35260, and 109090 cfs were simulated, facilitated by the New Years 2006 flood. Again, a different computational mesh was made for each discharge and the meshes all had an intermodal spacing of ~1 m. Validation of these models consisted of comparing model predictions against observations of water surface elevations made by surveying, water depths made with a top-setting wading rod, and velocities made with a Marsh-McBirney current meter.

The other site that FESWMS was used to model was the Englebright Dam Site (EDS) in the narrow canyon just below Englebright Dam. This site included the Narrows II Pool just downstream of Englebright Dam, a run, and then another pool upstream of Narrows I. This site was mapped in 2005 and FESWMS was used to model discharges of 800, 1190, 8809, 9580, 25100, 31800, and 91400 cfs.

#### C1e. RMA2 Modeling Of The LYR at the Brown's Valley Diversion

MEI (2008) used topographic data collected in 2006 to run an RMA2 hydrodynamic simulation of the LYR in the vicinity of the Brown's Valley diversion to evaluate the effects of the preferred fish screen design (Alternative 2-C). RMA2 is similar to FESWMS, but it cannot handle supercritical flows, which is why it was not used for other studies in the EDR or Timbuctoo Bend. Both models may be implemented within the Surface Water Modeling System (SMS) 8.1 graphical user interface. RMA2 models were run for both the baseline channel conditions and for the preferred fish screen design. The flows that were simulated with the 100- and 200-year flood events. Results were used to analyze hydraulic conditions, incipient motion, and bank stability for these very large floods.

#### C1f. SRH-2D Modeling Of The Entire LYR

With the recent availability of the highly efficient SRH-2D numerical model, the capability now exists to simulate the entire LYR with 1 m intermodal spacing. The primary limitation in model accuracy is topographic modeling and the degree to which the river's slope is in the acceptable range of the assumption of horizontal flow, which is embedded in all 2D models. Greg Pasternack ran a pilot test of SRH-2D in 2008 by re-modeling the TBAR 2004 site at 827 cfs and intercomparing FESWMS and SRH-2D. The results between the two models were very similar, except that SRH-2D slightly underpredicts the highest velocities on steep riffle crests at very low flows. This effect was not concluded to not be a concern.

Pasternack (2008) used SRH-2D to simulate flows of 855 and 1600 cfs in the EDR with ~1-m intermodal spacing, which is the reach from the Narrows II pool down to the junction with Deer Creek.

Pasternack (2008) used SRH-2D to simulate flows of 750, 930, 1669, 2986, 4303, and 5620 cfs for the Timbuctoo Bend Reach (Narrows Pool to Highway 20 bridge) with 1-m intermodal spacing in the bankful channel.

In spring 2010, the RMT prepared computational meshes for the entire LYR downstream of the highway 20 bridge to go with the pre-existing ones for upstream of the bridge. The model reaches now include the EDR, Timbuctoo Bend, the Hammon Reach (Highway 20 bridge to DPD), the Daguerre reach (DPD to USGS Marysville gaging station), and the Feather Reach (USGS gaging station to confluence with the Feather River). SRH-2D models of each reach and at different flows may be run concurrently on a single computer with multiple processor cores or across different computers.

Extensive observational data was collected 2008-2010 to test the SRH models of the LYR. During topographic and bathymetric surveying in 2008 and 2009 many water surface elevation points were surveyed at the flows present during the mapping efforts, which varied widely. In addition, an effort is being made to use the 2008 LIDAR points collected on the water surface to create a continuous water surface elevation map for the flow on the day of that flight, which could be compared against a model of the same flow. Given this large

amount of water surface elevation data, a smaller dataset of water depths was collected at cross-sections in December 2009. During December 2009 to August 2010, the RMT collected ~6000 observations of velocity between Hammon Grove Park and Hallwood Road—the area over which an RTK GPS base station could broadcast positional corrections from a benchmark located on DPD.

In summer 2010, 1-m resolution SRH models of the LYR were run at the discharges for which observational data was available to test the models. These flows range from 500 cfs to 5000 cfs. A detailed presentation showing the results of model validation is available from the RMT.

In autumn 2010 a suite of flows between 500-5000 cfs will be simulated using SRH to evaluate flow-habitat relations for the whole LYR systematically.

Overall, the LYR has been extensively modeled to determine depths and velocities. Models have provided information about floods, sediment incipient motion, geomorphic change, and fish habitat. The river changes every 5-10 years, so models must be updated to remain relevant. The new 1-m resolution SRH models of the entire LYR represent the most complete and advanced effort at river modeling in the Central Valley of California.

## *C2. Morphological Units*

A *morphological unit* is a discernible landform in the river valley that is typically visible at the spatial scale 1-10 channel widths. Landform pattern is reflected in hydraulic pattern and thus may be delineated with the aid of hydraulic information, but it is independent of hydraulics. Also, the shapes of morphological units are changed by flow over time.

Beak Consultants, Inc (1989) performed visual morphological unit classification for each 100' section of the LYR in October 1986 when the discharge was ~600 cfs above Daguerre Point Dam and ~300 cfs below it. The unit types that were used were low-gradient riffle, moderate-gradient riffle, run/glide, shallow pool, and deep pool. The percentage of river channel composed of each type in each reach was enumerated.

Moir and Pasternack (2008) defined 10 in-channel morphological units (forced pool, pool, chute, run, riffle entrance, riffle, glide, recirculation zone, backwater, and secondary channel) and used expert-based mapping to delineate their pattern at the TBAR site in 2004. They then used the 2004 TBAR FESWMS model results for 827 cfs to characterize water depth, velocity, and Froude number for each unit.

Pasternack (2008) defined an additional 10 morphological units to cover the terrestrial river corridor (lateral bar, point bar, medial bar, floodplain, tertiary channel, tributary delta, cutbank, terrace, tailings, hillside).

Pasternack (2008) used the 2006 Timbuctoo Bend Reach topographic map, a water depth map based on the intersection of aerial imagery and the topographic map, and expert-based

assessment of velocity pattern to delineate the morphological units in the entire river corridor in this reach. Physical attributes for each unit were calculated for units in Timbuctoo Bend, such as area, percent of total area, mean and standard deviation of water depth at specific flows, volumetric channel change 1999-2006, and average rate of downcutting 1999-2006.

The Yuba Accord RMT has a protocol in place based on Pasternack (2008) to create a morphological unit map for whole LYR facilitated by the SRH-2D model results. The map is likely to be done in autumn 2010 or winter 2001.

### *C3. Channel Change*

Pristine rivers experience channel change due to a variety of causal factors related to inputs and boundary conditions. Change is a normal and important aspect of the role of physical processes in providing ecosystem services. However, pristine rivers also show resiliency in providing ecosystem services in the face of natural processes that cause channel change. Often, human impacts that cause channel change break a river's natural resiliency, causing sustained impairment. By knowing the types and rates of natural channel change in a system as well as the underlying mechanisms of change and resiliency, one can determine whether a particular human impact is abnormally ecologically harmful.

#### C3a. Historic Channel Response To Historic Hydraulic Mining Sediment

Gilbert (1917) described sedimentation and sediment transport right after hydraulic mining stopped. Channel change was frequent and dramatic between 1898-1912.

Beak Consultants, Inc (1989) stated that it appears that the recovery from the influx of hydraulic mining debris (incision and accompanying stabilization) was largely complete by about 1950 on the basis of the interpretation that the channel had mostly changed its planform from a braided river to a single-threaded meandering river by that date. Limited specific quantitative evidence was available for this study.

James et al. (2009) discussed historic conditions and stated that, "The high sediment loads overwhelmed the transport capacity of valley channels and caused major geomorphic adjustments such as channel aggradation and avulsions."

USACE (1997) analyzed changes to the river's longitudinal profile between 1899, 1906, 1912, 1929, 1957, and 1992. The river was found to be incising rapidly after hydraulic gold mining was stopped and dams were built.

For over 100 years, the LYR has been a highly dynamic, wandering gravel-bed river. This was not its pre-settlement classification, but it is the template of what was present prior to dam construction. Since dam construction, sediment supply has been reduced, while geomorphically significant floods have continued. This enabled incision into historic deposits under the riverbed.

### C3b. Modern Channel Response After Flow Regulation (Post-1972).

Beak Consultants, Inc (1989) stated that channel change between 1973-1986 consisted of normal lateral migration. Their interpretation is that the river is stable in the sense required to justify application of the IFIM approach for determining flow-habitat relations. Specifically, they suggest that changes to the river would not change the statistical distribution of morphological units and would not impact flow-habitat relations. Limited specific quantitative evidence was available for this study.

Sawyer et al. (2010) used the 827, 5620, 11600, and 42930 cfs FWSWMS model results for the TBAR site to characterize hydraulic processes responsible for observed geomorphic changes through the May 2005 flood. The key finding is that flow convergence routing driven by the phasing of coherent bed and valley-width undulations is effectively causing geomorphic maintenance of morphologic units at different discharges at the TBAR site.

White (2008) and White et al. (in press) studied planform channel change and riffle-pool locations/persistence in Timbuctoo Bend for 1937-2006 based on historical aerial imagery and the 1999 and 2006 topographic maps. They found that significant planform channel change does occur in Timbuctoo Bend, contradicting the assumption/conclusion of Beak Consultants, Inc (1989). Further, the peak flood discharge between two aerial photo sets explained 65% of the area of planform channel change over the same time interval. They also found that valley width oscillations explained the locations of persistent riffles and pools in the reach.

Fulton (2008) used the 2005 TBAR model results to evaluate hydraulic processes responsible for observed geomorphic changes from 2005 to 2006 as a result of the New Years 2006 flood. The site underwent dramatic change as a result of this large flood.

Pasternack (2008) reported digital elevation model differencing between the 2006 and 1999 topographic maps of Timbuctoo Bend. This analysis yielded the spatial pattern of topographic change in ~1-m resolution and the net total export of sediment out of the reach. Roughly 600,000 yds<sup>3</sup> of sediment left Timbuctoo Bend in the 7-year period. That amount of change contradicts the contention of Beaks Consultants, Inc. (1989) that the river is stable. It is unknown yet where all that material went downstream. Also, the estimated vertical channel change and volumetric change were stratified by morphological unit. Each unit exhibited a different rate of change, which means that the statistical distribution of unit types cannot have remained constant, again contradicting Beaks Consultants, Inc. (1989).

Pasternack (2008) studied the mechanism of erosion of riffle crests and discovered that during low flows the riffles behave as upstream-migrating knickpoints. Using an anchored raft, the group positioned themselves in the convergent zone of riffles and measured velocities at the surface, mid-depth, and near the bed. Also, for one wadable riffle they directly measured lift and drag on grains at the bed using a special 6-component force/moment sensor. These measurements indicated that the hydraulic forces were sufficient to scour the bed at flows of ~800-1200 cfs. They also made repeat topographic

surveys of the riffles and confirmed that during the time of low flows the bed actually did change in a way that matched the flow configuration. Thus, during low flows water is focused or converged onto riffle crests causing them to erode and behave as knickpoints. The study by Sawyer et al. (2010) showed that during large floods the relief between riffles and pools is rejuvenated, which renews the cycle of riffle erosion for the next low-flow period.

RMT has data needed to assess perform DEM differencing 1999-2009 for the entire LYR, but has not implemented a study on it yet.

The LYR continues to be a highly dynamic wandering gravel-bed river. Damming did not alter the classification of the river as quickly as generally understood for regulated rivers, because so much sediment is stored in the river valley and because floods still occur on a regular interval. Anecdotally, reports suggest that the river has narrowed, incised, and slowly transitioned from braided to meandering as a result of the reduction in bankful flow and lack of upstream sediment supply. In Timbuctoo Bend the river is incising on the floodplain as well as the riverbed, suggesting that dynamics are not constrained by an overgrowth of bank vegetation or disconnection between channel and floodplain. The mechanism of river incision observed in Timbuctoo Bend involves a two-step process: 1) knickpoint-based riffle scour during low flows and 2) pool scour during high flows. This mechanism is facilitated by undulating valley walls and riffle-island formations in the widest valley cross-sections. Even though the river is still incising, it is sustaining an ecologically useful pattern of riffles, pools, and other morphological units.

#### *C4. Sediment Budgets*

A sediment budget is an accounting of all the fluxes of sediment in and out of an area as well as how much is stored within it. Sediment budgets are used to determine whether there is a steady state balance of movement in and out of a system or whether rivers are aggrading or incising.

##### *C4a. Sediment Budgets By Landform Analysis*

Gilbert (1917) described topographic changes and estimated sediment fluxes.

Pasternack (2008) created a sediment budget for Timbuctoo Bend by performing digital elevation model differencing between maps from 1999 and 2006. The sediment budget was also partitioned by morphological unit type.

RMT has data needed to assess changes in sediment storage 1999-2006, but has not implemented analysis yet.

##### *C4b. Sediment Budgets By Sediment Load Observation*

USACE (1997) presented a limited amount of suspended sediment load data based on observations at the Maryville gaging station.

### *C5. Sediment Transport and Incipient Motion*

A common metric used to understand the link between channel dynamism and fish habitat is the discharge associated with “incipient motion”, the condition under which sediment transport is just beginning. However, the idea of a single discharge of incipient motion has always been controversial and may not be useful for a dynamic river like the LYR. This question has been studied carefully on the LYR to find out, and the effort is on-going.

#### *C5a. Hydraulic Modeling of Shear Stress and Inference of Sediment Transport Regime*

One approach to evaluating the conditions at the moment of incipient motion is to perform hydraulic modeling to obtain depths and velocities, and then calculate the bed shear stress from those model outputs using one of several formulas. For any grain size, the Shields’ criterion for incipient motion may be used to calculate the critical shear stress above which observable transport begins. The method assumes a bed of non-cohesive, homogeneously sized particles. More recently, a new approach has been developed for non-cohesive, mixed-size beds that involves calculating a non-dimensional shear stress variable called “Shields stress” ( $\tau^*$ ) and then characterizing the overall sediment transport regime based on the transport mechanics for established ranges of Shields stress values. The classification is as follows:  $\tau^* < 0.01$  is no transport;  $0.01 < \tau^* < 0.03$  is intermittent entrainment;  $0.03 < \tau^* < 0.06$  is a range of a process known as “partial transport” in which any overabundance of finer particles is removed off the bed tending toward an equilibrium size-distribution for the mixture;  $0.06 < \tau^* < 0.10$  is full transport; and  $\tau^* > 0.10$  is likely a channel-altering condition.

USACE (1997) performed HEC-6 modeling of 100-y, 200-, and 400-year flood hydrographs to assess sediment transport capacity for those extreme events.

DWR and USACE (2003) analyzed the incipient motion conditions for flows of 4,000, 40,000, 65,000, 121, 000, and 161, 000 cfs using HEC-RAS hydraulic output and a sediment transport tool known as the Shields Diagram that relates. For each flow they determined the maximum particle size moved by the flow. This approach assumes that the entire mixture of sediment is this size and does not account for the effects of a heterogeneous bed.

Sawyer et al. (2010) and Pasternack (2008) used FESWMS 2D models of the Timbuctoo Bend Apex Riffle to evaluate the presence of flow convergence routing and the Shields stress transport regimes for the discharges modeled. They found that each morphological unit experienced the “full transport” ( $\tau^* > 0.06$ ) sediment transport regime over a unique range of flows. Thus, a single incipient motion threshold for the river is not appropriate as a metric for evaluating LYR sediment transport conditions and fluvial geomorphology. Fulton (2008) extended the flow range of the analysis to  $>109,000$  cfs.

Fulton (2008) used the FESWMS 2D model of the EDS in the EDR to evaluate the presence of flow convergence routing and the Shields stress transport regimes for the discharges modeled. As a test metric, more than 10% of the wetted area would have to be in full



transport in order for the EDS to be considered “unstable” at that flow. Based on this metric, a flow of 25,100 cfs would be required to mobilize gravel and cobble at the bottom of the Narrows 2 pool. When gravel is loosely piled much higher than the pre-existing bed level, the discharge required to move it would be lower, but no such scenario was investigated. Transport in the constricted channel downstream of the pool was predicted to begin at a lower discharge of 9,570 cfs. The model results for flows 800-91,400 cfs showed the absence of flow convergence routing. That means that present high points (nominally “riffles”) in the riverbed in the EDS are also narrow. As a result, any gravel added to the river over these riffles will wash away preferentially. Any gravel added into pools would be the most difficult to wash away.

#### C5b. Bedload Tracer Studies

Since a large fraction of bed material in the LYR is gravel and cobble sizes, it tends to roll and hop along the bed as “bedload”. Bedload is very difficult to measure directly. The standardized approach of lowering a Helley-Smith sampler down from a bridge, cableway, or boat-based platform and sampling for 2-minute intervals is notorious for its inability to capture the correct relation between bedload rate and flow rate. Few suitable locations exist on the LYR to perform such measurements anyway, given the lack of bridges and the large width off the river. An alternate approach is to place painted and/or magnetized “tracer” stones into the riverbed and then track their movements after each event. In 2003-2004 Dr. Hamish Moir and Prof. Greg Pasternack painted 28,439 stone tracers (8-64 mm in diameter) sourced from the LYR using 22 color combinations. Each set of stones with a unique color combination was cored deep into the bed at diverse sites in the Timbuctoo Bend Apex Riffle using a MacNeil Corer. Velocity profiles were conducted over the cores at 1-3 different discharges. Periodically through 2004 the tracer piles were examined for loss of tracers and efforts were made to locate tracers downstream and survey their locations with a robotic total station. Overall, flows were low in 2004 and little movement occurred. Monitoring continued until it was halted as a result of the May 2005 flood event that appeared to obliterate the tracer cores in that none of them could be subsequently found at the bed surface. However, later excavation at the specific locations the tracer cores determined that some had been entirely scoured away, while others had been covered over by deposited sediment. Generally, cores were entirely scoured away on the south side of the study site and covered over on the north side.

In November 2005, Moir and Pasternack placed 4 rows of painted, numbered tracer stones (366 stones total) with powerful imbedded neodymium magnets in them across the LYR at the Timbuctoo Bend Apex Riffle site. The tracers ranged in size class from 22.6 – 32 mm to 128 – 256 mm and in mass from 0.04 to 4.22 kg. A month later there was the enormous New Years 2006 flood that yielded a major reconfiguration to the river. When the flows finally receded enough in the summer to look for stones, 3 were found very close to the original locations and all the rest were gone with no hope of finding them down the next 20 miles of riverbed and floodplains.

As an alternate approach, in 2004 Moir and Pasternack also installed Bunte bedload traps along the flanks of the run just downstream of the Timbuctoo Bend Apex Riffle. These are short but

hefty rectangular metal tubes with wide openings and nets trailing behind to capture bedload. They require emptying periodically during sediment transport events, but they are highly effective at capturing the bedload rate as a function of discharge. Also, they were designed to be used in small streams where samplers may be operated from boardwalks over the channel. Unfortunately, no small transport events occurred in 2004 to yield data and the traps were removed. Had the traps been left in place they would have been wiped out by the May 2005 flood anyway.

Pasternack (2009) reported on the 2007-2009 bedload migration of 500 tons of distinct, rounded river gravel and cobble injected into the Narrows II Pool in November 2007. In the absence of significant flows over Englebright Dam during this initial study period, only a small fraction of that material has migrated so far and that has been for just a short distance downstream. Notably, that 50-ton sediment pile is laced with 361 painted, numbered tracer stones with imbedded neodymium magnets imbedded in them that may be trackable through the EDR.

The overall finding from these efforts is that direct observation of bedload transport on the LYR downstream of the Narrows Pool is extremely difficult to achieve. The river is so dynamic and sediment influx so small that it is far more effective to estimate sediment outflux and redistribution by detailed re-mapping of the river bed and applying DEM differencing.

## **D. Physical Habitat and Ecological Dynamics**

### *D1. Microhabitat Analyses*

The term “microhabitat” is defined as the localized depth, velocity, temperature, and substrate at a point in a river without regard to surrounding conditions

The U.S. Fish and Wildlife Service Instream Flow Branch (Gard, 2007, 2008) sought to establish flow-microhabitat relationships on the basis of 2D hydraulic modeling of 18 sites for flows of 400-4500 cfs (the full range of controllable flows). Ten sites were riffles thought to be preferred for spawning, and these were assessed for physical microhabitat for spawning and rearing life stages. Eight sites were in other mesohabitats and were only assessed for rearing life stages. Habitat suitability curves for depth, substrate, and velocity based on logistic regressions were developed for spawning, fry, and juvenile life stages, using modeled velocities and depths to represent “available” conditions. Other curves were also evaluated. Comparisons of observed habitat occurrence/utilization against model predictions of habitat presence/absence did not “bioverify” and the study results were thus inconclusive.

Pasternack (2008) used the 2004 and 2005 FESWMS 2D model results for the TBAR site along with observations of salmon spawning and redds to perform bioverification of utilization-based habitat suitability curves for fall-run Chinook salmon spawning from the lower Mokelumne River. Although the curves were from a different river in the Central Valley, they passed strict tests for predicting both presence and absence of observed spawning. Notably, no substrate suitability criterion was used.

Fulton (2008) used the 2005 FESWMS 2D model results for the TBAR site to evaluate fall-run Chinook spawning microhabitat conditions over a wide range of discharges. He also analyzed the hydraulic processes responsible for observed geomorphic changes 2005 to 2006.

Fulton (2008) used the FESWMS 2D model results for the EDS site in the EDR to evaluate fall-run Chinook spawning microhabitat conditions over a wide range of discharges. Only 3% of the area in the EDS had suitable hydraulics for Chinook spawning at flows  $\geq 800$  cfs. This is in contrast to 30% of the area in the Timbuctoo Bend Apex Riffle site. The little area with suitable hydraulics was composed of narrow patches flanking the channel and had no suitable spawning substrate. Also, no redds were observed at the EDS in 15 site visits over 2 spawning seasons.

Moir and Pasternack (2010) investigated the microhabitat interdependence of depth, velocity, and substrate size related to Chinook salmon spawning. The goal was to determine whether the preference of Chinook to use a single variable was limited to an “inelastic” range not conditioned by the values of the other variables. By comparing available and utilized hydraulics and substrates, it was possible to determine that in fact Chinook preference is very elastic. For example, fish chose to spawn in significantly coarser substrates when the ambient velocity was high enough to aid the fish in moving the material and chose fine substrates when the velocity was low.

Although the issue of what constitutes the best type of habitat suitability curves for the LYR is still under scrutiny, the results of the above studies show that it is possible to predict the spatial patterns of presence and absence of salmon spawning microhabitat to match observed patterns of actual redd locations. By lumping habitat quality types into broad categories, a lot of the uncertainty in 2D model predictions of local depth and velocity is eliminated. The availability of a whole-river 2D model based on SRH-2D now enables a comprehensive census of the flow-microhabitat relationship for the LYR.

## *D2. Mesohabitat Analyses*

Although it is often possible to empirically relate ecological function to microhabitat variables, doing so provides a limited understanding of how and why fluvial-ecological linkages are spatially related. The term “mesohabitat” is defined as the interdependent set of the same physical variables over a discernible landform known as a morphological unit. Three mesohabitat studies have been performed on the LYR, and of those two nest the microscale requirements of instream species within the mesoscale context of an assemblage of morphological units. Those studies found that linking the mesoscale of morphological units to microhabitat characteristics, did help explain fluvial-ecological linkages better.

U.S. Fish and Wildlife Service instream Flow Branch used an existing CDFG mapping scheme to field-map the mesohabitats for the LYR as it was prior to the 2005 and 2006 floods (Gard, 2008). The mesohabitats were not analyzed in and of themselves but were

instead used to facilitate sampling of juvenile salmonids on a equal effort basis for each mesohabitat type.

Moir and Pasternack (2008) used expert-based judgment and geomorphic concepts to map the morphological units at the Timbuctoo Bend Apex Riffle. Then they used the 827 cfs FESWMS 2D model results to quantify the microhabitat hydraulics of the morphological units. These results were lumped to the mesohabitat scale and integrated with observations of salmon spawning in 2004-2005 to delineate preferred mesohabitats and characterize their hydraulics. Analysis of the spatial pattern of flow was used to explain the structure of the mesohabitats.

Pasternack integrated the 2006 Timbuctoo Bend morphological unit map with mapped water depths and redd observations for fall 2006 to yield availability adjusted preferences for specific mesohabitats (i.e. forage ratios).

The RMT has a protocol in place to create a morphological unit map for the entire LYR similar to the approach of Pasternack (2008). Mesohabitats at specific discharges will be assessed for different lifestages.

### *D3. Vegetation patch dynamics*

Beak Consultants, Inc (1989) compared their riparian map to anecdotal reports and pre-existing riparian studies. They reported that the amount of riparian vegetation has been increasing over the decades in response to flow regulation, but is still insufficient to support juvenile salmonids.

## **E. River Management Actions**

For over 100 years people have been tinkering with the LYR to cope with the impacts of hydraulic mining sediments, flow regulation, and the unforeseen impacts of previous interventions into river conditions.

Gilbert (1917) and James et al. (2009) presented information on some of the early historic activities.

Activity between 1930-1990 has not been reconstructed.

Most recently, the USACE performed a pilot gravel injection of 500 short tons of gravel and cobble into the Narrows II pool at the top of the EDR in November 2007. Pasternack (2009) reported on what happened to that material through summer 2009. In autumn 2009 the RMT mapped redds spawning on the injected sediment. Presently, plans are under consideration for several river rehabilitation projects throughout the LYR.

## **Conclusion**

The LYR has been thoroughly studied over the years. Information exists on all aspects of geomorphology and its linkages to hydrology, hydraulics, and ecology. Timbuctoo Bend is the most thoroughly studied reach. Its fluvial geomorphic dynamics and underlying hydraulic mechanisms have been worked out and described in a series of peer reviewed journal articles. The RMT is planning to complete a suite of additional geomorphic observations by mid-2012 that will answer the same questions for the rest of the river.

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