LOWER YUBA RIVER ACCORD MONITORING AND EVALUATION PROGRAM

LANDFORMS OF THE LOWER YUBA RIVER

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Prepared for: The Lower Yuba River Accord Planning Team

by

Josh Wyrick, PhD., and Greg Pasternack, PhD.
University of California, Davis

Foreword

The lower Yuba River Accord (Accord) consists of a Fisheries Agreement and several other elements. The Fisheries Agreement includes descriptions of the River Management Team (RMT), the River Management Fund (RMF), and the Monitoring and Evaluation Plan (M&E Plan). The Fisheries Agreement in its entirety can be found on the Accord RMT website (http://www.yubaaccordrmt.com).

The RMT Planning Group includes representatives of the California Department of Fish and Game (CDFG), National Marine Fisheries Service (NMFS), Pacific Gas and Electric (PG&E), U.S. Fish and Wildlife Service (USFWS), Yuba County Water Agency (YCWA), and one representative for the four non-government organizations (Friends of the River, South Yuba River Citizen's League, The Bay Institute, and Trout Unlimited) that are parties to the Fisheries Agreement. The RMT planning group has developed an M&E Plan to guide study efforts through the efficient expenditure of RMF funds.

Multiple studies were identified by the RMT to address the specific analytics that are necessary to evaluate the performance indicators detailed in the M&E Plan. The purpose of this report is to document findings for the performance indicators that are enumerated in the M&E Plan.

The research and results detailed in this report were funded through a research grant to the University of California at Davis by the Yuba County Water Agency (Research Agreement # 201016094).

Executive Summary

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. The Yuba Accord River Management Team has been conducting applied research to understand the fluvial geomorphology of the lower Yuba River (LYR) downstream of Englebright Dam. The first major component of this research program involved characterizing and then analyzing the landforms in the river corridor at three spatial scales: segment (~10^3-10^4 W), reach (~10^2-10^3 W), and morphologic unit (~1-10 W), where W is channel width. Nine specific research questions were posed at all scales related to landform types, abundance, spatial patterns, and hydraulic attributes.

The procedure used in morphologic analysis involved four phases: topographic mapping, 2D hydrodynamic modeling, classification of hydraulic and topographic patterns, and analysis of resulting landform types at all three scales. A combination of ground-based surveying, boat-based bathymetry, and airborne LiDAR was used to construct a river-corridor digital elevation model (DEM), excluding the inaccessible Narrows Reach. The freeware hydrodynamic modeling program SRH-2D v.2.1 (Yong Lai, U.S. Bureau of Reclamation, Denver, CO) was then used to model the spatial pattern of water surface elevation, depth, velocity, and other derivable variables for the entire mapped river at discharges ranging from very low flows (300 cfs) to valley-filling floods (110,400 cfs). Some relevant discharges for mapping fluvial landforms included a representative base flow (880 cfs above Daguerre Point Dam and 530 cfs below it), a representative bankfull flow recognizing that channel capacity actually varies down the river (5000 cfs), and representative floodplain-filling flow (21,100 cfs).

Natural rivers in temperate climates typically fill their bankfull channel once every 1.5-2 years, or once every 2-5 years for rivers in semi-arid climates. On the LYR, however, bankfull discharge is reached once every ~1.25 years, which means that there is ~82% chance every year that the river will overflow its bankfull channel. The floodplain-filling flow has a ~2.5 year return interval (40% annual exceedance probability).

At the segment scale, metrics were calculated within the 2D-model derived wetted boundaries of the three representative flows. The LYR study segment has a wetted area of 510 acres and average wetted width of 195 ft at baseflow conditions. At bankfull flow conditions, the wetted area and width increase to 829 acres and 319 ft, respectively, both increases of ~ 63%. During flood conditions, the wetted area increases to 1703 acres and the wetted width to 654 ft, both an increase of >100% as compared to the bankfull values. The segment is not entrenched, and therefore considered to have a well-developed floodplain.

At the reach scale, eight distinct reaches were delineated and characterized for the LYR. The key geomorphic indicators of reach breaks were presence of tributary confluences, presence of dams, valley width, riverbed slope breaks, and substrate. From upstream to downstream the reaches are named Englebright Dam, Narrows, Timbuctoo Bend, Parks Bar, Dry Creek, Daguerre Point Dam, Hallwood, and Marysville Reaches. Tributary junctions form the upstream boundary of two reaches (Narrows and Dry Creek) and dams bound two more reaches (Englebright and Daguerre Point Dam). The other reach boundaries are formed by hydro-geomorphic variables: onset of emergent floodplain gravel (Timbuctoo Bend); transition from confined bedrock valley to wider, meandering system (Parks Bar); and decreases in bed channel slope (Hallwood and Marysville). Flow-dependent statistics were also calculated at the reach scale on channel widths and wetted areas.

Other relevant metrics at the reach scale are entrenchment and floodplain connectivity. The Englebright and Timbuctoo Bend Reaches exhibit moderate entrenchment, while the other reaches are slightly entrenched (i.e., well-developed floodplain). The floodway wetted area ranges from ~ 2-5 times as wide as the baseflow wetted area at the reach scale. Further, the floodway wetted area represents between ~50-88% of the geomorphically-active valley width.

Using 2D model results, four suites of morphological unit (MU) types that are discretely bounded by inundation levels were delineated within the LYR segment. Applying numerical thresholds to the baseflow depth and velocity, eight in-channel bed MUs were automatically and objectively delineated: pool, run, chute, riffle, riffle transition, fast glide, slow glide, and slackwater. Outside the baseflow wetted area, other fluvio-geomorphic data, such as topography, DEM difference maps, and conveyance (i.e., depth times velocity) rasters, were used to help hand-delineate bankfull, floodway, and valley MU types. The wetted area between the baseflow and bankfull discharges bounds the in-channel lateral bar, medial bar, point bar, and swale units. The wetted area between bankfull and floodway bounds the floodplain, flood runner, island-floodplain and mining pit units. Terrace, high floodplain, island high floodplain, and levee units are only delineated outside of the floodway wetted area. In total, 31 MU types were delineated, with the others occasionally transcending between the inundation region boundaries.

Statistical abundances were calculated for each MU type across the relevant discharge regimes. At baseflow, the most abundant MU is slackwater at the segment scale, while pool, fast glide, and riffle transition dominated at the reach scale. At bankfull flow, the most abundant MU at the segment scale is lateral bar, with pool still dominating in the highly constricted upper and lower reaches. Within the floodway boundary, the floodplain is the most abundant segment-scale MU and within the mid-segment reaches, but pool is still the most abundant in the highly constricted upper and lower reaches. Outside of the floodway zone, terrace is the most abundant unit at the segment scale, as well as all of the reaches except for Englebright, where hillside/bedrock dominates. The inequality of abundances and absences among the MUs at all discharges is one indicator that channel morphology is non-random in its spatial structure.

To further explore the question of random organization among the MUs, the in-channel baseflow units were analyzed with respect to the longitudinal distribution of each unit and adjacency probabilities between sets of units. If the LYR is randomly organized, then it would exhibit a uniform longitudinal distribution for all units, with equal probabilities of being located adjacent to any other unit type. The results from our analyses show that the LYR is not randomly organized, i.e. units exhibit spatial ‘preference’ and ‘avoidance’ for locations along the longitudinal profile and with respect to being next to each other. At the segment scale, chutes and runs are more predominant in the upper reaches of the LYR. Pools are unequally distributed with the highest abundance between the upper and lower reaches and lower abundance in the middle reaches, except for the large scour pool downstream of Daguerre Point Dam. Riffles exhibit uniform probabilities through most of the reaches, except for Englebright and Marysville. Riffle transitions trend generally upwards in occurrence probability from the Englebright to the DPD Reach, peaking in the Hallwood Reach, and then drastically declining into the Marysville Reach. Slackwater and slow glide units, however, are distributed fairly uniform across the segment. Results from the adjacency analyses show that there is a strong organizational structure evident in the adjacency probabilities. A majority of the units exhibit higher than random adjacencies to slackwater and slow glide, likely due to their near-ubiquitous presence along the baseflow channel margins. Each unit exhibited a much higher than random adjacency value towards at least one other unit.

The spatial organization of the MUs was also analyzed with respect to the longitudinal spacing between like units and the lateral variability of units across the channel width. Classic research states that some morphological units, such as pools and riffles, tend to be spaced about 5-7 channel widths (W) downstream from each other. The key finding of this analysis is that none of the morphological units exhibit the traditional 5-7 W spacing at the segment scale, with spacing between in-channel units ranging from 2.7 – 4.4 W. Given the high resolution of the topographic map, long segment size, and objective delineation of MUs, it is not surprising that the results deviated from classic studies. Some of the units, however, do exhibit the classic spacing metric at the reach scale, such as bedrock/boulder riffles in Englebright Dam Reach (6.4W) and pools in Parks Bar Reach (5.3W). To determine whether the LYR exhibits significant lateral variability, the number of MUs at each cross-section were counted and compared. At the segment scale, the bankfull LYR exhibits an average of 8.8 MUs per cross-section. At the reach scale, the variability was normalized by the average reach width in order to remove the possibility that wide channel sections have more spatial availability for more MUs than narrow channel sections. At the normalized reach scale, the Englebright Dam and Marysville reaches exhibit the highest lateral complexity of about 12 MUs, while the Daguerre Point Dam reach exhibits the lowest complexity of about 7.5 MUs per cross-section. Overall, these results demonstrate that the LYR exhibits significant longitudinal and lateral landform heterogeneity.

In conclusion, the landforms of the LYR were mapped and quantified at the segment, reach, and morphological-unit scales. Starting from 2D hydrodynamic model outputs, it was possible to identify laterally varying, flow-independent “morphological units” that serve as the basic building blocks of geomorphic processes at multiple spatial scales. Discovery of laterally explicit morphological units and the geomorphic characterization of their specific spatial organization is a major scientific advance. The LYR exhibits diverse landforms within four inundation levels, with each unit type further exhibiting significant local heterogeneity. Analyses of the channel morphology show that the fluvial landforms in the study segment are spatially organized, not randomly located. Thus, although the river has incised throughout the 20th century, the flow and sediment regimes have been sufficient to generate dynamic processes capable of resulting in a natural, complex river morphology. The data and maps from this mapping project are now being used in investigations of geomorphic processes related to landform resilience as well as the relations between landforms and biological observations.

Frequently Asked Questions

Is the LYR entrenched?
No. Entrenchment is qualitatively defined as the vertical containment of a channel and its degree of incision into the valley floor. The degree of entrenchment is quantitatively calculated as the ratio of the flood-prone width to the bankfull width. If this ratio is less than 1.4, then the channel is considered "entrenched". The mean entrenchment ratio for the LYR segment is 2.7 (Channel Classification, 22). No reaches have a ratio indicating entrenchment. There do exist short stretches of entrenchment in all reaches, but there also exist more and longer stretches that are not. Localized entrenchment can occur naturally or be influenced by anthropogenic factors.

Is the LYR sinuous?
No. Rivers may naturally occur in straight, meandering, braided, or anastomosing planform patterns (or in any transitional state between two of those). Sinuosity is a measure of the degree of meandering. It is measured as the ratio of thalweg length to valley length. A moderate to high sinuosity ratio is > 1.2. Comparing the thalweg length, as measured by locating the highest conveyance path at baseflow, to the valley length, as measured by the centerline of the geomorphically-active corridor, the sinuosity for the LYR is 1.1 (Channel Classification, 22).

Is the LYR meandering or braided?
Neither. The channel is qualitatively described as "transitional between straight and meandering" (Figure 8, 25).

Is the channel hydraulically connected to the floodplain?
Yes. Natural temperate rivers are known to spill out of their banks every 1.5 to 2 years, while rivers in semiarid and drier climates spill over bank less frequently. For the LYR, the representative bankfull discharge using only data since 1970 (after New Bullards Bar Dam was built) has a return interval of ~1.25 years, and the discharge for full inundation of the floodway has a return interval of ~2.5 years (Figure 4, 19). At the flood discharge (21,100 cfs), about 67% of the valley corridor is wetted (Table 1, 22). Therefore, the LYR floods more frequently than expected for natural rivers, despite some upstream flow regulation.

Are there distinct geomorphic reaches in the LYR?
Yes. Using major changes in geomorphic variables, eight distinct reaches were delineated (Reach Delineation, 26).

Is the LYR constricted by the presence of training berms in the Yuba Goldfields region?
No and Yes. Reach-average bankfull, floodway, and valley widths in the LYR are all greatest in the Yuba Goldfields region. The reason is that upstream of that region the corridor is confined by a narrow valley and downstream of it the corridor is confined by flood control levees and urbanization. Consequently, the present LYR corridor is not most constricted in the Yuba Goldfields. On the other hand, the training berms do isolate the river from historic alternate flow pathways back when the rivers had an anastomosing pattern. Left to itself, the LYR can and will

break out of the berms. However, those past pathways now consist of an artificial wasteland that is unsuitable for the river to pass through.

What is a morphological unit?

A morphological unit (MU) is defined as a discernible topographic landform within the channel and floodplain that represents a distinct form-process association, and whose size is typically at the length scale equivalent of 1-10 channel widths (but can be smaller) (Morphological Unit Definition, 35). Some common examples include pool, riffle, lateral bar, floodplain, and terrace (Table 6).

What is the difference between an MU and a mesohabitat?

An **MU** is a stage-independent landform that is an objective characterization of the channel topography. A **mesohabitat** is represented by the stage-dependent hydraulics (e.g., depth and velocity) that occur as a result of the discharge interacting with the underlying topography (Morphological Unit Definition, 35).

Are there distinct morphological units in the LYR?

Yes. Based on analyses of baseflow hydraulics, topography, erosion/deposition patterns, and conveyance paths, a suite of 31 distinct morphological units were delineated that comprehensively cover the full LYR corridor (Morphological Unit Scale Analysis, 35).

Does the LYR channel have a diversity of landforms yielding channel complexity?

Yes. There are 31 distinct morphological units in the LYR corridor (Morphological Unit Scale Analysis, 35) and there is an average of ~8-9 units across the river at any cross-sectional location. The river exhibits both longitudinal and lateral variation resulting in significant landform diversity and complexity. Comparing among reaches, there are widely different abundances of MUs in the different reaches, as indicated by a similarity index analysis (Table 15).

Are the morphological units randomly organized?

No. Statistical and spatial analyses of the MU organizational patterns show a deterministic structure. MUs exhibit distinct spatial ‘preferences’ and ‘avoidances’ in the longitudinal and lateral directions, as well as with respect to each other (Morphological Unit Spatial Organization, 56).

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Introduction

Geomorphology is the study of the landforms on the surface of the earth. Geomorphic analyses involve 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. A common practice in geomorphology involves focusing on specific spatial scales at which landforms have characteristic features (Grant et al. 1990; Rosgen 1996; Thomson et al. 2001). In the study of rivers, these scales are proportional to channel width (W) and include catchment (entire watershed scale), segment (~10^3-10^4 W), reach (~10^2-10^3 W), morphologic (or geomorphic) (~10^0-10^1 W), and hydraulic (~10^{-1}-10^0 W) units. Spatial scales are referenced to channel width, because many observers have recognized a similarity of forms among systems of different absolute size that are governed by the same underlying processes. Note that in this study the reach length is defined as 10^2-10^3 W, and that a gap exists for channel lengths of 10^1 to 10^2 W. This smaller 10^1-10^2 W is considered by some geomorphologists to be an assemblage of morphological units, while others simply call it a reach also (because they are not investigating the larger spatial scales beyond that, and thus do not require larger scale categories).

Dense topographic data, a GIS-based environmental informatics system, and ~3-ft resolution nodal results from 2D hydrodynamic modeling were leveraged to yield detailed, multi-scalar analyses (segment, reach, and morphologic unit scales) of the Lower Yuba River with greater spatial variability at each scale than has been traditionally possible using classical cross-section and longitudinal-profile geomorphic methods. The availability of spatially distributed 2D modeling results enabled representation of all areas of the wetted channel with equal emphasis (Pasternack, 2009).

The baseflow thalweg of the Lower Yuba River (LYR) is 25.2 mi long (from the Englebright Dam to its confluence with the Feather River), while the centerline of the geomorphically-active valley is 23.0 mi long. The average wetted channel has a width of ~195 ft at low flow conditions, so the scale of its entirety is 10^2-10^3 W. This scale of study area is slightly smaller than that of a generic segment scale; however the delineation of this segment is governed by the presence of Englebright Dam, a high concrete arch sediment barrier, at the upstream end and the river's confluence with the larger Feather River at the downstream end. Eight distinct reaches were delineated at the 10^1-10^2 W scale within the LYR segment based on analyses of such variables as: discharge from mainstem-tributary confluences, impacts of man-made structures and activities, valley width, bed slope, and bed material type (or absence of it). A morphological unit is defined by topographic forms within the channel and floodplain that represent distinct form-process associations. Correlative relationships between 2D model results, topographic contours, sediment change maps, and aerial imagery were used to delineate distinct in-channel bed units, bar units, and floodplain units.

Geomorphic analysis for instream flow assessment is often limited to a determination of whether the study area is "stable" or not. Traditionally it is 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 manage flows and/or rehabilitate an ecosystem to achieve resiliency in cases where it has been lost or it is desirable to be instilled, even if it was not historically present.

In light of these concepts, the objective of this study is to delineate and analyze the spatial structure of the landforms of the LYR at multiple spatial scales using the morphological unit as the basic unit for analysis. The specific scientific questions that were addressed by geomorphic analysis included the following:

- At the segment-scale, what are the values of wetted channel area, wetted width, and water-surface slope as a function of discharge?
- Based on thresholds in segment-scale attributes and the locations of tributaries, what is the delineation of reaches for the segment?
- At the reach scale, what are the values of wetted channel area, wetted width, and water-surface slope as a function of discharge?
- Does the study segment exhibit geometric organization at the reach scale?
- How is the channel classified at the segment and reach scales?
- Can 2D model results be used to rationally delineate morphological units in an alluvial river?
- What are the morphological unit types present in the Lower Yuba River? What are the abundances of each type?
- Are the morphological units delineated with a 2D model naturally organized into a coherent spatial structure that is non-random? If the structure is deterministic, then is it periodic or non-periodic? Are there systematic variations in morphological-unit organization and spacing along the segment?
- Does the river exhibit lateral variability in the morphologic units, or can the corridor be accurately described by a 1D representation?
- Are the morphological units organized at the segment and reach scales?

Answering these questions sheds light on the resiliency of the channel to flood disturbances, societal flow adjustments, and instream bed alteration. That helps to set reasonable expectations for the sustainability of physical habitat conditions over time. Subsequent studies will use the landform delineation to analyze physical processes directly, such as geomorphic change detection and patterns of Shields stress both segregated by landform type. That work is beyond the scope of this study and will be presented in a subsequent report.

Study Site – Lower Yuba River

The Yuba River is a tributary of the Sacramento River in north-central California that drains 3480 km^2 of the western Sierra Nevada range (Figure 1). The ~25.2 mi section between Englebright Dam and the Feather River confluence is defined as the Lower Yuba River (LYR). The LYR has a complex geomorphic history, because of the cumulative impacts of deposition of millions of tons of alluvial valley fill induced by historic hydraulic gold mining on contributing hillsides (Gilbert, 1917; James, 2005), dredger re-working of the ~4,000-hectare Yuba Goldfields and other areas in the ancestral river migration belt (James et al., 2009), installation of a high concrete arch sediment-barrier dam (Englebright Dam at 39°14'23.37"N, 121°16'8.75"W) in the canyon at the entrance to the LYR in 1941 (Snyder et al., 2004; Snyder et al., 2006), and moderate flow regulation from a suite of hydro facilities throughout the catchment (Yuba County Water Agency, 2009). Despite flow regulation, the LYR still experiences a dynamic winter storm and spring snowmelt hydrologic regime. Existing literature with more information about the hydrogeomorphic conditions of the LYR include Pasternack (2008), Moir and Pasternack (2008), James et al., (2009), Moir and Pasternack (2010), Pasternack et al. (2010), Sawyer et al. (2010), and White et al. (2010).

The LYR has incised greatly since hydraulic mining abated and Englebright Dam was built (Gilbert, 1917; Adler, 1980). However, unlike in pristine rivers that are dammed rivers (Williams and Wolman, 1984), incision on the LYR is not necessarily a bad thing or a cause of habitat degradation, because the river was previously subjected to unprecedented valley fill with hundreds of millions of tons of sediment. Therefore, it is important to not rush to apply simple, idealized conceptions of the effects of dams on pristine gravel bed rivers and first conduct a thorough scientific investigation to ascertain the landforms, patterns, and processes at work in the LYR. For example, Sawyer et al. (2010) and White et al. (2010) used hydraulic models of a modern flood and historic geomorphic analysis, respectively, to arrive at the conclusion that in the Timbuctoo bend Reach, the LYR maintains relief between pools and riffles in the face of the incision, because the landforms, patterns, and processes there are controlled by undulating valley walls that steer the dynamic flood regime for the LYR. Other studies have reported that the Timbuctoo Bend Reach has important riparian and aquatic ecological functionality as well (Beak Consultants, Inc., 1989; Pasternack, 2008; Moir and Pasternack, 2008; Moir and Pasternack, 2010). Thus, it is important to systematically analyze the geomorphology of the whole lower Yuba River prior to arriving at conclusions about the status of the river.

Most regulated rivers draining the Sierra Nevada have narrowed by about 50-70% due to vegetation encroachment, lost most active gravel bars, incised 1-2 m and become armored with cobbles since dams were built (e.g., Edwards, 2004). However, even though Englebright Dam blocks all bedload, the LYR remains a wandering gravel-bed river with a valley-wide active zone due to the gravel-rich hydraulic-mining deposits (James et al., 2009; White et al., 2010). The absence of bedload influx drives a remarkably rapid valley-wide incision rate on the order of ~10 m over 65 years. Yet, based on a comparison of photographs taken by G. K. Gilbert in 1906 and a series of aerial and ground-based photographs taken from 1937 to 2006, a sequence of pools and riffles has persisted for decades despite the rapid rate of long-term incision (White et al., 2010). Other historical channel changes in the lower valley include repeated dredger re-processing of the terrestrial river corridor in the ~4,000 hectare Yuba Goldfields and other areas, channel activation and abandonment, meander migration, riparian vegetation growth cycles and natural levee stabilization. In summary, the modern LYR is not natural in origin, but it has been subjected to decades of natural processes, including those driven by a dynamic range of flood sizes. An abundant supply of bed material and a relatively natural winter and spring flow regime have enabled riffles and pools to maintain themselves in the same locations for 30-70 years, characteristics usually associated with a meandering gravel-bed river (Pasternack, 2008; White et al., 2010). These factors make this river an appropriate and interesting venue for investigating pool-river self-maintenance in dynamic gravel-bed rivers, as well as diverse other processes that may be responsible for the landforms in the river corridor. Before those processes can be analyzed, it is first necessary to characterize what the landforms are and how they are distributed.

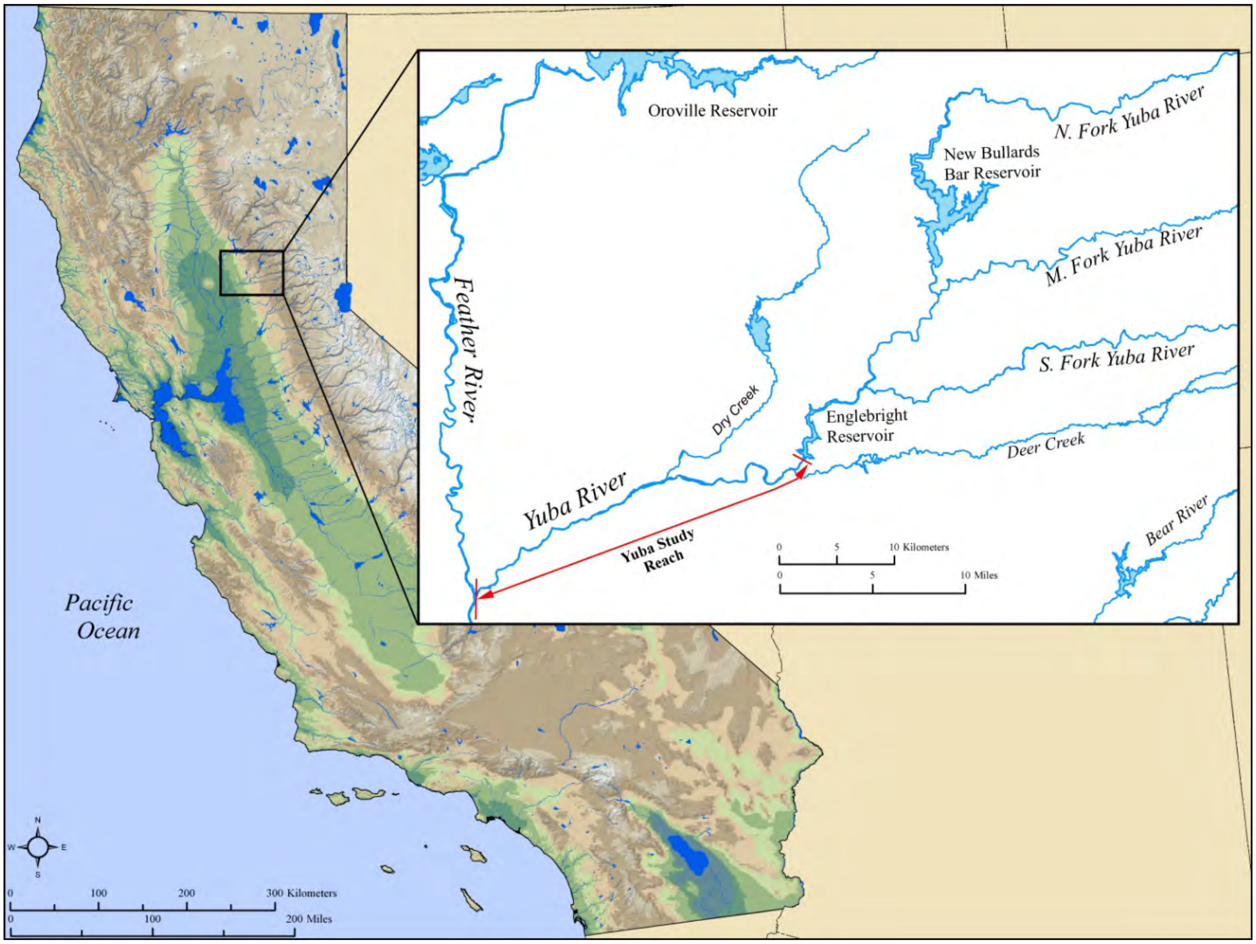

Figure 1. Location of Yuba River catchment and study segment

Segment Scale Analysis

Segment-scale stage-dependent fluvial characteristics were explored by subjecting the digital elevation model and 2D hydrodynamic model results to top-view and longitudinal profile analyses. These methods ascertain how segment-scale channel geometry and flow interact. It should be noted that the Narrows section (Figure 2) was not surveyed or modeled due to accessibility and safety issues in collecting field data, and therefore will exist as gaps in the following analyses.

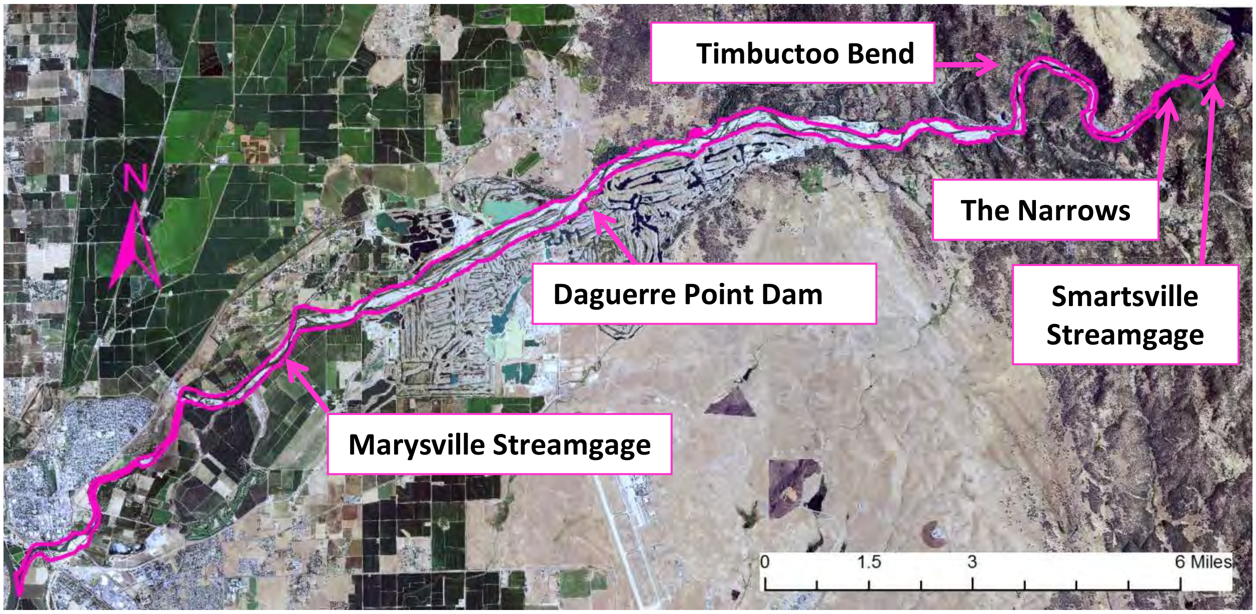

Figure 2. Lower Yuba River study segment with identifying features. Flow is to the left.

Segment Characteristics

The downstream boundary of the river segment is the confluence with the Feather River, and the upstream boundary is the Englebright Dam. The total segment length is ~25.2 mi measured along the baseflow thalweg (23.0 mi measured along the valley centerline). Riverbed thalweg elevations range from ~30-290 ft above mean sea level (Figure 3). Primary tributaries are Deer Creek (RM 24.5) and Dry Creek (RM 14.4). Daguerre Point Dam is a 26-ft high irrigation diversion structure located at RM 12.0 that creates a slope break and partial sediment barrier (Figure 3).

The river corridor is confined in a steep-walled bedrock canyon for the upper ~2.0 RM, then transitions first into a wider bedrock valley with some meandering through Timbuctoo Bend, then into a wide, alluvial valley from ~RM 19.3 to the mouth. The river has a history of hydraulic mining that is the source for much of the present alluvium. Tailings that remain from the hydraulic mining create training berms in some sections of the corridor. Hyporheic seeps have been noted in areas of the mined alluvium.

A 2D hydrodynamic model with ~1-3 m resolution has been developed for the entire LYR, except the inaccessible Narrows Reach (Barker et al., *in review*). Depth and velocity results of various discharge regimes from the 2D model were imported into ArcGIS and converted into 3x3

ft^2 rasters in the wetted area. A baseflow thalweg line was drawn through the raster points with the greatest conveyance (depth times velocity). The associated bed channel and water surface elevations were extracted from along this thalweg line. The average bed channel slope of the thalweg from the upstream end of Timbuctoo Bend (downstream extent of The Narrows) to the confluence with the Feather River is 0.16%, while the average bed channel slope between The Narrows and Englebright Dam is 0.31% (Figure 3). The average water surface slope at baseflow conditions is 0.17% (Figure 3).

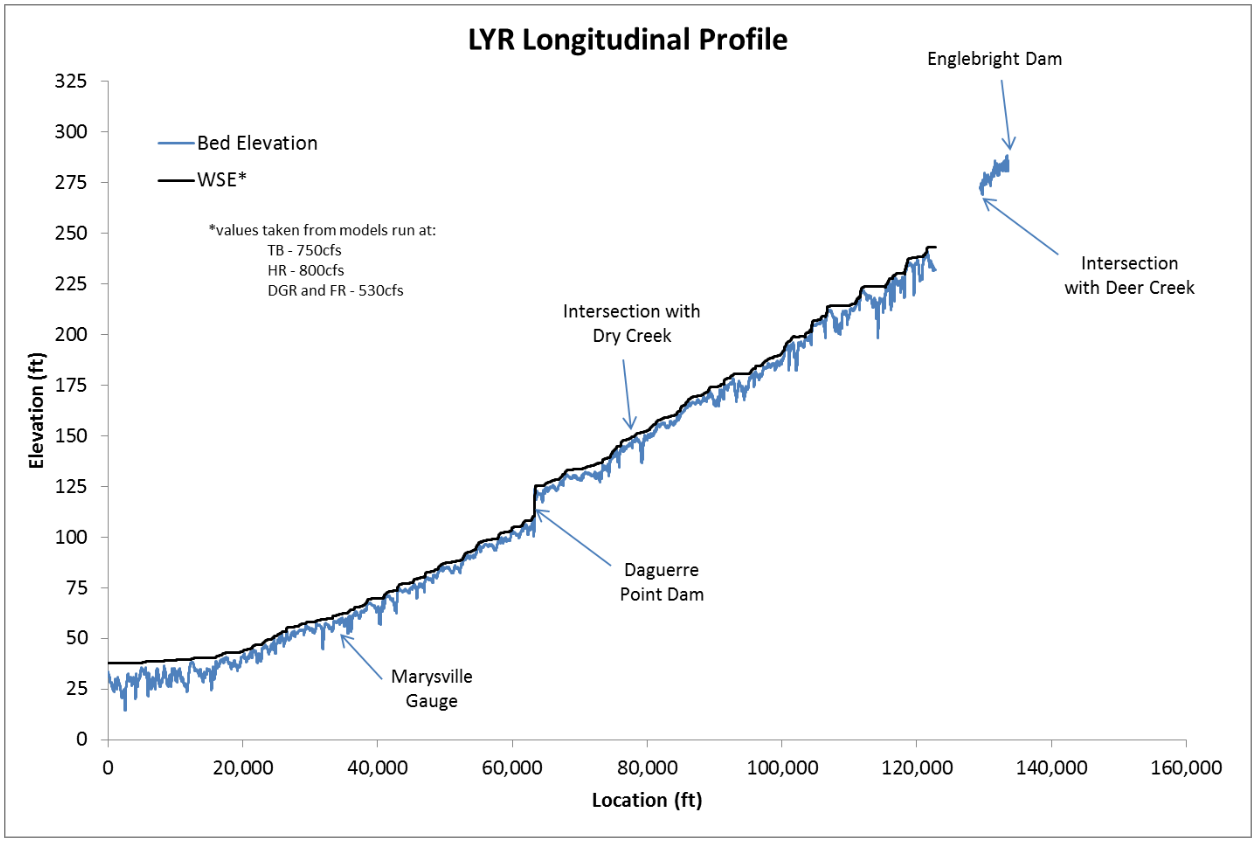

Figure 3. Longitudinal thalweg profile of LYR segment. Bed elevations based on 2006-2009 bathymetric survey; Water surface elevations (WSE) based on 2D hydrodynamic model results at indicated low flows. Note that the gap in bed elevation data represents the un-surveyed Narrows section.

Discharge Regimes and Inundation Zones

The term "bankfull" is designated as the topographic elevation over which incipient flooding occurs. Bankfull discharge is an important concept in fluvial geomorphology because it is inherently associated with the formation and maintenance mechanisms of the channel (Dunne and Leopold, 1978). For natural rivers in temperate climates, the bankfull discharge typically has a recurrence interval of ~1.5-2 years (or, ~50-67% of occurring each year). Some common physical indicators of bankfull stage include: breaks in the bank slopes; elevations of depositional features; changes in substrate material; inundation of floodplain swales; etc.

Within the LYR, discharge measurements are estimated from a suite of USGS flow gages, namely Smartsville (#11419000) near Englebright Dam, Marysville (#11421000) near the mouth

(Figure 2), and along one of its main tributaries in Deer Creek (#11418500). Some important discharge analyses for the lower Yuba River include the modern bankfull discharge since New Bullards Bar Dam was built (1971), the long-term averaged bankfull discharge since Englebright Dam was built (1942), and the floodplain-filling discharge of ~20,000 cfs (Pasternack, 2008). Bankfull discharge may be estimated using many different methods, which may vary in value. Using the 1971-2004 log-transformed annual peak daily discharge series, the statistically calculated flow with a 1.5-year recurrence interval ($Q_{1.5}$) is 5,600 cfs (Sawyer et al., 2010). Meanwhile, geometric slope break indicators for some streambanks and most swales on the floodplain inundate at a lower flow of ~3,000 cfs. The medial bar at the apex of Timbuctoo Bend overflows at ~5,000 cfs. Therefore, although bankfull discharge is a useful concept, it is highly uncertain on a dynamic river at the transition between meandering and braided, as the LYR is. Above ~20,000 cfs, the primary exposed alluvial surfaces in the river valley are terraces and artificial training berms. For modeling and analysis purposes, the bankfull discharge will be estimated as 5,000 cfs and the flood discharge as 21,100 cfs (Figure 4). The return period of the bankfull discharge is ~1.25 years, which is more frequent than other similar rivers. The implication of this (and the high frequency of flood flows) is that the channel is likely undersized and flows spill onto the floodplain more often than expected.

Return Period (yrs)	Discharge (cfs)
500	385,729
200	287,324
100	223,917
50	169,397
20	110,016
10	73,980
5	44,980
2	16,464
1.25	5,612
1.11	3,106
1.05	1,877
1.01	702

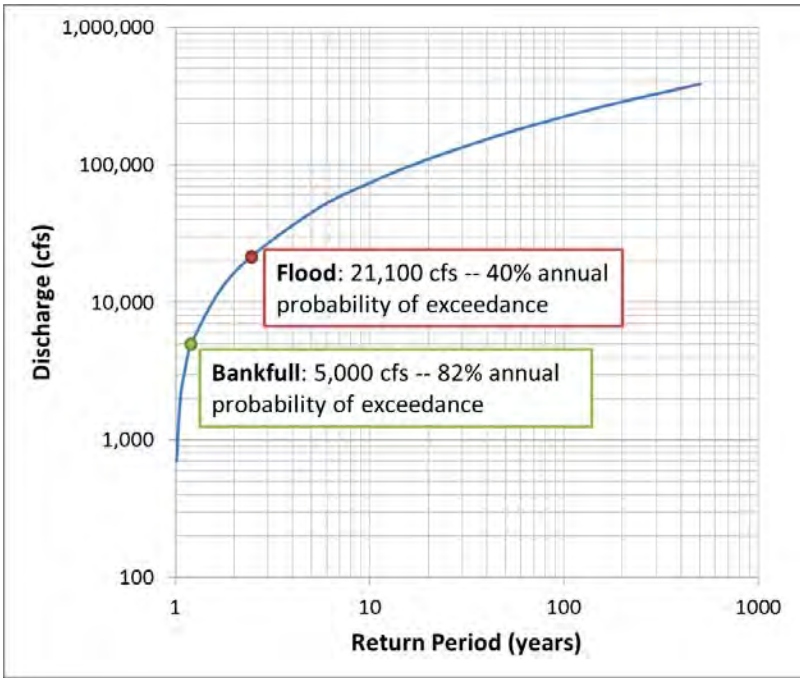

Figure 4. Flow frequency curve for the USGS Marysville gage annual peak discharges between 1970-2010 water years. Frequency data calculated with HEC-SSP v. 2.0 (USACE, Davis, CA).

Figure 5. February 2004 photo of the apex of Timbuctoo Bend showing inundated island and banks at a flow of 5000 cfs.

Hydrologic analyses show that during September through December flows range from 500-1500 cfs (~0.1-0.3 times bankfull). This also corresponds to the period when flow and channel form produce mesohabitat conditions suitable for spring run Chinook (*Oncorhynchus tshawytscha*) adult spawning, so the morphological units during that period equate with vital mesohabitats (Moir and Pasternack, 2008). The final baseflow regime selected for use in the study was the condition with a Smartsville discharge of 880 cfs, no discharge out of Deer Creek (whose outflow tends to be 0-5 cfs in the absence of rain or upstream reservoir maintenance), no discharge out of Dry Creek (whose outflow tends to be 0-5 cfs in the absence of rain or upstream reservoir maintenance), and a societal withdrawal of 350 cfs of water at Daguerre Point Dam (DPD), yielding a Marysville gage flow of 530 cfs. Because of this withdrawal, it is appropriate to use a paired discharge regime (i.e., combining model results for 880 cfs above DPD with 530 cfs results below DPD) for morphological unit delineation to account for the diversion, instead of using a theoretical constant discharge for the whole river.

The three modeled discharge regimes for the LYR used for these analyses are therefore baseflow (880cfs above DPD and 530 cfs below), bankfull (5000 cfs), and flood (21,100 cfs). These regimes create three distinct inundation areas that slice the LYR valley longitudinally (Figure 6), and allow for further spatial comparisons. In some sections of the river corridor, the floodway inundation zone is not appreciably wider than the bankfull or baseflow zones (e.g. Figure 6A), whereas other sections exhibit flood flows that are much wider than bankfull and almost fill the valley corridor (e.g. Figure 6, B and C). A visual examination of the wetted areas shows a more sinuous flowpath at baseflow as compared to a straighter flowpath during flood events (e.g. Figure 6D). High floods can and do exceed the capacity of the floodway, in which case water spills out onto the broader valley floor. In this study, this fourth region is termed the “valley”.

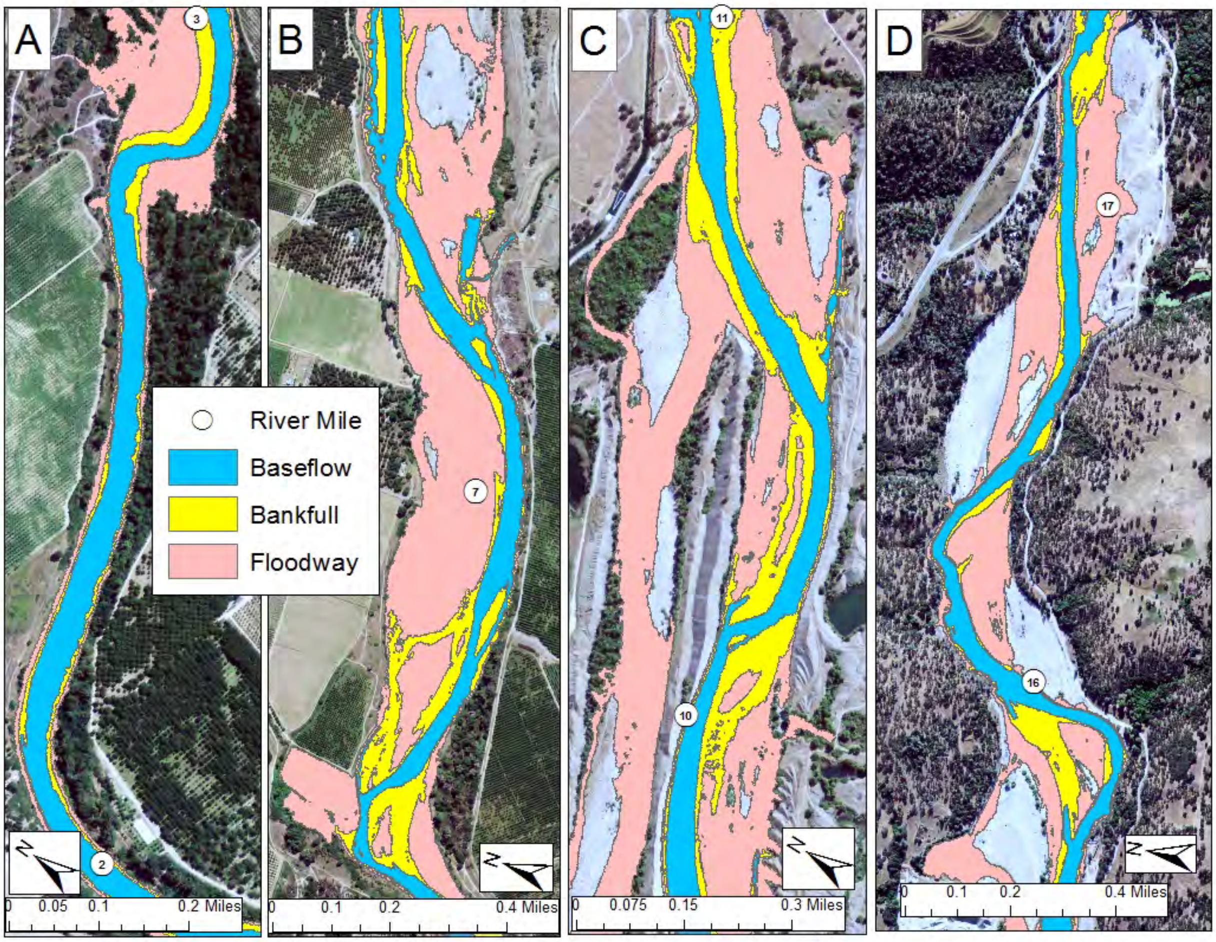

Figure 6. Inundation regions within the LYR. Baseflow is 880 cfs above DPD (RM 11) and 530 cfs below; Bankfull is approximated as 5000 cfs; Floodway is 21,100 cfs. Uncolored alluvia illustrate the valley floor outside the floodway. Flow directions in all images are from top to bottom.

Plan-view Analysis

Wetted area polygons for the discharges of interest were produced from 2D model results. A polygon delineating the geomorphically active valley width was manually created in ArcGIS and a centerline was drawn through it. Points were distributed every 20 ft along the valley centerline, and then polylines were created perpendicular to the centerline at each point. These lines were buffered and converted into individual polygons, then clipped to the wetted area boundary of interest. This process yielded 20-ft rectangles distributed down the river that were used for width and morphologic-unit analyses. Some of these rectangles overlapped or underlapped at meander bends, creating smaller polygons rather than rectangles, but no manual labor was done to adjust the rectangles. Instead, it was decided that the overlaps and underlaps balanced each other out, and the data in these units were as important as in all other units, so all data were kept and analyzed. Using the valley centerline creates less overlaps/underlaps than would result from using the thalweg line. The one exception to this was for the analysis of the lateral distribution of MUs. In that case, where rectangles were turned by a sharp meander bend such that they were not across the channel but along it, then the results from those rectangles were excluded from the analysis, because they did not in fact represent lateral variation.

The Lower Yuba River study segment has a wetted area of 510 acres and average wetted width of 195 ft at baseflow conditions (880/530 cfs above/below DPD). At near-bankfull flow conditions (5,000 cfs) the wetted area increases to 829 acres and the wetted width to 319 ft (Table 1), both an increase of ~ 63%. During flood conditions (21,100 cfs) the wetted area increases to 1703 acres and the wetted width to 654 ft, both an increase of over 100% as compared to the bankfull values.

Table 1. Wetted channel area and width as a function of discharge

Discharge (cfs)	Wetted Area (ac)	Average Width (ft)
Baseflow - 880/530	510	195
Bankfull - 5,000	829	319
Flood - 21,100	1703	654

Channel Classification

Currently, there is no established baseline as to how to characterize the morphology of the LYR. The morphological form and function of any river are the results of the channel's responses to its evolutionary sequence. Rivers are not homogeneous, and therefore, neither should be the management strategies. Stream classification is a hierarchical inventory system that objectively describes a channel "so that consistent, reproducible descriptions and assessments of condition and potential can be developed" (Rosgen, 1996). Specifically, a goal for classifying the Lower Yuba River is to use its inherent morphology to predict its behavior, and therefore provide a frame of reference for predicting its potential salmonid habitat. Using a hierarchical classification system allows the driving forces and response variables to be linked at any spatial scale. The exact classification method used to describe the baseline morphology of the LYR is less important than the ability to define the context with which to ascribe relevant channel characteristics and compare to other fluvial systems. With this in mind, the Rosgen Stream Type classification method (Rosgen, 1996) was used because it incorporates objective and qualitative metrics that have relevance to landform analyses beyond just channel classification.

Rosgen (1996) describes a detailed methodology for identifying key morphological features and stratifying those features into a classification system that has become popular within the fluvial sciences. The hierarchy of the Rosgen classification system is comprised of several assessment levels: Geomorphic Characterization; Morphological Description; Stream Condition; and Validation. For the purposes of the LYR, characterizing the channel to Level II (Morphological Description) will be sufficient. The classification is applied to the full LYR segment and the eight geomorphic reaches. To apply the classification, several physical characteristics of the channel and valley must be determined. These include: channel pattern; channel slope; entrenchment ratio (ratio of flood-prone width to bankfull width); width/depth ratio (at bankfull discharge); channel sinuosity (ratio of baseflow centerline length vs. valley corridor length); and substrate composition.

Entrenchment is a characterization of the channel's vertical containment and how incised it is within its banks. It is a key metric for determining how often adjacent alluvia are flooded. The degree of entrenchment can be calculated qualitatively as the ratio of the flood-prone width to the bankfull width. The flood-prone width is defined as the width at which the depth is twice the bankfull depth (Rosgen, 1996).

The LYR segment is a single-thread channel, which narrows the Level I classification down to A, B, C, E, F, or G stream type. The channel is slightly entrenched (> 2.2), which narrows the classification down to either E or C. The width/depth ratio is moderate to high (> 12), which it is classified as a C type channel. The sinuosity, however, is low (< 1.2), which does not fit with the expected values for a C stream type (> 1.2). However, Rosgen (1996) qualifies the continuum of these physical variables such that values for sinuosity can vary by +/- 0.2 units, and carries the least weight among the criteria. The LYR sinuosity value of 1.1 is therefore within the limits of "high sinuosity" and it is reasonable to classify the channel as a C type. At the Level II hierarchy, the LYR exhibits an average channel slope of 0.0016 and an average substrate diameter of 103 mm. Therefore, the LYR is classified as a C3 stream type (Table 2).

Rosgen (1996, p. 5-92) describes a C3 stream type as:

> "slightly entrenched, meandering, riffle/pool, cobble-dominated channel with a well-developed floodplain. The C3 stream type is found in U-shaped glacial valleys; valleys bordered by glacial and Holocene terraces; and very broad, coarse alluvial valleys typical of the plains area. … The riffle/pool sequence of a C3 stream type is on average at 5-7 bankfull channel widths. The streambanks are generally composed of unconsolidated, heterogeneous, non-cohesive, alluvial materials that are finer than the cobble-dominated bed material. Consequently, the channel is susceptible to accelerated bank erosion. Rates of lateral adjustment are influence by the presence and condition of riparian vegetation. Sediment supply is low, unless streambanks are in a high erodibility condition."

Table 2. Hierarchical classification of the LYR based on Rosgen (1996) stream types.

Channel Characteristic	LYR Value
# of Threads	Single
Entrenchment Ratio	2.7
Width/Depth Ratio	80
Sinuosity	1.1
Slope	0.0016
Mean Substrate Size (mm)	102.6 *(Small Cobble)*
Rosgen Stream Type	**C3**

For comparison, examples of other reaches classified as a C3 stream type include: Fay Creek, California (Figure 7A); Wind River, Washington (Figure 7B); Rock Creek, California (Figure 7C); and Little Snake River, Colorado (Figure 7D). Each of these examples streams exhibit similar channel characteristics as the LYR, except for Rock Creek which has a lower slope (C3c) and Little Snake River which has a gravel bed (C4).

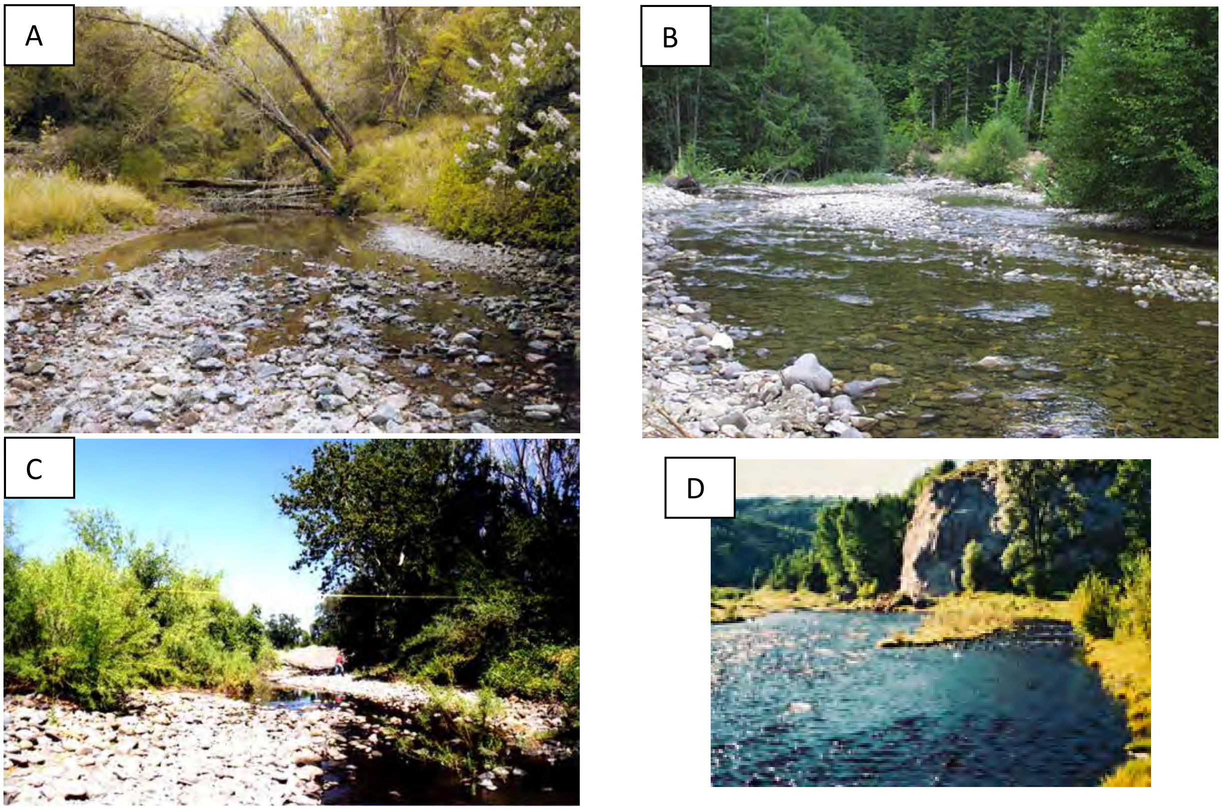

Figure 7. Examples of other western rivers classified as C3, similar to the LYR. (A) Fay Creek, CA; image by Bodega Land Trust, (B) Wind River, WA; image by Bair of Wild Fish Habitat Initiative, (C) Rock Creek, CA; image by Big Chico Creek Watershed Alliance, (D) Little Snake River, CO; image by Global Restoration Network.

That the sinuosity of the LYR is less than expected based on the Rosgen Stream Type analysis should not necessarily lead to any conclusions about the functionality of the channel. Whether a channel is 'straight', 'meandering', or 'braided' is largely a function of the flow instability or disturbances along the streamlines (Callander, 1969). Parker (1976) devised a quantitative method to determine whether a channel is inherently straight, meandering, or braided. His methodology compares the ratios of slope and Froude number (dimensionless ratio of inertial and gravitational forces) with depth and width. The average Froude number for the LYR at bankfull flow is 0.26 (sub-critical), and the other relevant values are already known through the Rosgen analysis (Table 2). Using the Parker (1976) definitions and analyses of channel type, the LYR is considered as transitional between straight and meandering (Figure 8). Some examples of natural rivers that are also classified as transitional include: Smoky Hill River, Kansas (Figure 9A); Watts Branch, Maryland (Figure 9B); and Buttahatchie River, Mississippi (Figure 9C).

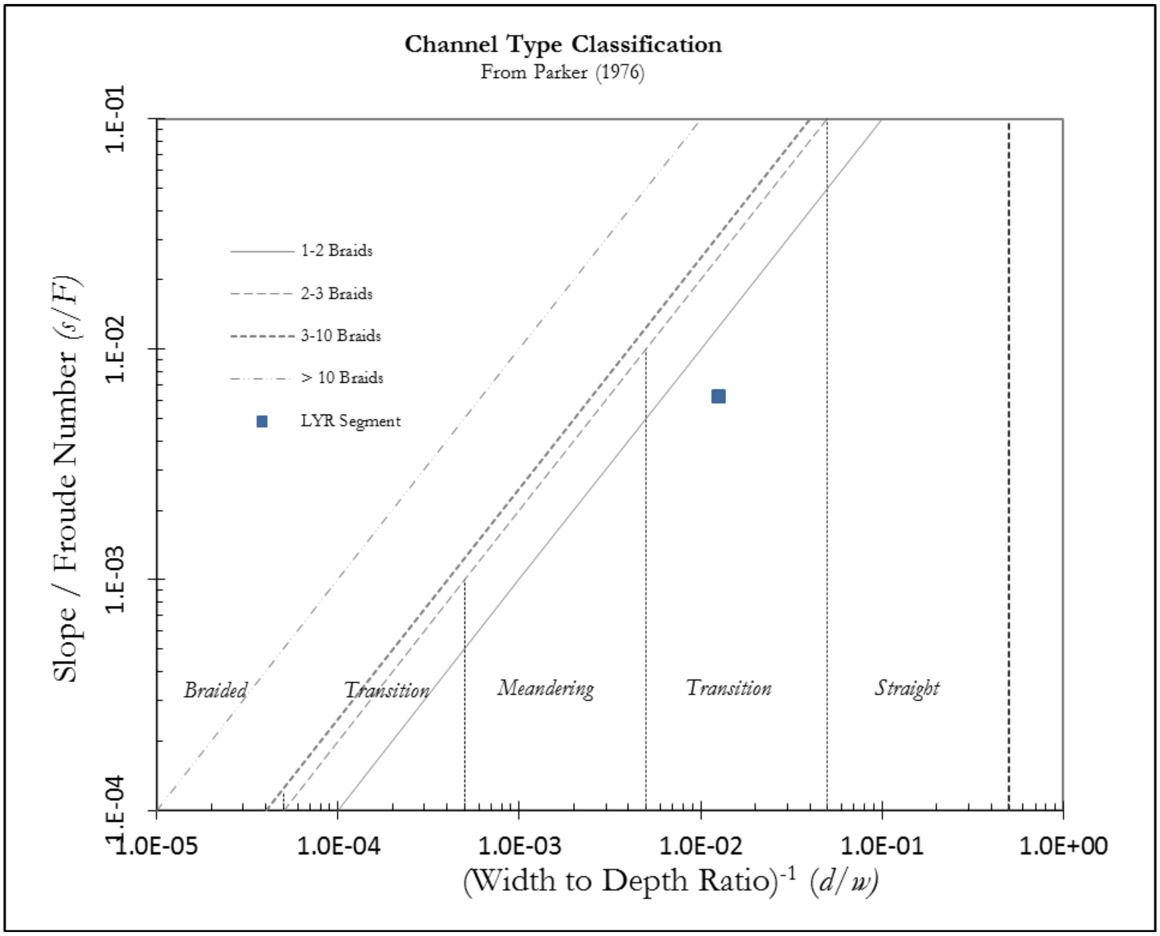

Figure 8. Channel type classification based on flow instability (Parker, 1976).

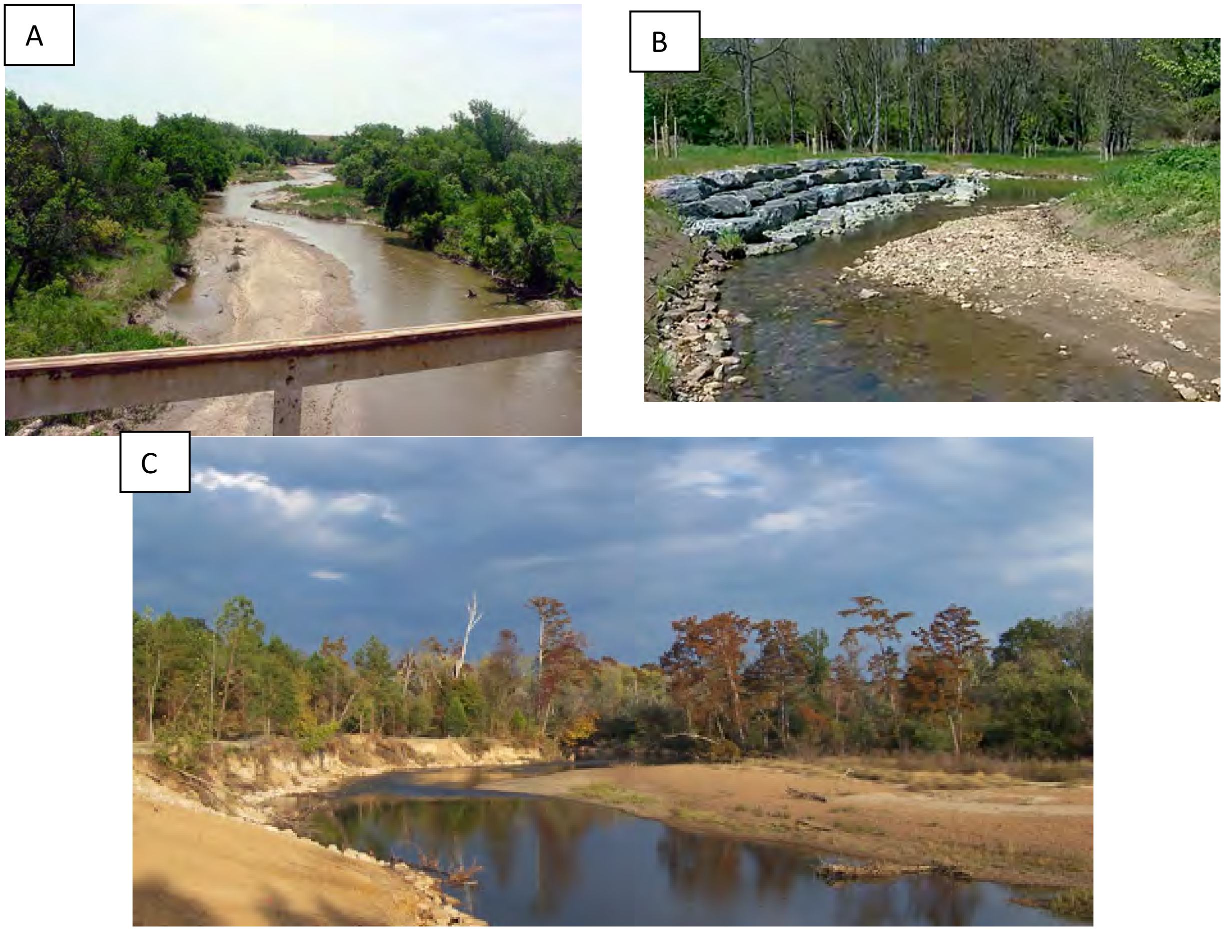

Figure 9. Examples of streams classified as Transitional using the Parker (1976) methodology. (A) Smoky Hill River, KS; image from Wikimedia Commons, (B) Watts Branch, MD; image from bit-player.org, (C) Buttahatchie River, MS; image by The Nature Conservancy.

Reach Scale Analysis

A reach is a section of river with a characteristic set of attributes controlled by the balance of sediment transport capacity, sediment supply, and topography. These governing factors are expressed through the following variables: discharge from mainstem-tributary confluences, impacts of man-made structures and activities, valley width, bed slope, and bed material type (or absence of it). Major changes in these underlying variables were used to transparently delineate the eight distinct reaches within the LYR (10^1-10^2 W). Hydrogeomorphic characteristics of each reach were then analyzed and compared.

Reach Delineation

Previously, the LYR was delineated by Beak Consultants (1989) and CDFG (1991) into four reaches: Narrows, Garcia Gravel Pit, DPD, and Simpson Lane. The only explanations provided for these reach breaks derive from their descriptions of the starting points of each: Englebright Dam, onset of emergent gravel in the floodplain upstream of Blue Point Mine, Daguerre Point Dam, and the upstream extent of the Feather River backwater effect, respectively.

Because the previous reach delineations were unclear, a new, transparent method was used to delineate eight distinct regions within the LYR segment based on the longitudinal profile and associated geomorphic variables (Table 3, Figure 10). Tributary junctions form the upstream boundary of two reaches and dams form the boundary for two more reaches. The other reach boundaries are formed by hydro-geomorphic variables: onset of emergent floodplain gravel; transition from confined bedrock valley to wider, meandering system; and decreases in bed channel slope. Valley widths (Table 3) were calculated in ArcGIS using the perpendicular lines radiating from the valley centerline stations and clipped to the valley polygon. The bed slopes and lengths were calculated from the baseflow thalweg line.

Table 3. Newly proposed reaches of the Lower Yuba River with geomorphic delineations.

	Valley Width (ft)					
Reach Name	**Min**	**Mean**	**Max**	**Bed Slope (%)**	**Thalweg Length (ft)**	**Starting Point Description**
Englebright Dam	316	415	693	0.31	4,130	Englebright Dam
Narrows	162	304	596	*n/a*	6,700	Confluence with Deer Creek
Timbuctoo Bend	373	589	1866	0.201	20,790	Onset of emergent gravel floodplain upstream of Blue Point Mine
Parks Bar	387	1007	1432	0.188	25,980	Highway 20 Bridge
Dry Creek	783	987	1552	0.135	12,470	Confluence with Dry Creek
DPD	755	1628	2305	0.176	18,500	Daguerre Point Dam
Hallwood	573	1175	2394	0.131	27,500	Slope break near Eddie Drive
Marysville	325	744	1842	0.052	17,500	No evident feature

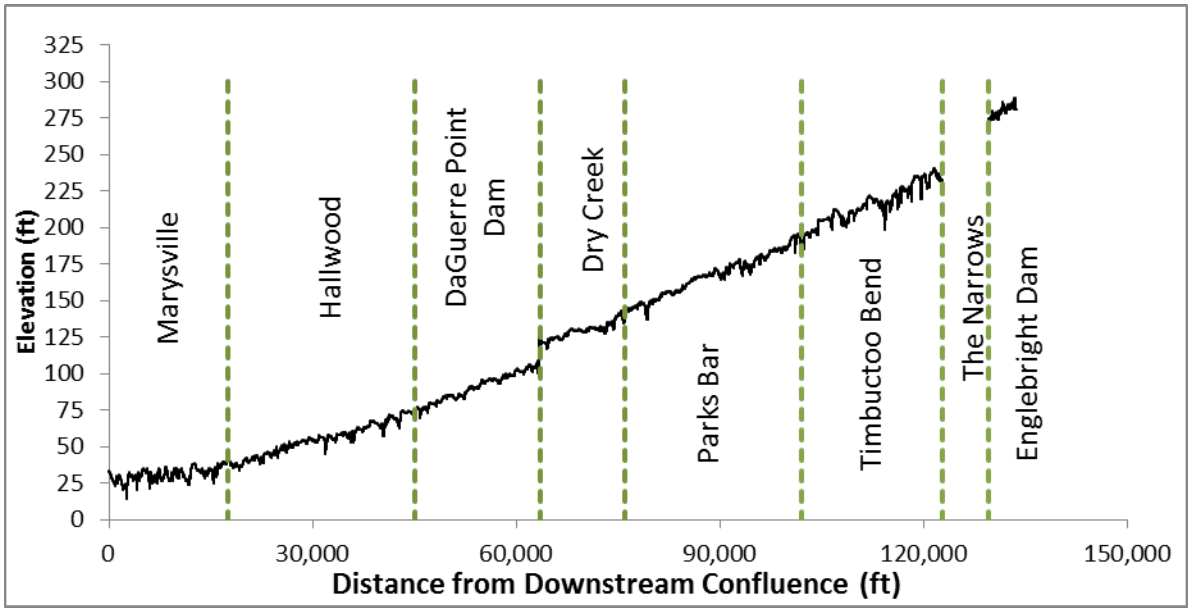

Figure 10. Longitudinal thalweg profile showing reach breaks described in Table 2.

Reach Characteristics

The Englebright Dam Reach (Figure 11) is the upstream-most reach in the LYR segment, and extends from the Englebright Dam to the tributary confluence with Deer Creek. Because the dam is a sediment barrier by design, there is no river-rounded gravel/cobble substrate or finer sediments in this baseflow wetted areas in this section. As reported by Pasternack (2008), there is a residual mixture of angular gravel/cobble, probably derived from the 1997 erosion of a road or from the blasting done at the time Englebright Dam was built. There is some gravel/cobble sediment predating Englebright Dam stored on and within Sinoro Bar. The reach is girded on both sides by steep, bedrock valley walls, which create the smallest increase between baseflow width and valley width of all the reaches (Table 4). The Englebright Dam reach exhibits the greatest bed channel slope and is the shortest reach (Table 3).

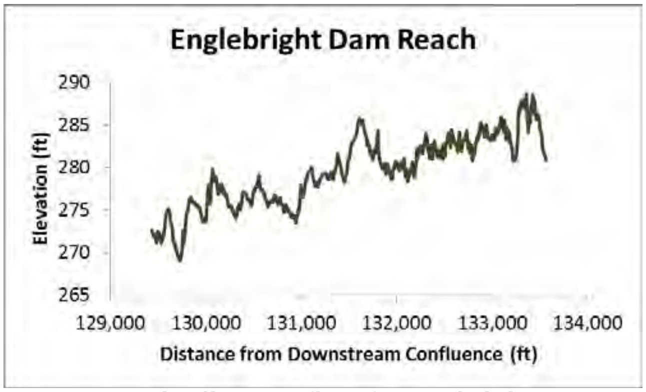

Figure 11. Longitudinal profile of Englebright Dam Reach

The next reach is the Narrows, which extends from Deer Creek to the onset of emergent gravel within the floodplain near Sinoro Bar and Blue Point Mine. Similar to the Englebright Dam reach, this reach is also characterized by steep bedrock valley walls and a lack of surficial river-rounded sediments. A few cobble bars that predate Englebright Dam have persisted in the wider, upper section of the Narrows, and their subsurface composition is unknown. However, the Narrows reach becomes even more confined (Table 3), which creates some Class III rapids that prevent topographic and bathymetric surveys due to safety and accessibility issues. Therefore, the wetted area width, slope, and thalweg location cannot be accurately determined at this time.

The Timbuctoo Bend Reach (Figure 12) extends from the emergent gravel bar at Blue Point Mine to the Highway 20 Bridge. Within the reach, the river corridor is confined by bedrock valley walls, but there is a floodplain and the channel is wider than in the upstream reaches. There exist some space for meandering within the corridor in this reach. Bedrock outcrops intersect the baseflow channel, creating hydraulic controls. At the downstream end, the valley begins to widen and transition into an alluvial, meandering system. The highway 20 bridge was located where it was, because there is a natural valley constriction there. There is a backwater effect during floods induced by this constriction, which causes gravel to deposit in the backwater zone, yielding medial bars and a braided channel planform. The reach ends at this natural constriction.

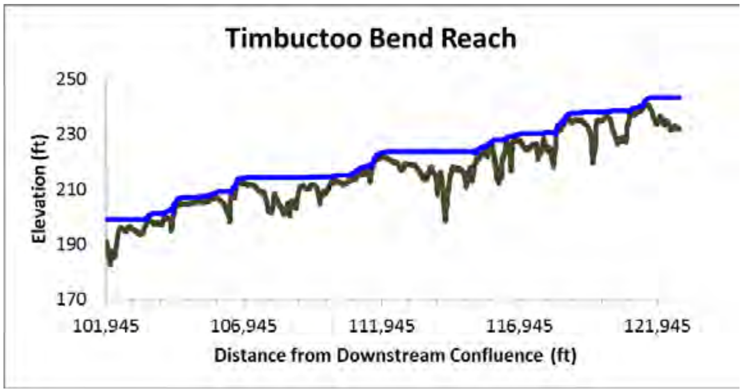

Figure 12. Longitudinal profile and baseflow water surface elevation for Timbuctoo Bend Reach

The Parks Bar Reach (Figure 13) begins at the valley widening after Timbuctoo Bend and extends to the tributary confluence with Dry Creek. Within this reach, the average valley width almost doubles from the Timbuctoo Bend reach. The extra width enables wider bankfull sedimentary bars, floodplains, islands, and terraces. The channel slope is similar, but decreasing. The upper half of the reach exhibits high bed relief as in Timbuctoo Bend, whereas the lower half has subtle bed relief.

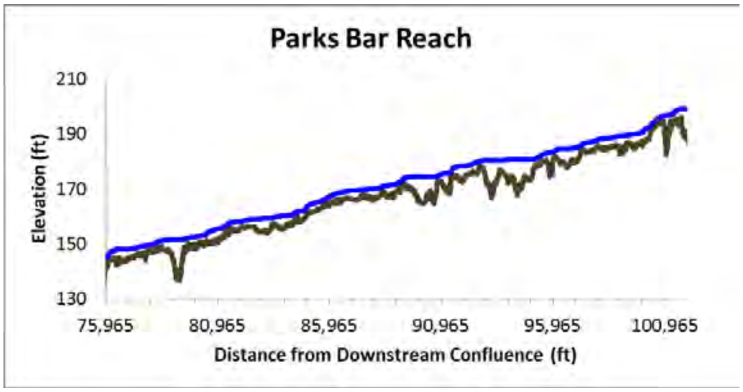

Figure 13. Longitudinal profile and baseflow water surface elevation for Parks Bar Reach

The Dry Creek Reach (Figure 14) extends from the tributary confluence with Dry Creek to the Daguerre Point Dam. The high average valley width and presence of wide bars, floodplains, island, and terraces are similar to what is present in the Parks Bar reach; however the channel slope decreases significantly (Table 3). This creates a nominally braided section with multiple flowpaths and backwater channels.

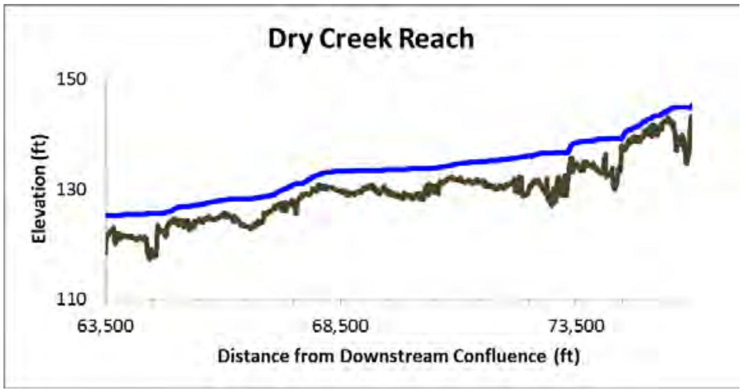

Figure 14. Longitudinal profile and baseflow water surface elevation for Dry Creek Reach

The Daguerre Point Dam Reach (Figure 15) begins at the dam and extends to another significant slope break. This reach is characterized by a single-threaded meandering channel, with multiple floodplains flowpaths and backwater ponds. This is the widest alluvial reach in the segment by ~ 50% (Table 3). A notable planform feature of this reach is the presence of a long parallel floodway to the north of the perennial channel, termed “Daguerre Alley”. There is a floodplain channel (i.e. flood runner) in Daguerre Alley with some permanently inundated deeper scour holes as well as a large backwater at the downstream end. This parallel floodway is separated from the main channel by a training berm that is open at both ends. The exact discharge at which this activates is unknown as of yet, but is between 10,000 to 21,100 cfs. Daguerre Alley is under further investigation.

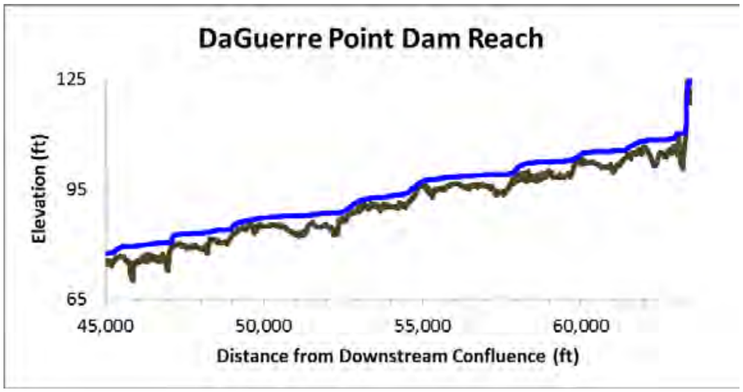

Figure 15. Longitudinal profile and baseflow water surface elevation for Daguerre Point Dam Reach

The Hallwood Reach (Figure 16) begins near Eddie Drive where the channel decreases in bed slope and extends to another significant slope break. This reach was historically braided and anastomosing, but is now confined by levees. It is also the longest reach.

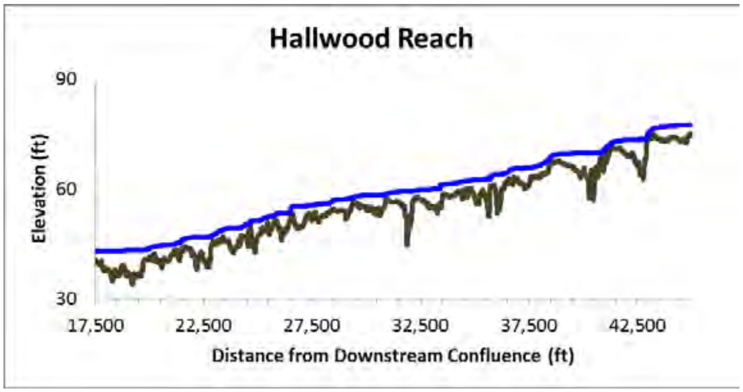

Figure 16. Longitudinal profile and baseflow water surface elevation for Hallwood Reach

The most downstream reach is Marysville (Figure 17), which is separated from the Hallwood Reach by a slope break (Table 3) and encompasses the backwater zone of the Feather River. This reach was also historically wide, braided, and anastomosing, is now leveed and highly channelized. Because the levees go to the channel bank along most of its length, there is little area of floodplain landforms. The bed slope and water surface slope are very low, and the reach is therefore characterized by large areas of slow, deep waters (Figure 17).

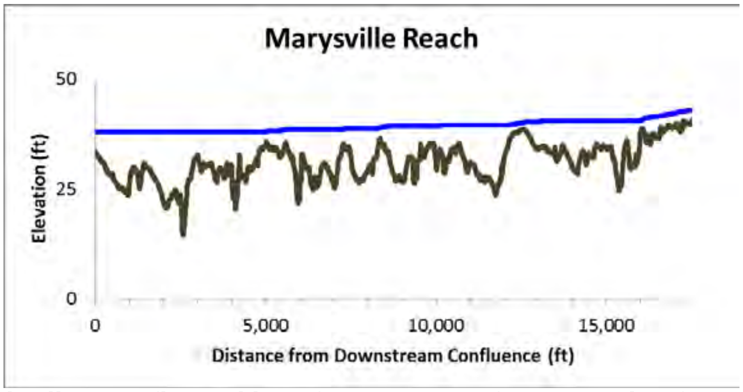

Figure 17. Longitudinal profile and baseflow water surface elevation for Marysville Reach

To investigate the differences in discharge-width relationships between the reaches at the key inundation levels, model-predicted wetted area polygons for baseflow (880/530 cfs), bankfull (5000 cfs), and floodway (21,100 cfs) were used. These wetted area polygons were used to cut the cross-sectional lines located along the valley centerline to determine the widths at each centerline station (Figure 18). The average widths per reach were then calculated and recorded (Table 4). Between baseflow width and near-bankfull width, the Marysville and Timbuctoo Bend Reaches experience the smallest increase in flow width of ~33%. The DPD Reach, on the other hand, almost doubles in width between baseflow and bankfull, and also experiences the greatest overall increase in width as the floodway is ~ 5.2 times as wide as the baseflow wetted area, which benefits from the overflow filling of an adjacent channel just downstream of Daguerre Point Dam. The Englebright Reach is the most confined as its canyon width is only ~2 times wider than the baseflow width, although the ratio for both the Marysville and Timbuctoo reaches are only slightly larger. The Narrows Reach is likely more confined than the rest of the segment, but we do not have model results with which to compare. The Hallwood and Marysville reaches are likely stunted in their width increases by the levees and dredging activities present in the lower sections of the LYR.

Table 4. Average widths per reach as a function of discharge

Reach	Baseflow* Width (ft)	Bankfull Width (ft)	Floodway Width (ft)
Englebright Dam	120	169	237
Narrows	*-n/a-*	*-n/a-*	*-n/a-*
Timbuctoo Bend	205	277	441
Parks Bar	199	316	678
Dry Creek	248	427	865
Daguerre Point Dam	197	393	1028
Hallwood	183	335	692
Marysville	174	231	379

*Baseflow is a paired discharge of 880 cfs above DPD and 530 cfs below; Bankfull = 5,000 cfs; Floodway = 21,100 cfs.

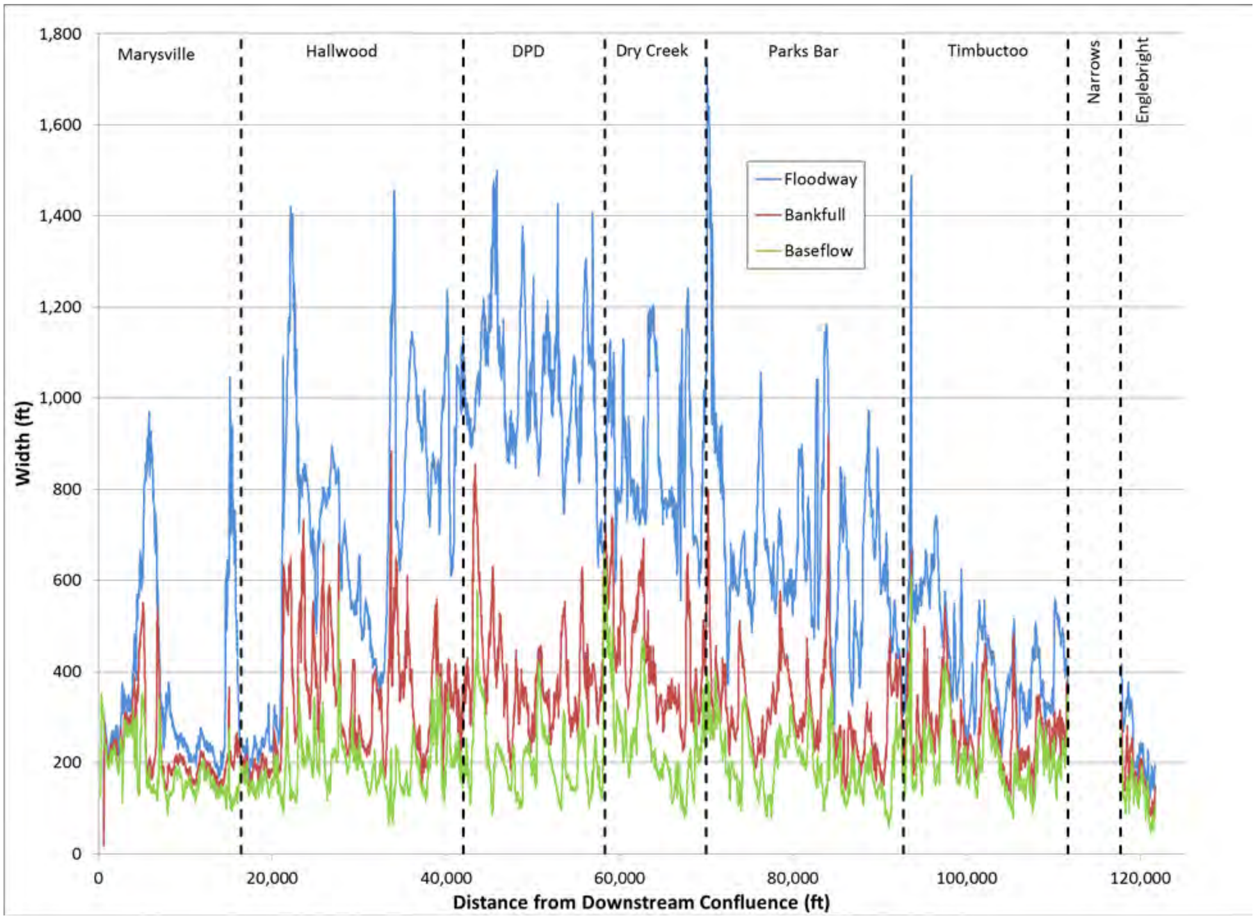

Figure 18. Variability of wetted area and corridor widths at the segment and reach scales for baseflow (green line), bankfull (red), and flood conditions (blue).

Entrenchment is the ratio of widths that coincide with the bankfull depth and twice the bankfull depth (Rosgen, 1996). The smaller this ratio is (i.e., the closer the two widths are to each other), the more entrenchment the channel is. The average entrenchment ratio (ER) for the segment scale has been previously shown (Table 2), which indicates that the channel, on the whole, has a well-developed floodplain. Similarly, no reach is entrenched when considering its reach-scale average ER value. However, there are variations at the reach and cross-sectional scales that indicate there are some short sections of the LYR that are entrenched (Figure 19). Entrenched sections do exist within the Marysville and Hallwood reaches; however, these reaches also exhibit some of least entrenched sections (highest ratio). Most of the reaches are classified as "slightly entrenched" or "well-developed floodplain" (ER > 2.2), similar to the segment scale. Timbuctoo and Englebright, however, are classified as "moderately entrenched" on average (1.4 < ER < 2.2), although each reach does exhibit some sections of "slightly entrenched" and "entrenched" (ER < 1.4). Thus, the spatial scale used to analyze and characterize a river is important.

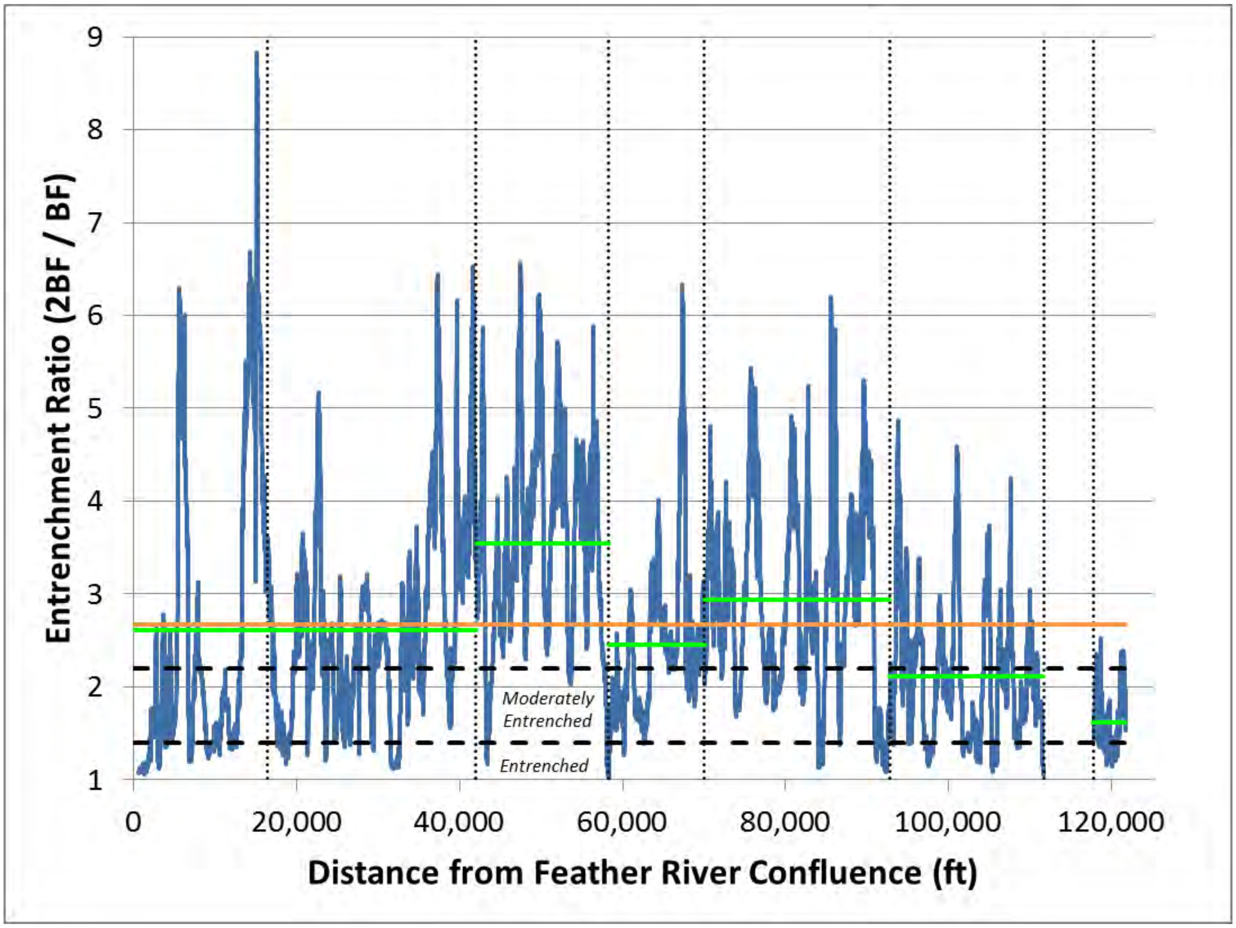

Figure 19. Variability of entrenchment ratios among all cross-sections of the LYR. The orange and green lines represent the segment and reach averages, respectively. An entrenched section exhibits a ratio < 1.4 and a moderately entrenched section exhibits 1.4 < ER < 2.2. Sections with ratios greater than 2.2 are considered slightly or not entrenched.

Reach Classifications

Similar to the channel classifications presented above for the LYR segment, the individual reaches can also be analyzed and compared. The Rosgen Stream Type classification at the segment scale (C3) represents the morphological characteristics averaged for the full corridor, however at the reach scale, these characteristics may not be consistent. Three of the seven reaches match the segment-scale Rosgen Stream Type (Table 5). The Englebright and Timbuctoo reaches exhibit a higher entrenchment ratio (< 2.2) than the segment, which classify them as a B-type stream. The larger substrate sizes within Englebright classify it as a B2c, whereas the Timbuctoo is a B3c stream type. The Hallwood Reach has smaller substrate sizes as compared to the segment (gravel vs. cobble), thus classifying it as a C4. The Marysville Reach has a slope sufficiently smaller than the segment average to change its stream type to a C3c-.

Similar to the segment-scale classification, the sinuosities of the reaches are slightly less than the expected for that Rosgen stream type. Applying the Parker (1976) classification, the channel types for each reach are also considered as transitional between straight and meandering (Figure 20).

Table 5. Stream type classification based on Rosgen (1996) for LYR reaches. Compare to segment-scale characteristics in Table 2.

Reach	Threads	Entrenchment Ratio	Width/Depth Ratio	Sinuosity	Slope	Substrate (mm)	Stream Type
Englebright	single	1.6	31	1.04	0.0031	298	**B2c**
Timbuctoo	single	2.1	82	1.10	0.00201	163	**B3c**
Parks Bar	single	2.9	108	1.14	0.0019	120	**C3**
Dry Creek	single	2.5	122	1.06	0.0014	88	**C3**
DPD	single	3.5	85	1.13	0.0018	87	**C3**
Hallwood	single	2.6	71	1.08	0.0013	61	**C4**
Marysville	single	2.6	23	1.07	0.00052	85	**C3c-**

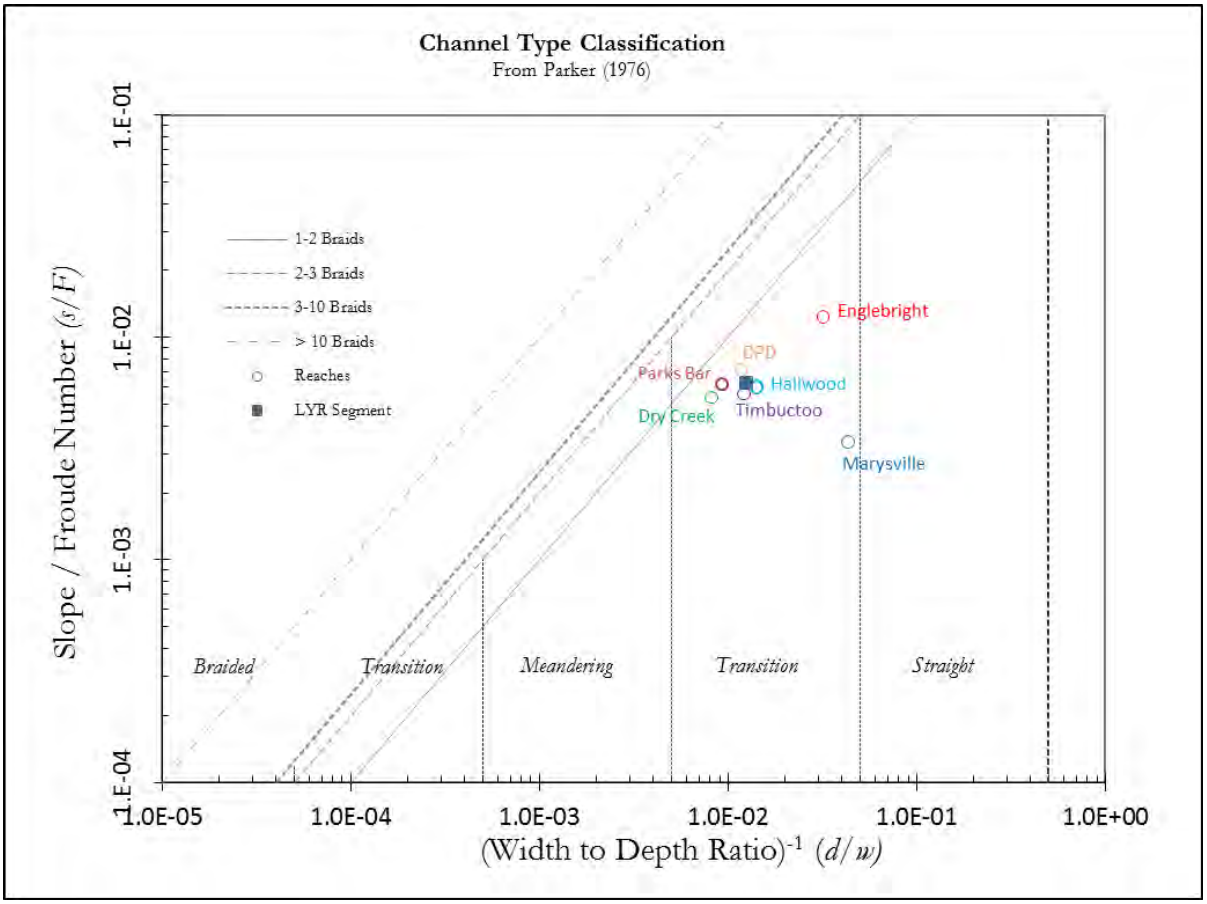

Figure 20. Channel type classification for LYR reaches based on Parker (1976).

Morphologic Unit Scale Analysis

Morphological Unit Definition

A review of the literature reveals several terms and definitions for discernable units of channel morphology at the ~10^0-10^1 W scale, such as “physical biotope” (e.g. Newson and Newson, 2000), “channel geomorphic unit” (e.g. Hawkins et al., 1993), “channel unit” (e.g. Grant et al., 1990), and “morphological unit” (e.g. Wadeson, 1994). There is little distinction in the literature between the definitions; therefore, the latter will be used in this study for consistency by preference. A morphological unit (MU) is defined by topographic forms within the channel and floodplain that represent distinct form-process associations (Thomson et al., 2001), and whose size is typically at the length scale equivalent of 1-10 channel widths (but can be smaller). Assemblages of morphological units exhibit both longitudinal and lateral variability within large rivers. The MU is a basic unit for assessing instream habitat considering that ecohydraulic variables such as depth, velocity and substrate have been shown to be closely controlled by channel morphology (Nanson and Nanson, 2000). It is important to note that an MU is not a habitat definition, and therefore not dependent on stage or discharge, but rather a classification of the landforms that create the environmental requirements of a biologic community. The meso-scale habitat (mesohabitat) reflects aquatic habitat conditions based on combinations of hydraulic and biologic conditions, and are therefore largely dependent on stage and discharge. The term "mesohabitat" is defined as the interdependent set of the ecohydraulic variables over a morphological unit. The term "microhabitat" (i.e., micro-scale habitat) is defined as the localized depth, velocity, temperature, and substrate at the hydraulic-unit scale without regard to the surrounding conditions. It is often possible to empirically relate ecological function to microhabitat variables (Bovee, 1986), but doing so provides a limited understanding of how and why fluvial-ecological linkages are spatially related. There is a general lack of studies that nest the micro-scale requirements of aquatic species within the meso-scale context of an assemblage of morphological units.

Previous studies have provided justification why morphological units should be able to explain fluvial-ecological relations. First, they are considered to be the "fundamental building blocks of rivers systems" (Brierly and Fryirs, 2000). Also at the meso-scale, the concept of morphological units has been proposed as a framework for classifying streams based on their physical characteristics that is typically linked to instream habitats (Padmore et al., 1998). Newson and Newson (2000) stated that a morphological unit approach "represents an important linking scale between the detail of micro-scale habitat hydraulics and the need for network-scale appraisals for management of channels and flows." Second, some studies have found that mesohabitat is a good predictor of fish utilization patterns (Geist and Dauble, 1998; Hanrahan, 2007). Finally, the type and distribution of morphological units have been found to be sensitive to land use within the watershed (Beechie et al., 2003). In terms of practicality, the meso-scale provides a manageable resolution of analysis that balances scientific detail with the potential for catchment-scale application (Padmore et al., 1998); the study of the form, function and distribution of morphological units is therefore useful both in terms of scaling-up to watershed scale estimates of habitat capacity and for assessing how this might be impacted by human activity (Frissell et al., 1986; Reeves et al., 1989; Beechie et al., 2001).

Previously, objective delineations of MU or mesohabitat have been difficult, with most studies focusing on qualitative observations of surface flow patterns, surface water slope, and localized point measurements of depth and velocity (e.g. Nanson and Nanson, 2000; Borsanyi et al., 2004). Using these methods however, mesohabitat maps are inherently subjective to the observer. In fact, Jowett (1993) described how the visual assessment of mesohabitat was partially influenced by classification of the area surrounding the observer rather than fully by the local conditions of the site. In addition to the possibility of field misidentification, there are also the issues of transferability across spatial scales and dependence on discharge range. Morphological units, in contrast, should be an objective classification that is based on the landform identification, despite recent innovations in the use of terrestrial laser scanning to identify water surface characteristics (Milan et al., 2010). For example, O'Neill and Abrahams (1984) described a method for objectively determining riffle crests and pool lows based on the longitudinal profile of a channel's bathymetry. They used variances in the topographic slope as the indicators since any method that involves depth and velocity would be inherently dependent on discharge. Large rivers, however, contain lateral variability across its widths that cannot accurately be captured with a 1D classification. Increased use in LiDAR and GIS applications has provided more robust datasets as the basis for increased MU variability and user objectivity. For example, Hauer et al. (2009) used LiDAR data to create a full-coverage areal map of the Kamp River, Austria that delineated binned values of velocity, depth and shear stress. They used an algorithm to objectively map mesohabitat regions for a range of discharges.

In prior studies on the lower Yuba River, both expert-based and semi-objective approaches have been tested prior to this study. Moir and Pasternack (2008) hand-delineated MUs at one pool-riffle-run sequence and then used results from a 2D hydrodynamic model and a Chinook red survey to demonstrate that their MUs were in fact hydraulically and ecologically distinct. Subsequently, Pasternack (2008) expanded the test domain to all of Timbuctoo Bend and used objective data sources (e.g. high-resolution topographic map, aerial-image-derived wetted area polygons, inferred depth maps for several discharges from the previous two sources combined, and other sources of information) to get as far as possible with objective classification, but then when it came down to the need to differentiate landforms on the basis of associated velocities, then that had to be done on an expert basis. This new study sought to make the entire baseflow landform delineation objective.

Morphological Unit Delineation Procedure

Ideally, detailed 3D topography of a riverbed and its floodplain would be objectively analyzed to delineate individual landforms, but no numerical method yet exists for that, although that is a popular topic of research at this time. A key challenge in that stems from the fact that landform properties are often non-stationary, so a simple rule cannot be repeated to work at all locations. Instead, the best available technology is that of 2D hydraulic models, since channel hydraulics closely reflect topographic variations (e.g. Pasternack et al., 2006). In general, the lower the discharge, the more hydraulics is steered by topography, because the flow has less momentum to drive itself. Still, prior to this study it was uncertain how sensitive the outcome is to the choice of low discharge value used in MU delineation. If the flow used is too low, then the wetted area is too small to matter, because the landforms are exposed, not underwater. If the flow used is too high, then the momentum of the water will be so high that hydraulics can drive themselves and not be steered by landform shape as well as some topographic controls can be drowned out (Pasternack et al., 2006; Wyrick and Pasternack, 2008). These high-flow conditions result in hydraulics with decreased longitudinal velocity variation. For example, past research has demonstrated that at low flow, rivers with bed undulations (e.g. riffle-pool morphology) are dominated by longitudinal velocity variation at low in-channel flows and lateral velocity variation at overbank flows (Stewardson and McMahon, 2002; Brown and Pasternack, 2008; Sawyer et al., 2010). Consequently, an in-channel low flow is most appropriate for delineating in-channel landforms in a river with bed undulations, such as the LYR. For the current study, this is the methodology that was employed. From experience and iteration, a flow of ~0.2-0.4 of bankfull dimensions yields water depths and velocities that are strong indicators of the underlying landform features, though a sensitivity analysis was also done to be sure. It is important to note that once identified, the MUs are not stage-dependent, even though low-flow hydraulics were used to infer the morphological patterns. They are the fixed landforms in the topographic map at the time the river corridor was surveyed; the hydraulics just help identify them.

The approach used in this study was to delineate in-channel morphologic unit types quantitatively using the 2D-model baseflow hydraulics and then inspect the unit types to assign names to them consistent with geomorphic lexicon. To do this, 3x3 ft^2 depth and velocity rasters were generated from SRH-2D model results and then ArcGIS Spatial Analyst was used to generate trial morphological unit patterns with a variety of possible depth and velocity thresholds. Resulting trial patterns were overlain on ~3 ft resolution NAIP imagery and a visual inspection made to determine if each trial pattern made sense. The co-authors who performed the analysis have years of ground-based experience with the river that also aided evaluation and interpretation of trial patterns. In addition, the RMT's river managers, aquatic biologists, and data collection staff provided input about the veracity of the number of MUs and their specific depth and velocity threshold values. This led to a trial-and-error sensitivity analysis to examine the performance of different classification details. Even though the classification scheme included expert-based setting of thresholds, once those were established, ArcMap Spatial Analyst objectively delineated the actual spatial pattern of morphological units. Compared to an individual drawing lines on a map, this more objective and much more detailed. The hydrodynamic model results were used to delineate eight in-channel morphological units (Table 6) based on quantitative thresholds of depth and velocity (Figure 21) in ArcGIS. For the bar units (those that exist between the baseflow wetted area and bankfull boundary), floodway units (those between the bankfull boundary and the flood boundary), and the off-channel units (those outside the flood wetted area) (See examples of these inundation zones in Figure 6), a combination of topographic contours, sediment change maps, and aerial imagery was used to hand-delineate distinct morphological units based on the qualitative descriptions in Table 6. A more detailed procedure for delineating the morphological units along the LYR in ArcGIS is available in the Specific Sampling Protocols and Procedures for Delineating Morphological Units report (Wyrick and Pasternack, 2011). This method resulted in a morphologic unit map for the wetted channel that was used in the geomorphic and hydraulic analyses presented herein. Morphological unit delineations were visually compared against field experience.

By way of comparison, this approach is similar to supervised cluster analysis in that the expert defines the number of units (e.g., Johnson, 1967; Maxwell et al., 2002). A supervised cluster analysis involves selecting the beginning centroids of clusters ("seeds") and having the boundaries be calculated mathematically. The choice of seeds can impact the final cluster delineations, which is not desirable. Also, supervised cluster analysis aims to find the combinations of depth and velocity with the most occurrences of observations in the smallest area, but such a cluster is not necessarily representative of a landform at the morphological-unit scale. In the approach presented herein, the boundaries are selected based on experience with the study segment, iterative trial, and consultation with local river scientists and managers. The boundaries are more important to identifying landforms than the centroids, so carefully choosing those is more important than carefully choosing the centroids.

Table 6a. Qualitative descriptions of in-channel bed morphological units mapped in the LYR.

Type	Unit Name	Description
In-Channel Bed	Chute	Area of high velocity, steep water surface slope, and moderate to high depth located in the channel thalweg. Chutes are often located in a convergent constriction downstream of a riffle as it transitions into a run, forced pool, pool, or glide.
	Fast Glide	Area of moderate velocity and depth and low water surface slope. Commonly occur along periphery of channel and flanking pools. Also exist in straight sections of low bed slope.
	Pool / Forced Pool	Pools are areas of high depth and low velocity, and low water surface slope. The distinction between 'forced pool' and 'pool' cannot be made automatically within GIS. A 'forced pool' is one that is typically along the periphery of the channel and is "over-deepened" from local convective acceleration and scour during floods that is associated with static structures such as wood, boulders, and mostly bedrock outcrops. A 'pool' is not formed by a forcing obstruction.
	Riffle	Area with shallow depths, moderate to high velocities, rough water surface texture, and steep water surface slope. Riffles are associated with the crest and backslope of a transverse bar.
	Riffle Transition	Typically a transitional area between an upstream morphological unit into a riffle, or from a riffle into a downstream morphological unit. Water depth is relatively low. Velocity is low, but increases downstream due to convective acceleration toward the shallow riffle crest that is caused by lateral and vertical flow convergence. The upstream limit is at the approximate location where there is a transition from a divergent to convergent flow pattern. The downstream limit is at the slope break of the channel bed termed the riffle crest.
	Run	Area with a moderate velocity, high depths, and moderate water surface slope. Runs typically occur in straight sections that exhibit a moderate water surface texture and tend not to be located over transverse bars.
	Slow Glide	Area of low velocity and low to moderate depths and low water surface slope. May be located near water's edge as a morphological unit along the channel thalweg transitions laterally towards the stream margins.
	Slackwater	Shallow, low-velocity regions of the stream that are typically located in adjacent embayments, side channels, or along channel margins. Velocities are near stagnant during baseflow conditions and rise slower than other bed units' as stage increases.

Table 6b. Qualitative descriptions of in-channel bar morphological units mapped in the LYR.

Type	Unit Name	Description
In-Channel Bar	Lateral Bar	Area located at the channel margins at an elevation band between the autumnal low-flow stage and bankfull stage. Lateral bars are orientated parallel to the flow. The feature slopes toward the channel thalweg with an associated increase in both flow depth and velocity when submerged. Sediment size tends to be smaller than in adjacent sections of the channel.
	Medial Bar	Area that is separated from the channel banks at low-flow stages at an elevation band between low-flow and bankfull stages. Can be accreting or eroding.
	Point Bar	Accreting area located on the inside of a meander bend at an elevation band between the low-flow stage and bankfull stage. Point bars are curved and begin where there is clear evidence of point-bar deposition. The feature slopes toward the channel thalweg with an associated increase in both flow depth and velocity when submerged. Sediment size tends to be smaller than in adjacent sections of the channel.
	Swale	A weakly-defined geometric channel or adjacent bench on the floodplain that only conveys flow at stages above low-flow.
	Bridge Pier*	Man-made structural supports for road and rail crossings. Typically composed on concrete and steel. Units also exist at stages above Bankfull flow to a lesser extent.

Table 6c. Qualitative descriptions of floodway morphological units mapped in the LYR.

Type	Unit Name	Description
Floodway	Floodplain	Natural alluvium located at an elevation higher than the bankfull channel and lower than the upper wetted extent of the floodway (defined as 21,100 cfs here).
	Flood Runner	Relatively straight floodplain channel with uniform geometry and low depths that conveys a concentrated flow at stages above bankfull.
	Island-Floodplain	Natural alluvium on a medial bar located at an elevation higher than the bankfull channel and lower than the upper wetted extent of the floodway (defined as 21,100 cfs here).
	Mining Pit	Artificial depression created for mining purposes that is adjacent to the flow channel and continuously wetted. May have an artificial connection to floodway channel that is normal to the flow direction.
	Backswamp*	Natural depression within the floodplain whose bed elevation intersects with the groundwater table creating a continuously wetted or swampy area. Typically contains vegetation. Units also exist within Bankfull and Valley boundaries to a lesser extent.
	Pond*	Natural depression with a continuously measurable depth located on the floodplain and is not attached to the main channel by a surface opening during the low flow at which the in-channel bed morphological units are mapped. Units also exist within Bankfull boundaries to a lesser extent.
	Tributary Channel*	Those sections of perennial tributary streams that are located within the bankfull and higher wetted areas of the main channel. Units also exist within Bankfull and Valley boundaries to a lesser extent.
	Spur Dike*	Artificial bank protection composed of very large riprap. Usually located along steep banks to prevent further erosion. Units also exist within Bankfull and Valley boundaries to a lesser extent.

Table 6d. Qualitative descriptions of morphological units mapped in the LYR that are off-channel, but within the active geomorphic valley width.

Type	Unit Name	Description
Valley	Terrace	A natural alluvial deposit separated from the floodplain surface by a vertical topographic riser. Terraces are generally abandoned floodplains that have been separated from the channel by vertical incision of lateral migration.
	High Floodplain	Natural alluvium located between the terrace riser and the 21,100 cfs wetted area floodplain.
	Island-High Floodplain	Natural alluvial deposit on a medial bar located at an elevation higher than the island-floodplain surface.
	Levee	Artificially-built flood control berm located parallel to the channel.
	Hillside / Bedrock*	Natural colluvium and bedrock at an elevation greater than the valley toe slope break. Units also exist within the Bankfull and Floodway boundaries to a lesser extent.
	Bank*	Steep, near-vertical bank that separates bar units from terraces. Gravel/cobble alluvium that line the main channel and not actively experiencing lateral erosion. Units also exist within the Bankfull and Floodway boundaries to a lesser extent.
	Cutbank*	Steep, near-vertical bank that separates bar units from terraces. Located on the outside of a meander bend and created by active lateral erosion through local alluvia. Units also exist within the Bankfull and Floodway boundaries to a lesser extent.
	Agriplain*	Agriculture field inundated at flows higher than bankfull. These units also exist within the Floodway boundary to a lesser extent.
	Tailings*	Steep alluvium artificially piled up adjacent to the channel during historic gold dredging operations. Units also exist within the Bankfull and Floodway boundaries to a lesser extent.
	Tributary Delta*	Alluvial fans penetrating the floodplain and main channel at tributary junctions. Units also exist within the Bankfull and Floodway boundaries to a lesser extent.

All of the In-channel Bed units are bounded by the baseflow wetted area (880/530 cfs). The bankfull wetted area (5,000 cfs) bounds the Lateral Bar, Medial Bar, Point Bar, and Swale units. The flood wetted area (21,100 cfs) bounds the Floodplain, Flood Runner, Island-Floodplain and Mining Pit units. Some sections of the other Floodway type units may be wetted at higher or lower flows, but are not delineated at all below the baseflow regime. The Terrace, High Floodplain, Island High Floodplain, and Levee units are only delineated within the areas outside of the 21,100 cfs wetted area. Some sections of the other Valley type units may be wetted at lower flows (except baseflow).

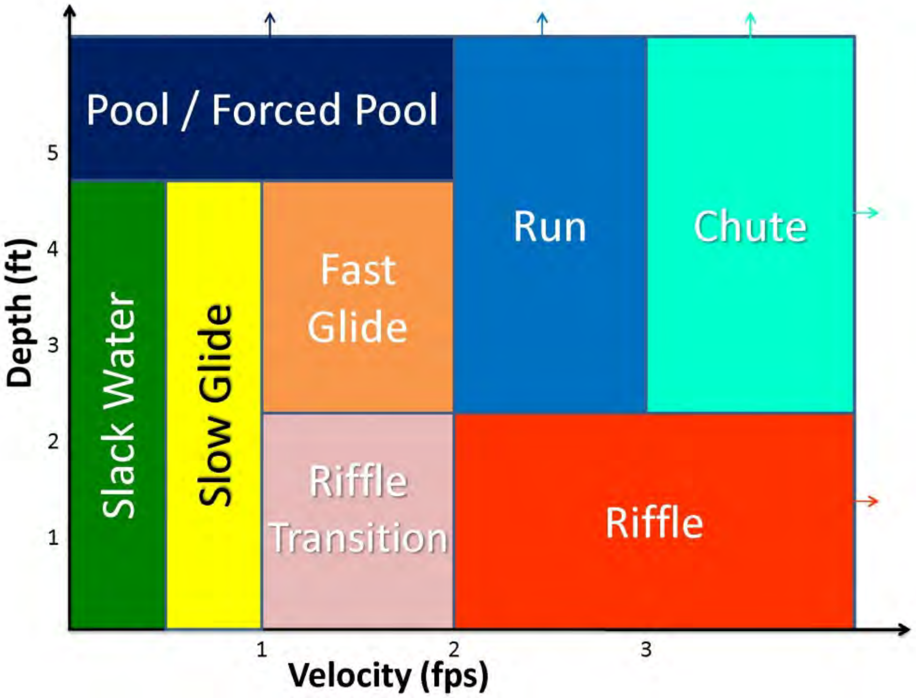

Figure 21. Baseflow hydraulics used to delineate in-channel morphological unit domains

An example application of the morphological units mapping is illustrated in Figure 22 - Figure 25 for the Rose Bar area of Timbuctoo Bend (~ RM 23). Results from the baseflow depth and velocity rasters were stratified into discrete areas that represent thresholds of the morphological unit classification metrics (Figure 22, Figure 23). These baseflow units were automatically delineated within ArcGIS (See: Specific Sampling Protocols and Procedures for Delineating Morphological Units report (Wyrick and Pasternack, 2011) for more details on this procedure).

The areal differences between the baseflow and bankfull wetted areas are the regions that were manually delineated into the suite of Bar units, and those between bankfull and flood wetted areas were manually delineated into the suite of Floodway units (Figure 24). Examples of these objectively delineated morphological units are highlighted in Figure 25 and Figure 26. The remaining surface areas that exist outside of the floodway region but still within the geomorphically-active valley were manually delineated into the suite of Valley units.

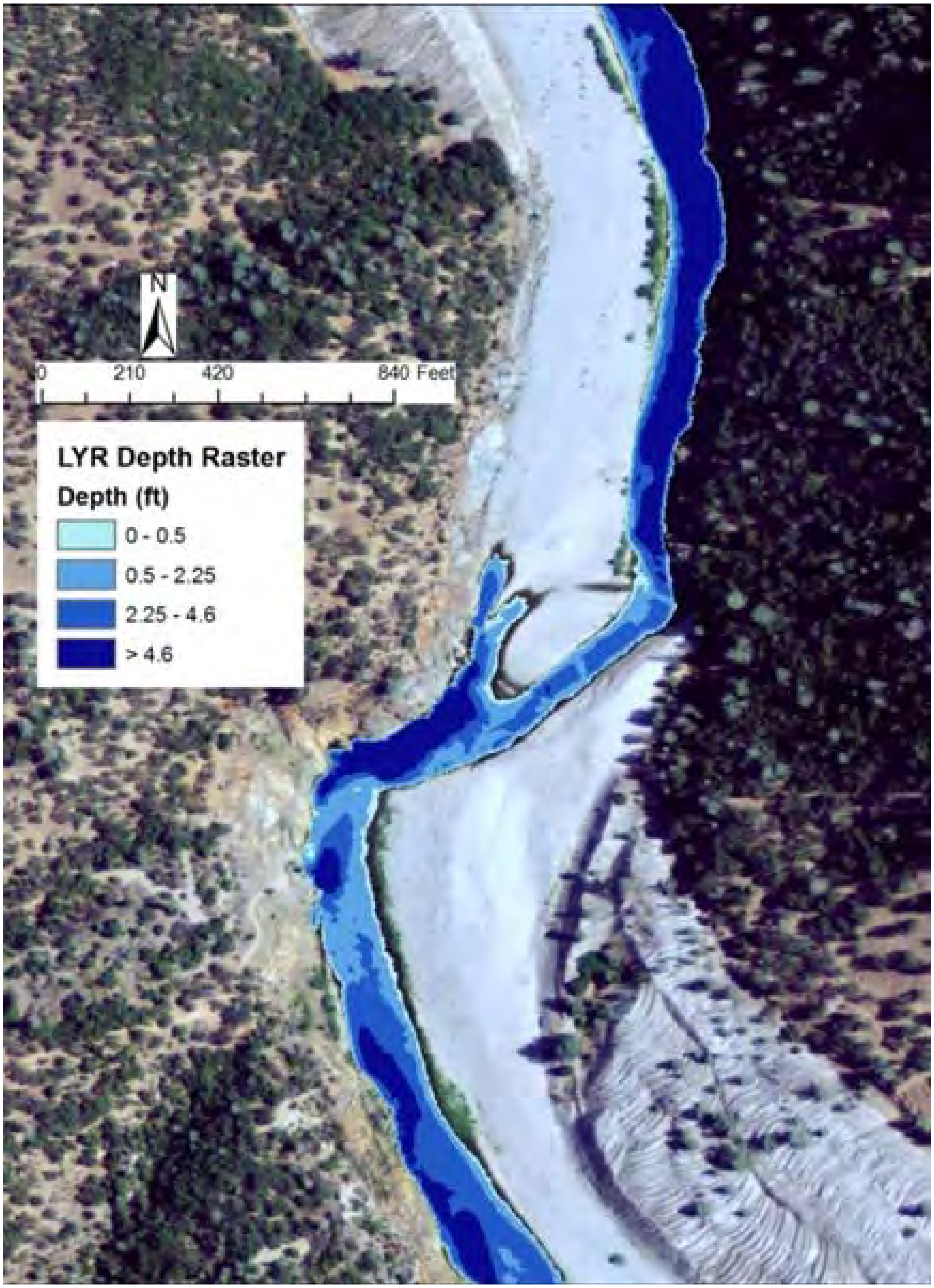

Figure 22. Depth raster for baseflow conditions at Rose Bar (Timbuctoo Bend reach) stratified into MU classification hydraulic metrics. Base image is 2009 NAIP.

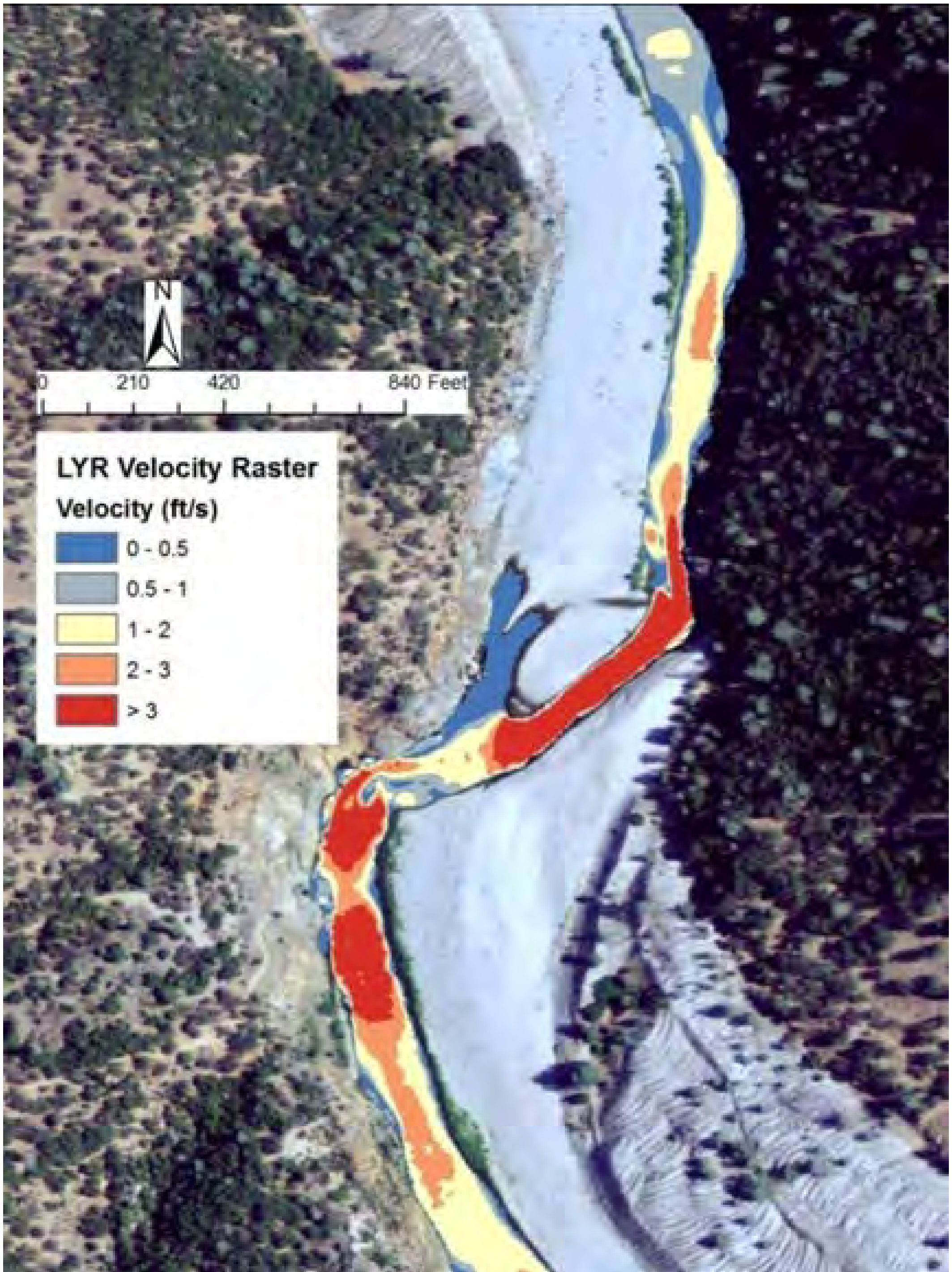

Figure 23. Velocity raster for baseflow conditions at Rose Bar (Timbuctoo Bend reach) stratified into MU classification hydraulic metrics. Base image is 2009 NAIP.

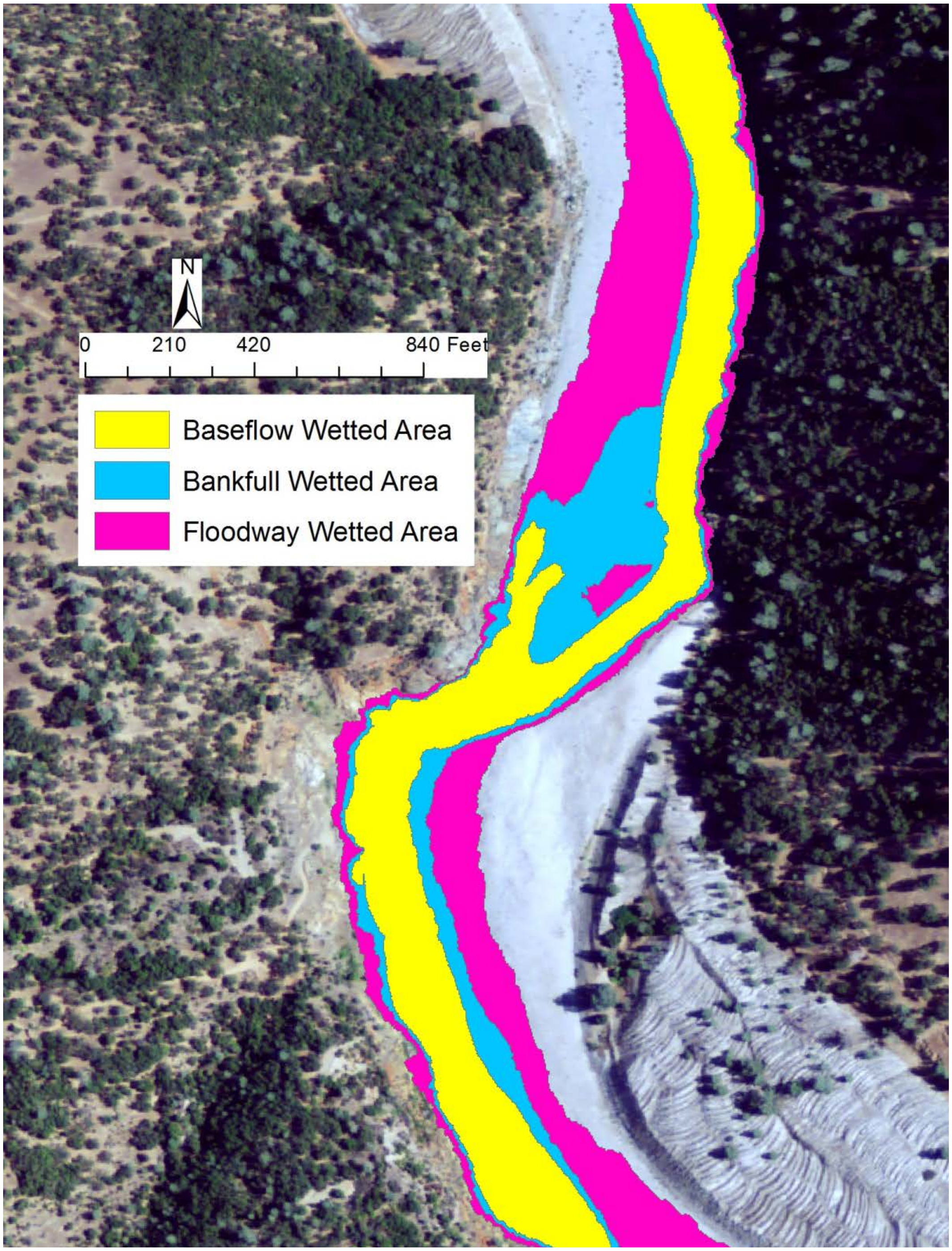

Figure 24. Baseflow, bankfull, and floodway wetted areas used to delineate boundaries for in-channel, bar, and floodplain units. Terrace units are located outside of the floodway wetted area.

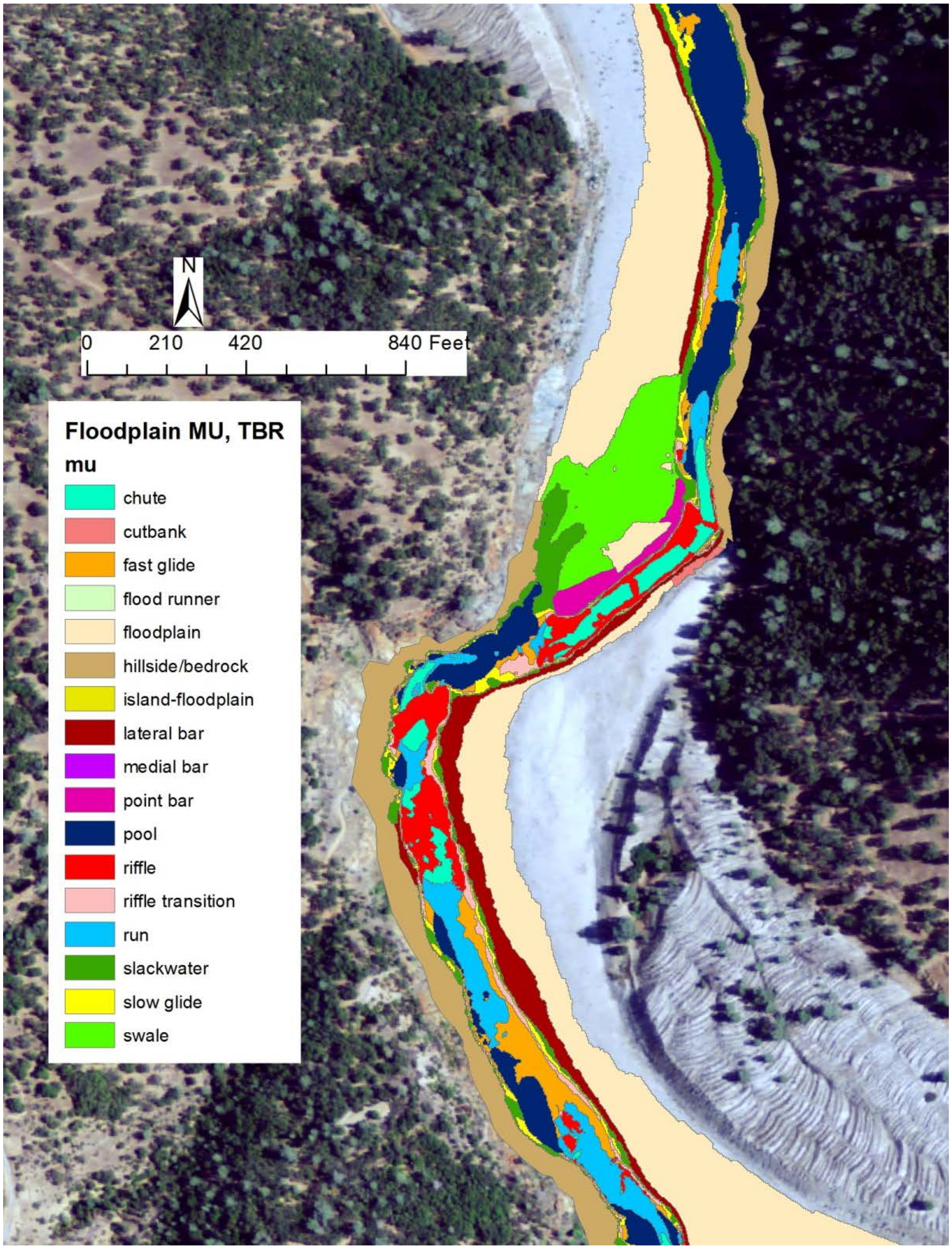

Figure 25. Morphological units map of the In-channel and Floodway types for Rose Bar (Timbuctoo Bend reach). Base image is 2009 NAIP.

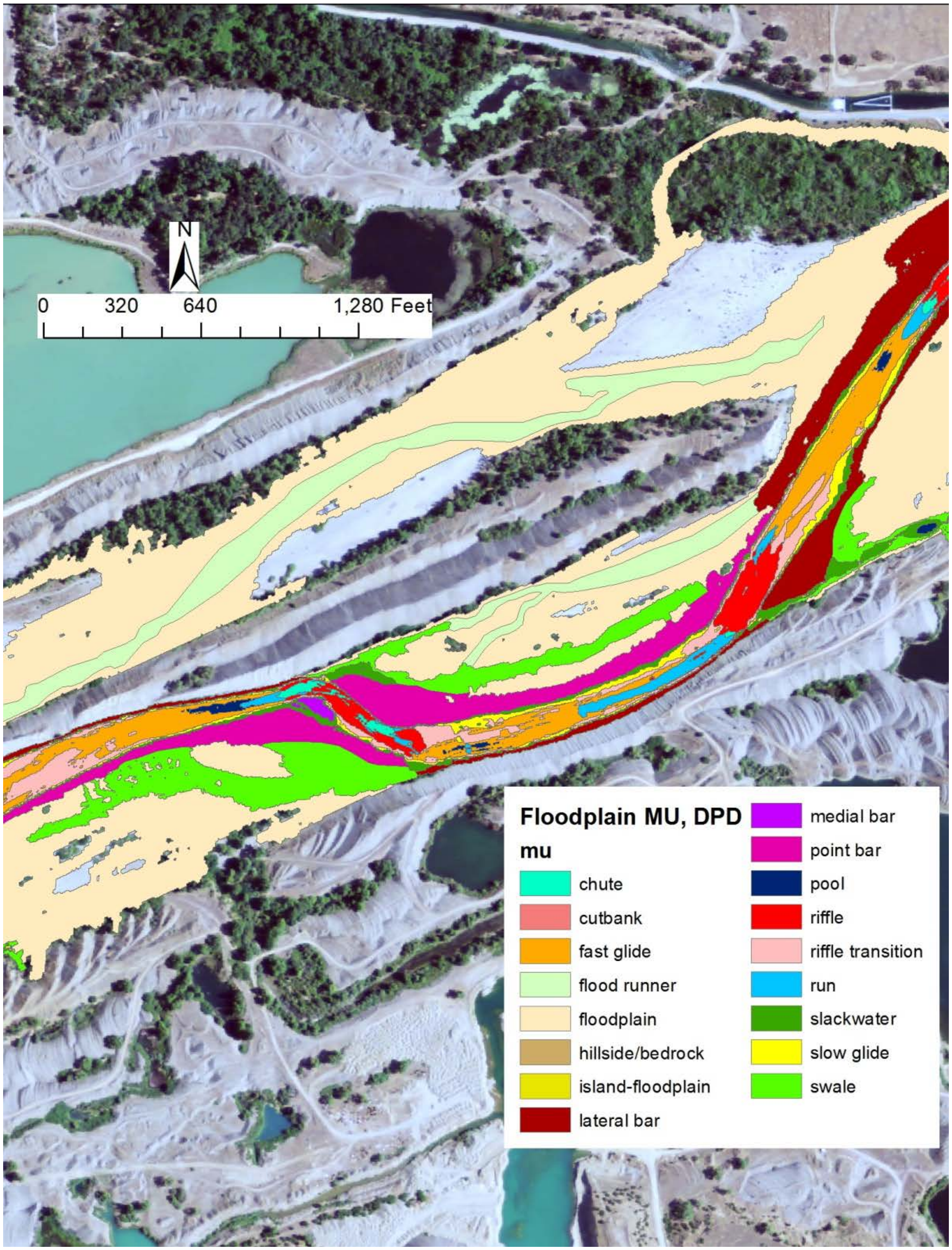

Figure 26. Examples of morphological unit distribution of the In-channel and Floodway types in the DPD Reach just below the Daguerre Point Dam. Base image is 2009 NAIP.

The delineation procedures for the units outside of the baseflow inundation region (e.g., Figure 6 and Figure 24) utilized all available data, such as topography contours, DEM difference maps, and depth and velocity rasters, to reduce the subjectivity as much as possible while still adhering to the qualitative descriptions in Table 6. Within the bankfull channel, Point Bar and Lateral Bar units are manually separated and delineated by the location of the transition between erosion and deposition from a DEM difference map at or near a meander bend (Figure 27). The outer boundary of Floodplain unit is automatically delineated as the 21,100 cfs wetted area. The area between a Floodplain and the Valley boundary may transition as either High Floodplain or Terrace, depending on the location of any steep alluvial risers. The transition between Floodplain and High Floodplain is gradual and is only distinguished by the 21,100 cfs wetted boundary (Figure 28). The transition between either Floodplain or High Floodplain and Terrace, however, is distinguished by a steep rise that leads to another flat alluvial surface at some higher elevation (Figure 29). These transitions were manually delineated with the aid of 1-ft contour maps. Cutbanks were visually identified in the field and located with a handheld GPS unit in order to delineate them within ArcGIS.

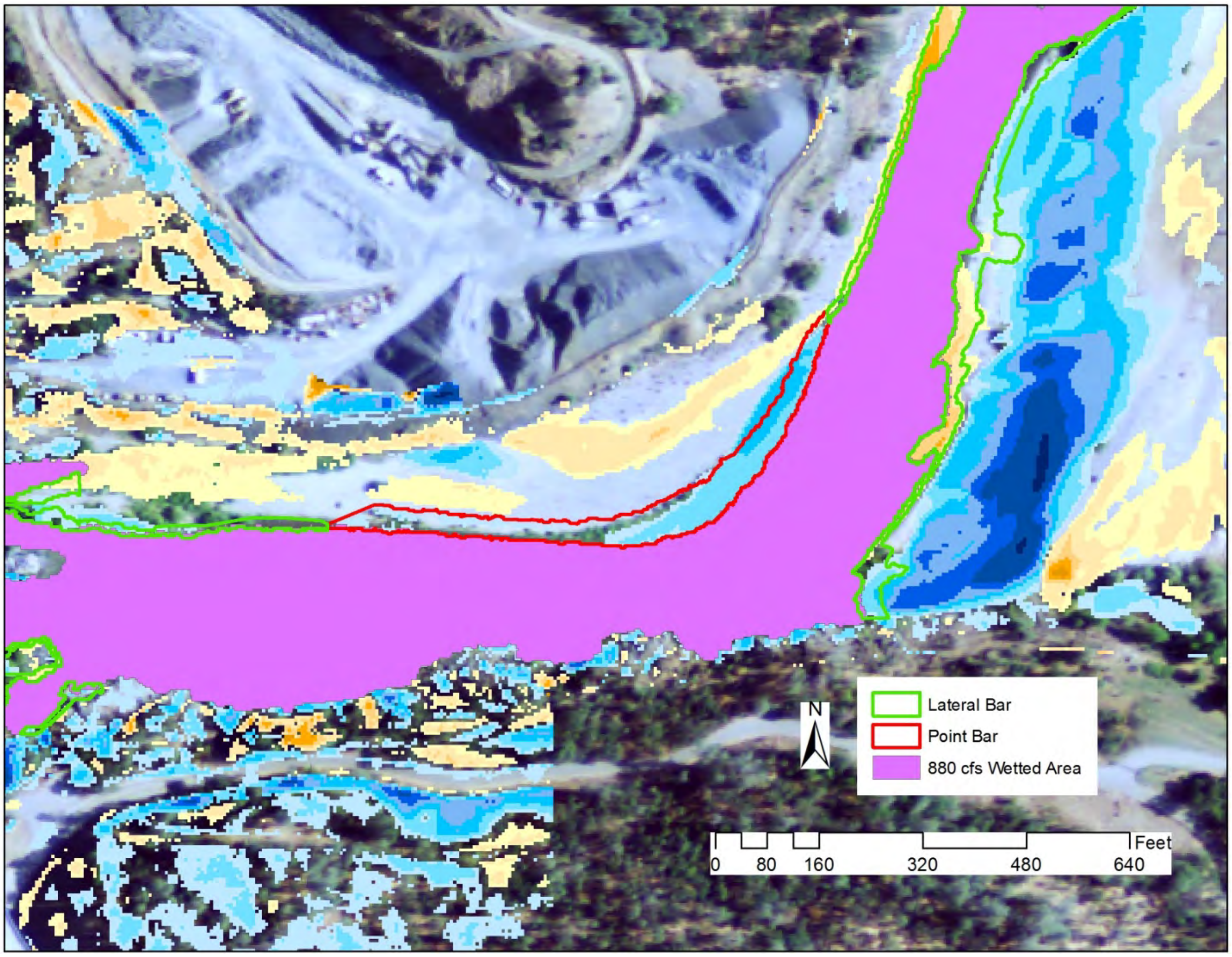

Figure 27. Example of a Point Bar (located just upstream of Highway 20) that has been manually delineated to encompass those areas on the inside bend of the bankfull channel that are experiencing deposition (blue shades within the red outline), as distinguished from the areas of erosion (orange shades) that are delineated as Lateral Bar (green outlines).

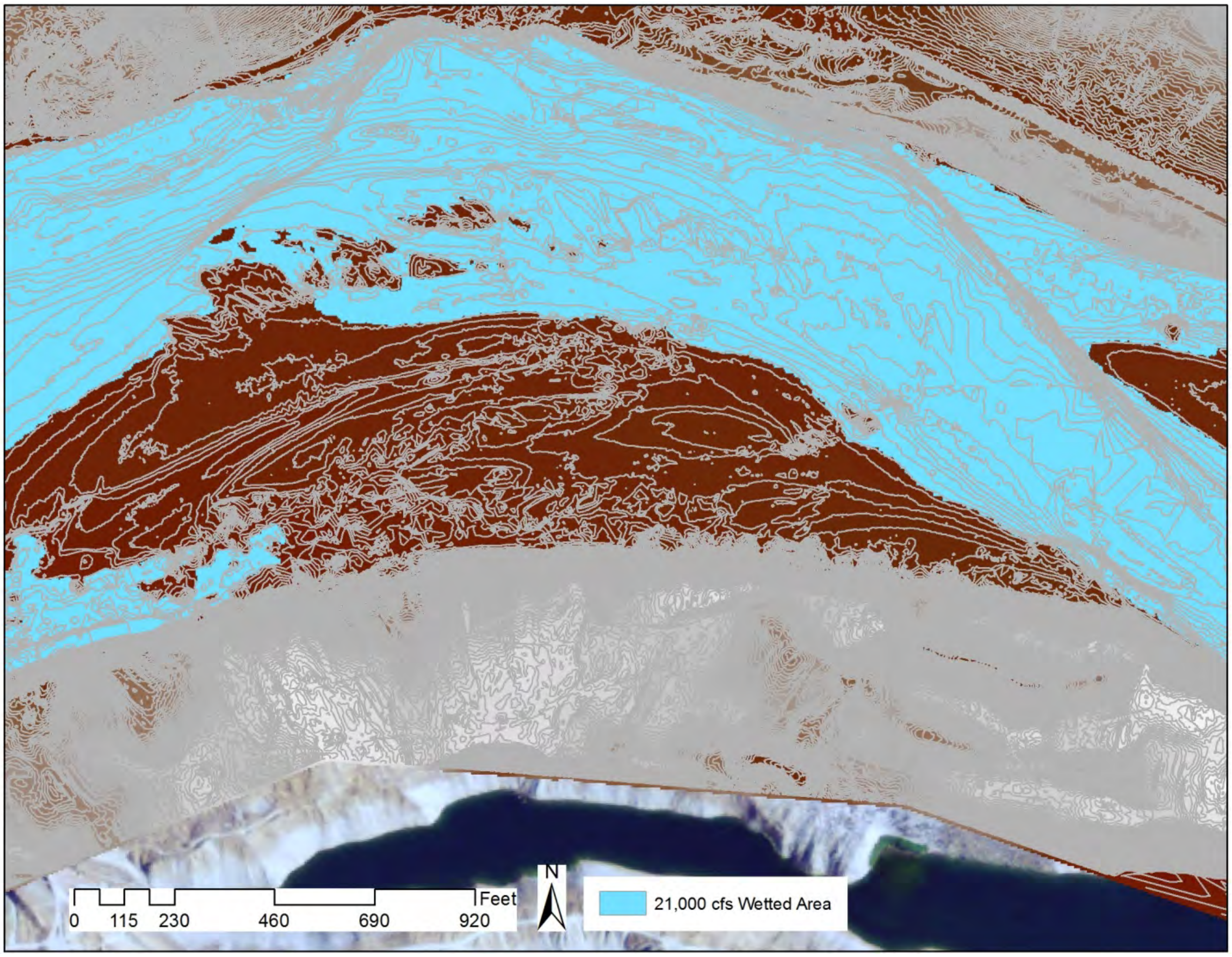

Figure 28. Example of the gradual transition between Floodplain and High Floodplain units. The light blue area is the wetted surface of the 21,100 cfs flow, which would include the Floodplain units. The dark brown areas on the south side exhibit no steep alluvial distinction from this wetted channel, as highlighted by the 1-ft contours (grey lines), therefore these areas would be classified as High Floodplain. Note that just to the south of the brown area is a topographic riser, as indicated by the dense contours.

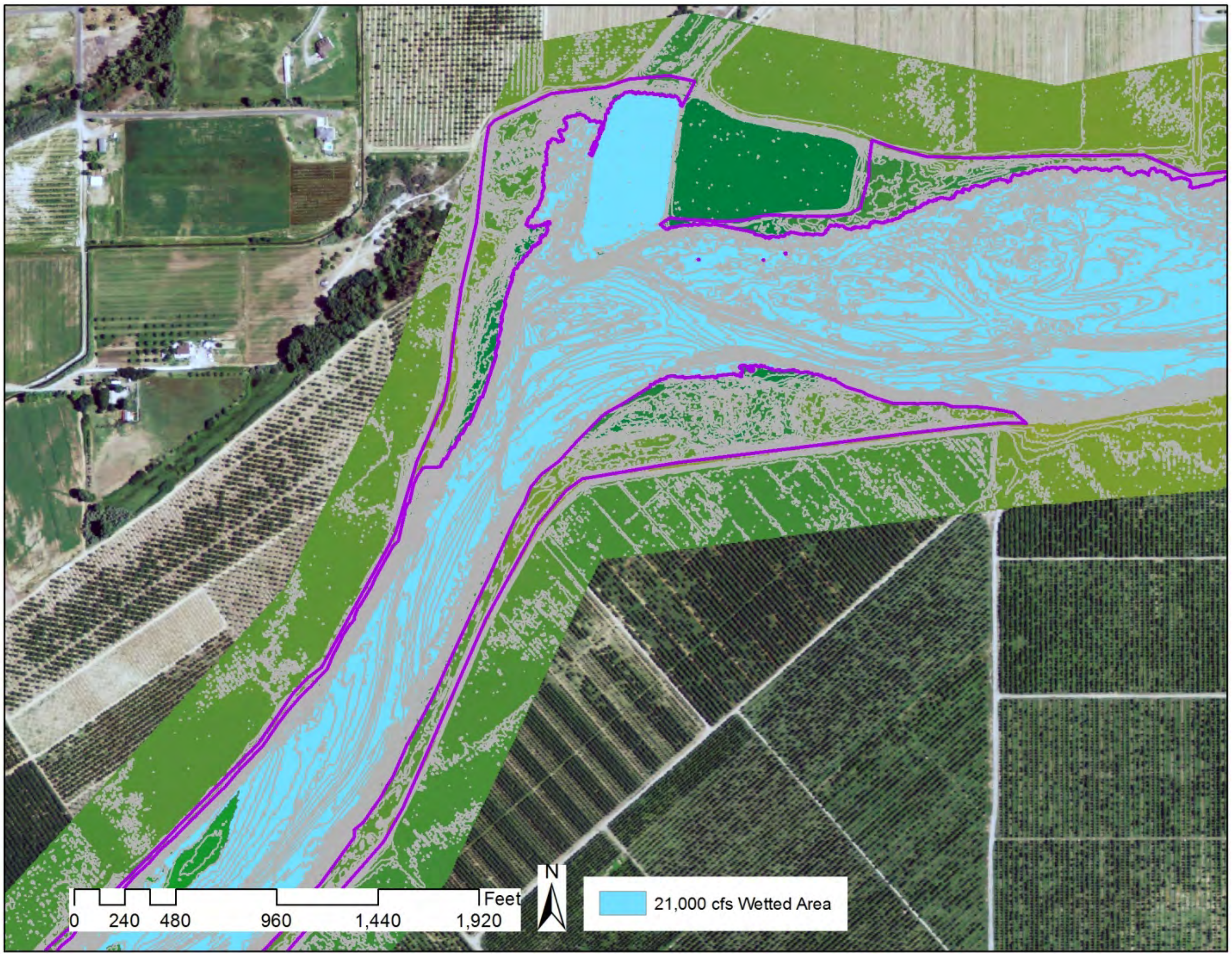

Figure 29. Example of Terrace classification. The blue area represents the 21,100 cfs wetted channel. In this example, the channel abuts against some steep topography on both banks. Therefore the areas outlined in purple would be classified as Terrace, not High Floodplain.

The presence of swales along the valley floor throughout the segment corridor (e.g., Figure 25 and Figure 26) illustrates the complexity in delineating a true bankfull discharge regime. In some regions at 5,000 cfs, the water is flowing over the floodplain sediments through weakly-defined channels separated from the main channel. The longitudinal and lateral complexity of the geomorphic corridor is visually apparent within the morphological unit maps (Figure 25 and Figure 26). The following sections will statistically analyze the randomness and variability inherent within the distribution of these units.

Selection of Low Flow Discharge for Morphological Unit Delineation

The protocol for the delineation of instream channel morphological units calls for utilizing low-flow hydraulics as the indicator of MU landforms. The low-flow regime on the LYR is roughly 500<Q<1500 cfs (<0.25 times bankfull discharge). In this study, the choice was made to use the 2D model output data from a flow of 880cfs above Daguerre Point Dam (DPD). This is a commonly occurring low flow in non-flood periods throughout the year, because flow releases are operated to be somewhat above the minimum instream flow requirement. According to the Lower Yuba River Fisheries Agreement, Schedule A years for flows above DPD (i.e., those in

Schedule 1, 2, 3, or 4 years for the Marysville gage below DPD) have a minimum requirement of 700 cfs, so there is absolutely no reason to pick a discharge below that as the basis for delineating MUs. To test the robustness of the choice of using 880 cfs, the same hydraulic delineations were applied to flows of 700 cfs (~20% less) and 1000 cfs (~14% greater). The total wetted area above DPD at 880cfs is 11,740,832 ft^2. The total wetted area at 700 cfs is 11,514,734 ft^2, a decrease of 1.9%. The total wetted area at 1000 cfs is 12,103,873 ft^2, an increase of 3.1% (i.e., much less than the differences in discharge).

As a first sensitivity analysis, the same MU hydraulic thresholds as derived for the 880 cfs regime (Figure 21) were applied to the 700 cfs and 1000 cfs rasters. The total number, areal coverage (sq ft), and percent area of each MU were compared to the original 880 cfs results (Table 7). Without any adjustments to the metric thresholds or raster boundaries, there are minimal differences in total percent area (within ±1%) for the Fast Glide, Pool, and Riffle morphological units between all three flow regimes (Table 8). Between the 700 cfs and 880 cfs hydraulics, the greatest differences are in the total coverage of Run, Slackwater, and Chute units. The weighted average absolute difference in MU areas is 1.53%. Between 880 cfs and 1000 cfs, the greatest differences are in the Chute, Run, and Slow Glide units, and the weighted average absolute difference is 0.85% (Table 8).

Table 7. Comparison of morphological unit delineations for different low flows using the same class thresholds as in to the 880 cfs delineation. Note that the test area is the region above DPD.

	Count			Area (sq ft)			Percent Area		
MU **cfs**	*880*	*700*	*1000*	*880*	*700*	*1000*	*880*	*700*	*1000*
Chute	458	499	505	796,932	452,106	1,067,826	6.79%	3.93%	8.82%
Fast Glide	1813	1509	1801	1,515,130	1468452	1501014	12.90%	12.75%	12.40%
Pool	515	447	511	1,509,150	1,483,743	1,505,476	12.85%	12.89%	12.44%
Riffle	1312	1154	1518	1,900,610	1,891,718	1,887,049	16.19%	16.43%	15.59%
Riffle Trans	4137	3281	3607	1,498,040	1,646,728	1,442,357	12.76%	14.30%	11.92%
Run	1003	981	1038	1,411,170	938,053	1,653,541	12.02%	8.15%	13.66%
Slack water	7900	6137	7074	1,740,010	2,052,611	1,778,842	14.82%	17.83%	14.70%
Slow Glide	7777	7463	8626	1,369,790	1,581,323	1,267,767	11.67%	13.73%	10.47%
Total LYR	24915	21471	24680	11740832	11514734	12103873			

Table 8. Absolute differences in coverage area percentages between varying flow regimes and original 880 cfs regime for all morphological units using unadjusted hydraulic metrics. The Total LYR percentages are weighted by total coverage area of each MU (Table 7)

MU	700 cfs	1000 cfs
Chute	2.86%	2.03%
Fast Glide	0.15%	0.50%
Pool	0.03%	0.42%
Riffle	0.24%	0.60%
Riffle Transition	1.54%	0.84%
Run	3.87%	1.64%
Slackwater	3.01%	0.12%
Slow Glide	2.07%	1.19%
Total LYR	**1.53%**	**0.85%**

For the next comparison, the original 880 cfs hydraulic thresholds were adjusted to better suit the hydraulics of the 700 cfs and 1000 cfs rasters. In order to determine how much to adjust the thresholds, the first step was to create equal-area rasters of each flow by clipping the depth and velocity rasters to the same wetted area (the smaller of the two flow regime wetted areas being compared). The equal-area rasters were then subtracted from each other, i.e., the 700 cfs rasters were subtracted from the 880 cfs rasters, and the 880 cfs rasters from the 1000 cfs rasters. The differences between each raster sets were calculated and averaged using statistical analysis tools in ArcGIS. These average differences were used to shift the original delineating hydraulic metrics for the new flow regimes.

As a simple test of threshold adjustment, all MU hydraulic metric boundaries in Figure 21 were shifted an equal amount accordingly. For the 700cfs regime, the hydraulic metrics were shifted down by a uniform 0.20 ft and 0.20 ft/s for depth and velocity, respectively. For the 1000cfs regime, the hydraulic metrics were shifted up by a uniform 0.163 ft and 0.164 ft/s. In full implementation of the morphological unit protocol, individual boundaries could be adjusted individually and independently to minimize the differences resulting from choice of discharge is used, as was done for the original 880 cfs hydraulics.

After adjusting the MU threshold metrics for the 700 cfs and 1000 cfs flows, the total number, areal coverage (sq ft), and percent area of each MU were compared to the original 880 cfs results (Table 9). The differences in the total MU areas between the 700 cfs and 880 cfs analyses generally reduced as compared to the unadjusted-metrics analysis (Table 9). Individually, six of the eight units experienced a convergence to equal total areal percentages as the 880 cfs. Fast Glide and Pool areal differences increased, but are still within ±1%. The greatest differences are still with the Slackwater and Slow Glide, units typically located along the baseflow channel margins and therefore more susceptible to changes in wetted area. Overall the weighted average absolute difference in MU area percentages reduced from 1.53% to 0.85% using the adjusted hydraulic metrics (Table 8, Table 10).

The differences accrued for the 1000cfs adjusted metrics comparison are all within ±1%, except for Slackwater (Table 9, Table 10). Five of the eight MUs experienced a decrease in absolute area difference percentages. Fast Glide, Pool, and Slackwater difference percentages experienced an increase. Overall the weighted average absolute difference in MY area percentages increased slightly from 0.85% to 0.9% using the adjusted hydraulic metrics (Table 8, Table 10).

Table 9. Comparison of morphological unit delineations for different low flow regimes using adjusted hydraulic metrics.

		Count			Area (sq ft)			Percent		
MU	cfs	*880*	*700*	*1000*	*880*	*700*	*1000*	*880*	*700*	*1000*
Chute		458	513	444	796932	691383	796262	6.79%	6.00%	6.58%
Fast Glide		1813	1818	1688	1515130	1603124	1451237	12.90%	13.92%	11.99%
Pool		515	446	487	1509150	1525533	1500328	12.85%	13.25%	12.40%
Riffle		1312	1397	1346	1900610	1859921	1943994	16.19%	16.15%	16.06%
Riffle Trans		4137	3411	3559	1498040	1550575	1506581	12.76%	13.47%	12.45%
Run		1003	1027	982	1411170	1322189	1373430	12.02%	11.48%	11.35%
Slack water		7900	11748	7074	1740010	1460282	2162572	14.82%	12.68%	17.87%
Slow Glide		7777	7210	8588	1369790	1501730	1369470	11.67%	13.04%	11.31%
Total LYR		**24915**	**27570**	**24168**	**11740832**	**11514737**	**12103873**			

Table 10. Absolute differences in coverage area percentages between varying flow regimes and original 880 cfs regime for all morphological units using adjusted hydraulic metrics. The Total LYR percentages are weighted by total coverage area of each MU (Table 9)

MU	700 cfs	1000 cfs
Chute	0.78%	0.21%
Fast Glide	1.02%	0.91%
Pool	0.39%	0.46%
Riffle	0.04%	0.13%
Riffle Transition	0.71%	0.31%
Run	0.54%	0.67%
Slackwater	2.14%	3.05%
Slow Glide	1.37%	0.35%
Total LYR	**0.85%**	**0.90%**

Visually, the MU maps for all the flow hydraulic metrics are very similar (Figure 30, Figure 31). The percentage differences seem to have mostly affected the smaller MU polygons. This is evidenced by the highest percent differences being associated with those MUs that exhibit the highest number of smallest polygon sizes (i.e., Slackwater and Slow Glide). The larger, and more field-identifiable, MU polygons are in the same locations across each analysis, with negligible changes to their perimeters.

This sensitivity analysis finds only minor differences in morphological unit delineations that arise from using different specific discharge values to characterize the hydraulics of the low-flow regime. The hydraulic metrics used with the 880cfs regime were initially based on expected parameters for each unit, but then adjusted accordingly based on user knowledge of the river morphology. Comparing both the unadjusted and uniformly adjusted MU maps of the new flow regimes to the original 880 cfs map reveal some minor differences. It should be noted that this sensitivity analysis was not meant to explore the proper methodology for applying MU hydraulic metrics to different flow regimes, but rather explore the differences that any methodology has to the original MU maps. That being said, applying a uniform shift to the 700 cfs hydraulic metrics achieved an MU map that was more similar to the original map than using the unadjusted metrics, while the uniform shift applied to the 1000 cfs metrics created an MU map with slightly greater differences relative to the unadjusted metrics. Had either of these discharges, or any other low flow discharge, been chosen to use as the basis for instream bed units, then those metrics would have also been subjected to manual adjustments (not uniform shifts) to fit the known river (as was done for the 880 cfs regime metrics), and perhaps a map even more similar to the original 880 cfs would have been produced. However, even applying only a uniform shift to the hydraulic metrics, the maps and percent areas of MUs are still similar to within ±1%.

In conclusion, sensitivity analysis shows that the MU delineation procedure has little sensitivity to the exact value of discharge used. Using 700, 880, or 1000 cfs would not yield significantly different geomorphic interpretations of the physical spatial structure of in-channel landforms in the LYR. The reason is that small systematic shifts in discharge generally yield disproportionately smaller systematic shifts in depth and velocity, so the spatial pattern is mostly unchanged. This is to be expected based on what is known about at-a-station hydraulic geometry relations, which state that the depth is proportional to Q^b and velocity is proportional to Q^m, where 'b' and 'm' are both less than one (Leopold and Maddock, 1953). As a result, it is justifiable to proceed using the 880 cfs simulation, MU delineation, and analysis.

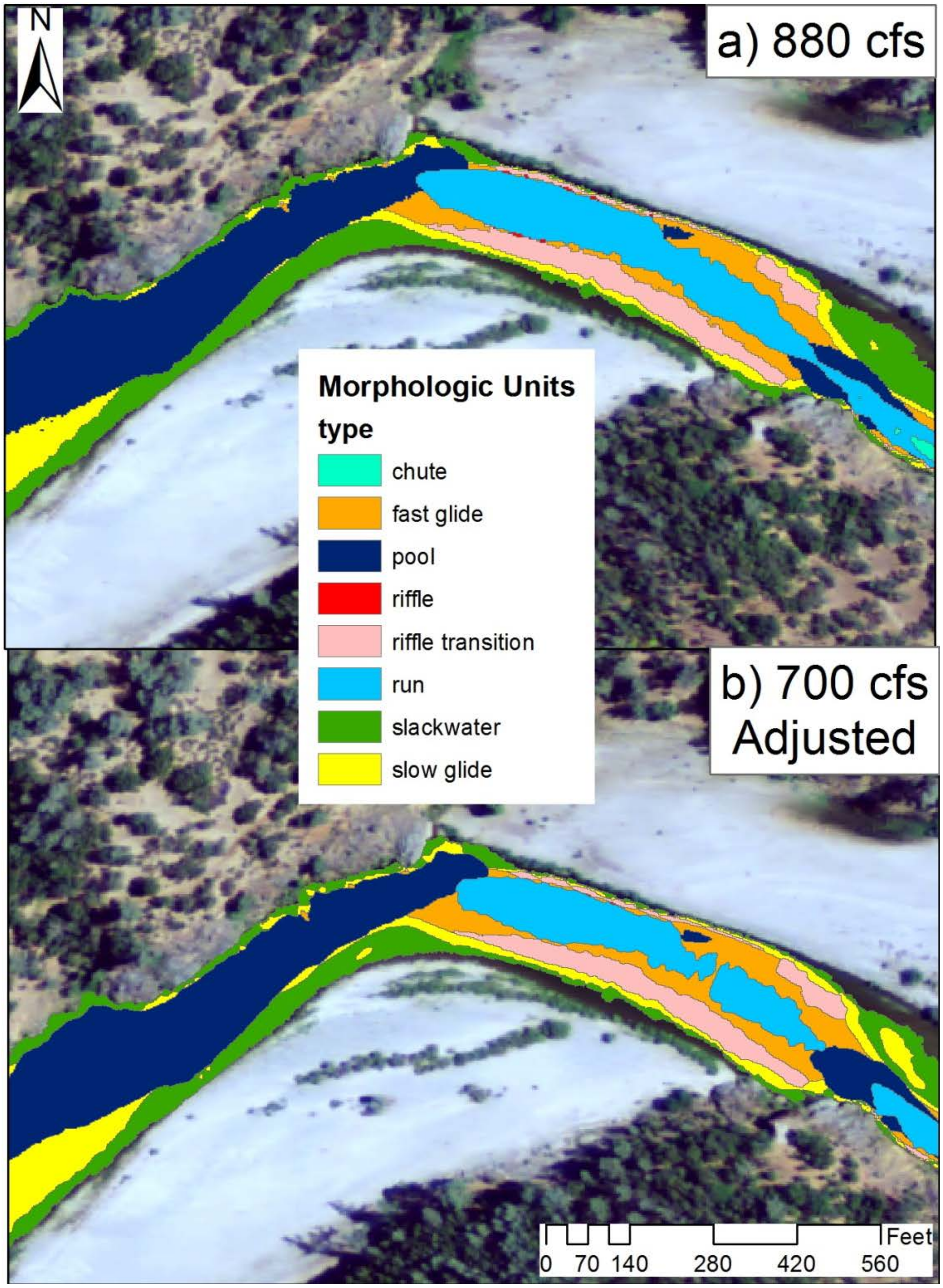

Figure 30. Visual comparison of MU layout between a) the original 880 cfs metrics map and b) the adjusted 700 cfs metrics map. The larger and easily-identifiable morphologic units are still present and in the same location between the two flow regime analyses. Some of the smaller, marginal units have changed or been omitted entirely, however. Some changes in a large unit is exampled by the Run, which is a long continuous unit in the 880 cfs analysis, but is broken up into smaller units as the surrounding Fast Glides and Pools increase in size in the 700 cfs analysis.

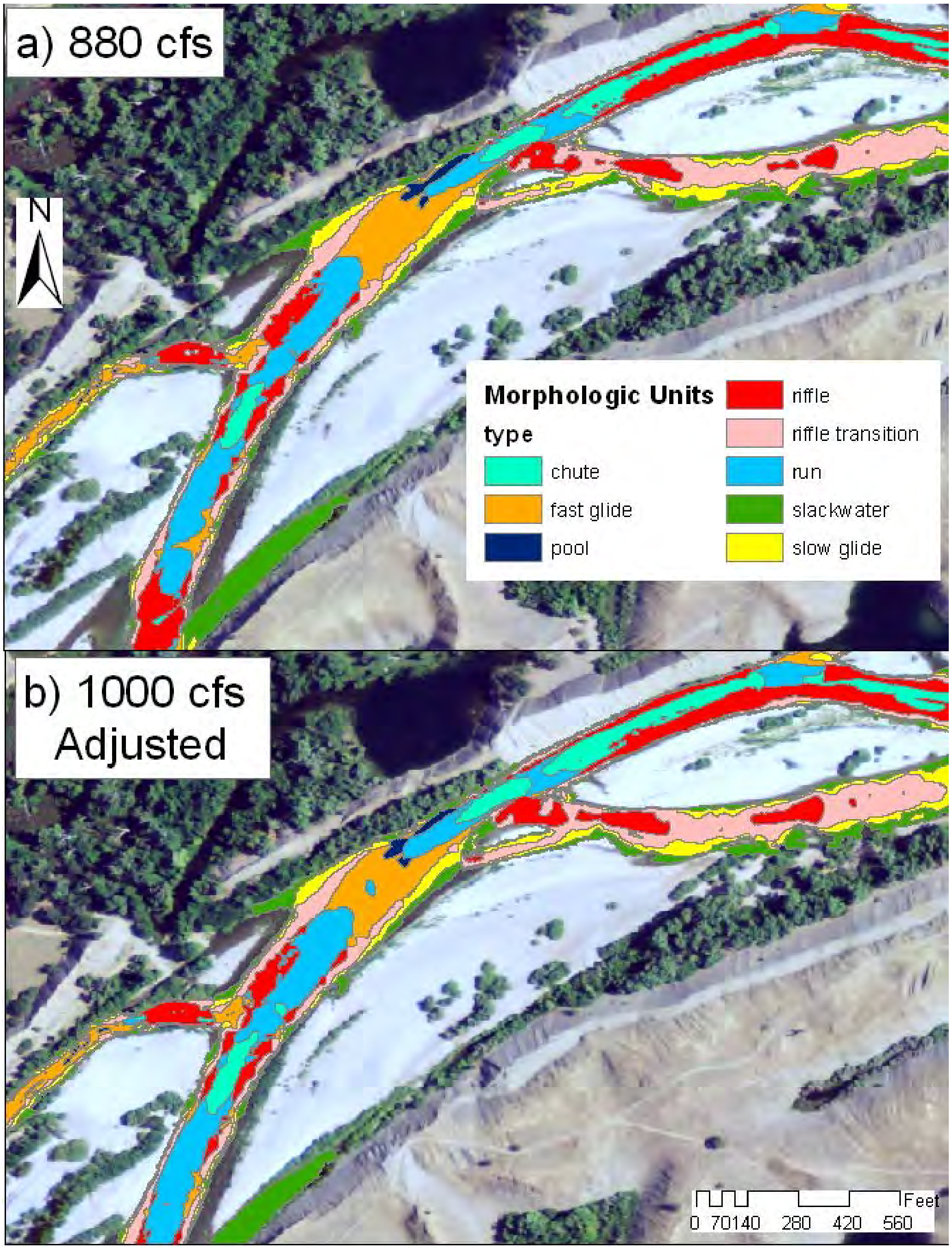

Figure 31. Visual comparison of MU layout between a) the original 880 cfs metrics map and b) the adjusted 1000 cfs metrics map. The larger and easily-identifiable morphologic units are still present and in the same location between the two flow regime analyses. Some of the smaller, marginal units have changed or been omitted entirely, however.

Morphological Unit Spatial Organization

A central question in fluvial geomorphology at the 10^0-10^1 W spatial scale is whether morphological units are naturally organized into a coherent spatial structure that is non-random. If the structure is indeed deterministic, then is it periodic or non-periodic? This section will outline the basic scientific questions and analysis results of the spatial structure of morphological units, and relate them to the segment- and reach-scales.

At the segment and reach spatial scales, the Lower Yuba River is composed of a number of unequally distributed morphological units. Each unit type has a characteristic set of discharge-independent geomorphic attributes. In terms of their spatial organization, analyses found that morphological units were preferentially ordered down the river segment in a nonrandom structure, with most unit types having a "preference" for adjacency to only a few other unit types. In this usage, the term preference means co-occurrence at a higher frequency than would occur if occurrence were random. Since units are inanimate objects that cannot choose their location, the concept of a "preference" relates to the role of underlying, stage-dependent, physical processes that control unit-type sequencing. A natural order to the sequencing is indicative of underlying natural laws in processes.

Spatial Abundance

Morphological unit types within the Lower Yuba River study segment exhibit an unequal abundance, with each unit type having unique geomorphic attributes. Within the low flow regime (880/530 cfs), the most abundant morphological unit in the LYR segment by area is Slackwater at 16.4% (Table 11, Table 12). The next most abundant units are Pool (15.9%) and Riffle Transition (15.3%). At the reach scale, Slackwater is not the dominant unit within any given reach, however (although it is tied for the most percentage with Fast Glide at 18% in the Dry Creek reach). Pool is dominant in the Englebright and Marysville reaches, more than doubling the percentages of the next most abundant unit (Table 12).

Table 11. Total areas (ft^2) of in-channel bed morphological units per reach

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	Timbuctoo	Englebright	Total
Chute	13,707	83,070	60,687	133,177	448,439	182,646	32,481	**954,207**
Fast Glide	184,523	908,979	554,146	517,380	538,810	433,390	25,524	**3,162,753**
Pool	1,472,166	392,445	164,141	190,639	338,022	772,176	209,585	**3,539,173**
Riffle	63,036	539,586	433,080	307,727	858,952	705,735	22,689	**2,930,805**
Riffle Transition	110,277	922,062	881,915	369,958	678,146	436,824	12,230	**3,411,412**
Run	80,955	216,425	216,196	368,563	645,719	332,550	64,323	**1,924,731**
Slackwater	654,540	711,858	534,413	518,019	600,298	518,680	101,805	**3,639,614**
Slow Glide	240,359	716,917	333,429	469,281	397,817	458,232	44,010	**2,660,046**
Total	**2,819,562**	**4,491,342**	**3,178,009**	**2,874,744**	**4,506,204**	**3,840,234**	**512,647**	**22,222,741**
Percent	**12.7%**	**20.2%**	**14.3%**	**12.9%**	**20.3%**	**17.3%**	**2.3%**	

Table 12. Percentages of in-channel bed morphological units per reach (Bold indicates highest abundances)

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	Timbuctoo	Englebright	Total
Chute	0.5%	1.8%	1.9%	4.6%	10.0%	4.7%	6.3%	4.3%
Fast Glide	6.5%	**20.2%**	17.4%	**18.0%**	12.0%	11.3%	5.0%	14.2%
Pool	**52.2%**	8.7%	5.2%	6.6%	7.5%	**20.2%**	**40.9%**	15.9%
Riffle	2.2%	12.0%	13.6%	10.7%	**19.1%**	18.4%	4.4%	13.2%
Riffle Transition	3.9%	20.5%	**27.7%**	12.9%	15.1%	11.4%	2.4%	15.3%
Run	2.9%	4.8%	6.8%	12.8%	14.3%	8.6%	12.6%	8.7%
Slackwater	23.2%	15.9%	16.8%	**18.0%**	13.3%	13.5%	19.9%	**16.4%**
Slow Glide	8.5%	16.0%	10.5%	16.3%	8.8%	11.9%	8.6%	12.0%

If the morphological units exhibited a random probability of occurrence, the percent coverages would each be equal at 1/8 = 12.5%. Since the units are not situated randomly in the Lower Yuba River (Table 12), those units which individually contribute to more than 12.5% of the total area represent a greater geomorphic "preference". Those units that do exhibit a greater-than-random abundance are Slackwater, Pool, Riffle Transition, Fast Glide, and Riffle (Table 12). When unit percent area is notably lower than 12.5%, then it its absence is nonrandom, so it can be thought of as geomorphically "avoided". Chutes are the least abundant unit with a strongly nonrandom absence.

There also exist reach-scale variations of morphological unit abundances (Table 12). For instance, while Slackwater is the most abundant unit at the segment-scale, Pool is dominant in three of the seven reaches – Englebright (40.9%), Timbuctoo (20.2%), and Marysville (52.2%). The middle reaches vary in which unit exhibits the highest abundances with Fast Glide (Hallwood and Dry Creek), Riffle Transition (DPD), and Riffle (Parks Bar). Some of the units that contribute a less-than-random percentage to the total segment area do account for greater-than-random percentages at the reach-scale. For example, Run units only account for 8.7% of the total area, but make up 12.6%, 14.3% and 12.8% of the area in the Englebright, Parks Bar, and Dry Creek reaches respectively. The lowest overall percentage for an in-channel bed morphological unit is that for Chute (4.3%), which becomes even scarcer in the downstream reaches of the segment (e.g., only 0.5% of the area in the Marysville Reach).

Within the bankfull flow regime (5,000 cfs), the wetted area expands to include more morphological units (Table 6b). The combined areas of the in-channel bed units (Table 11) dominate the overall area of the bankfull wetted area at ~62% (Table 13). Of the newly wetted units, the most abundant are Lateral Bar (14.8% of all bankfull area), Swale (9.9%), Point Bar (6.6%), and Medial Bar (4.2%). Lateral Bar is also the most abundant at the reach scales as compared the other in-channel bar units.

Table 13. Total areas (ft^2) of in-channel morphological units per reach wetted at bankfull flows. *All Baseflow* units refer to the sum of those unit areas in Table 11.

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	Timbuctoo	Englebright	Total
All Baseflow	*2,819,562*	*4,491,342*	*3,178,009*	*2,874,744*	*4,506,204*	*3,840,234*	*512,647*	***22,222,741***
Lateral Bar	532,230	1,470,861	1,053,349	671,178	895,811	595,305	62,089	**5,280,824**
Medial Bar	29,439	585,601	47,115	437,674	208,270	189,964	0	**1,498,063**
Point Bar	169,625	377,956	776,246	297,889	543,871	141,129	37,835	**2,344,550**
Swale	173,688	1,322,299	950,288	330,583	652,026	131,549	0	**3,560,433**
Backswamp	0	1,666	260	18,155	4,165	0	0	**24,246**
Bank	10,414	9,574	0	0	0	0	0	**19,987**
Bridge Pier	4,850	0	0	0	0	0	0	**4,850**
Cutbank	6,800	6,645	0	0	1,517	2,451	0	**17,412**
Hillside/ Bedrock	0	0	0	1,039	113,510	166,684	57,620	**338,854**
Pond	0	0	258,941	135,849	0	0	0	**394,790**
Spur Dike	0	3,240	549	0	15,732	0	0	**19,521**
Tailings	0	0	4,670	2,118	6,040	0	0	**12,828**
Tributary Channel	0	0	0	1,129	71,706	0	0	**72,834**
Tributary Delta	0	0	0	0	0	2,161	0	**2,161**
Total	**3,746,608**	**8,269,183**	**6,269,427**	**4,770,358**	**7,018,853**	**5,069,477**	**670,190**	**35,814,096**

The major units that become wetted between the baseflow and bankfull flows are Lateral Bar, Medial Bar, Point Bar, and Swale. These units are maximally bounded by the bankfull wetted area, whereas the other units may also be delineated within the floodway or valley zones. In fact, these other units combine to make up only ~6.7% of the bankfull inundation region (Table 14). Therefore, it is of more interest to focus our bankfull analyses on just the four major bar units. Among all of the individual bankfull units (in-stream bar), Lateral Bar is the most abundant at the segment scale, and this holds true at the reach scales (Table 14). Considering just these four units, a geomorphically random abundance value would be 25%. Lateral Bar exhibits greater-than-random abundance at the segment and all reach scales. Swale is random at the segment scale, with notable absences in the Englebright and Timbuctoo Reaches and notable abundances in the DPD and Hallwood Reaches. Medial Bar exhibits a greater-than-random absence at the segment scale and most reach scales, except for its near-randomness in Dry Creek Reach. Point Bar is random within the Englebright, Parks Bar, and DPD reaches, but otherwise exhibits a greater-than-random absence. Of the minor MUs, the unit of most interest is Hillside/Bedrock in the Englebright reach that makes up 36.5% of the bankfull inundation area (Table 14).

Table 14. Percentages of the in-channel bar units within the bankfull inundation region at the segment and reach scales. Bold values indicate the highest relative abundances per reach.

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	Timbuctoo	Englebright	Total
lateral bar	**57.41**	**38.93**	**34.07**	**35.41**	**35.65**	**48.43**	**39.41**	**38.85**
medial bar	3.18	15.50	1.52	23.09	8.29	15.45	0.00	11.02
point bar	18.30	10.00	25.11	15.71	21.65	11.48	24.02	17.25
swale	18.74	35.00	30.74	17.44	25.95	10.70	0.00	26.20
backswamp	0.00	0.04	0.01	0.96	0.17	0.00	0.00	0.18
bank	1.12	0.25	0.00	0.00	0.00	0.00	0.00	0.15
bridge pier	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.04
cutbank	0.73	0.18	0.00	0.00	0.06	0.20	0.00	0.13
hillside/ bedrock	0.00	0.00	0.00	0.05	4.52	13.56	36.57	2.49
pond	0.00	0.00	8.38	7.17	0.00	0.00	0.00	2.90
spur dike	0.00	0.09	0.02	0.00	0.63	0.00	0.00	0.14
tailings	0.00	0.00	0.15	0.11	0.24	0.00	0.00	0.09
tributary channel	0.00	0.00	0.00	0.06	2.85	0.00	0.00	0.54
tributary delta	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.02

The similarities between reach-scale abundances/absences can be further analyzed by comparing the difference residuals in the areal percentages of the in-channel bed and bar units. A similarity index was calculated by summing the absolute differences of percentages of like units between reaches then subtracting that sum from 100% (Table 15). Similar reaches would exhibit index values near 100%. It is unclear as to what is a statistical threshold for these similarity residuals (i.e., what should be expected), but they can at least be compared relatively. The most similar adjacent reaches are DPD-Hallwood which exhibits 67.4% similarity index between MU abundance (Table 15), although Hallwood exhibits a greater similarity with the non-contiguous Dry Creek Reach (67.9%). The least similar adjacent reaches are Hallwood-Marysville at 11.6%, although Marysville exhibits a 48.1% similarity with Englebright (both pool-dominated entrenched channels). The reach that best represents the whole segment is Parks Bar with a 74.3% similarity index value, while the least indicative reach is Englebright at 23.3%.

Table 15. Percent similarities between reach-scale morphological unit abundances (in-channel units only). Higher values indicate greater similarity. Bold values indicate adjacent reaches.

Reach	Timbuctoo	Parks Bar	Dry Creek	DPD	Hallwood	Marysville	LYR
Englebright	32.2%	20.7%	14.3%	-2.4%	-2.2%	48.1%	23.3%
Timbuctoo		**61.7%**	54.5%	34.6%	47.9%	21.9%	69.6%
Parks Bar			**61.8%**	58.3%	56.7%	10.1%	74.3%
Dry Creek				**54.8%**	67.9%	16.2%	71.8%
DPD					**67.4%**	13.4%	63.4%
Hallwood						**11.6%**	69.1%
Marysville							26.4%

As the wetted area is again expanded to the flood flow extents (21,100 cfs), even more morphological units are inundated, uniquely the Floodplain, Flood Runner, Island Floodplain, and Mining Pit units (Table 6c). The combined area of the bankfull channel is only slightly greater than the Floodplain MU (48.7% compared to 39.2% of the segment area) (Table 16). Within just the floodway inundation region, the Floodplain units are the most abundant, and exhibit a greater-than-random coverage at the segment (76.5%) and reach (~66 – 84%) scales. All other units exhibit a greater-than-random absence at all scales, except for Hillside/Bedrock in the Englebright reach which covers ~34% of the floodway inundation region. Among all of the individual units within the floodway wetted area, however, Pool is still the most abundant in the entrenched Englebright and Marysville reaches.

Table 16. Total areas (ft^2) of morphological units per reach wetted at flood flows. *All Bankfull* units refer to the sum of those unit areas in Table 13.

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	TBR	Englebright	Total
All Bankfull	*3,746,608*	*8,269,183*	*6,269,427*	*4,770,358*	*7,018,853*	*5,069,477*	*670,190*	***35,814,096***
Floodplain	1,426,969	6,504,632	8,666,454	3,369,508	6,035,332	2,648,786	174,117	28,825,797
Flood Runner	123,805	177,785	792,684	0	149,651	0	0	1,243,925
Island Floodplain	0	396,353	0	612,609	761,000	203,839	0	**1,973,802**
Mining Pit	0	0	210,759	0	225,506	0	0	**436,265**
Agriplain	0	254,811	0	0	0	0	0	**254,811**
Back-swamp	104,959	900,444	44,320	634,820	182,968	0	0	**1,867,511**
Bank	367,029	393,317	1,020	0	4,272	0	0	**765,638**
Bridge Pier	1,494	0	0	0	0	0	0	**1,494**
Cutbank	24,593	13,355	0	0	8,607	11,680	0	**58,235**
Hillside/ Bedrock	0	0	0	29	205,161	251,527	88,627	**545,345**
Pond	0	0	498,034	417,392	0	0	0	**915,426**
Spur Dike	0	132,553	20,615	0	39,656	0	0	**192,823**
Tailings	0	962	141,272	32,673	71,816	0	0	**246,723**
Tributary Channel	0	0	0	5,137	291,851	0	0	**296,988**
Tributary Delta	0	0	0	0	0	37,888	0	**37,888**
Total	**5,795,457**	**17,043,395**	**16,644,583**	**9,842,527**	**14,994,672**	**8,223,198**	**932,935**	**73,476,766**

Finally, the wetted area is extended to include to full alluvial river corridor. This area does not represent any particular discharge, because training berms, levees, and valley walls impinge on the valley floor at different positions, but incorporates an area that may be considered impacted by any flood > 21,100 cfs. The units unique to the Valley inundation region (Table 6d, Figure 6) are Terrace, High Floodplain, Island High Floodplain, and Levee. Within just the valley inundation region, Terrace (38.8%), High Floodplain (31.3%), and Tailings (18.4%) are the most abundant units at the segment scale (Table 17). Within the Englebright reach, there are no terraces due to the steep banks; therefore, the Hillside/Bedrock unit dominates the area outside of the bankfull channel instead (and Pool still dominates within). In the Timbuctoo and Parks Bar reaches, High Floodplain dominates with Terrace covering most of the remaining area and all the other units notably absent. Tailings dominate in the Dry Creek and DPD reaches, with High Floodplain a close second and other units absent. In the Hallwood and Marysville reaches, Terrace units greatly dominate while all other units exhibit greater-than-random absences.

Table 17. Total areas (ft^2) of morphological units per reach within the full valley. ***All Floodway*** **units refer to the sum of those unit areas in Table 16.**

MU	Marysville	Hallwood	DPD	Dry Creek	Parks Bar	TBR	Engle-bright	Total
All Floodway	*5,795,457*	*17,043,395*	*16,644,583*	*9,842,527*	*14,994,672*	*8,223,198*	*932,935*	***73,476,766***
Terrace	4,539,569	7,926,338	400,362	505,461	1,738,324	803,009	0	**15,913,064**
High Floodplain	609,130	1,167,358	3,508,893	849,936	5,103,167	1,557,532	32,731	**12,828,748**
Island High Floodplain	0	0	0	288,849	648,830	0	0	**937,679**
Levee	280,095	0	0	0	0	0	0	**280,095**
Agriplain	54,934	630,815	0	0	0	0	0	**685,749**
Back-swamp	0	430,187	403	0	2,961	0	0	**433,551**
Bank	276,765	838,996	52,627	0	77,674	0	0	**1,246,062**
Cutbank	0	0	0	0	164	80,853	0	**81,017**
Hillside/ Bedrock	0	0	0	0	71,574	205,490	661,095	**938,159**
Spur Dike	0	1,798	781	0	316	0	0	**2,896**
Tailings	0	236,500	5,567,863	1,076,547	678,405	0	0	**7,559,315**
Tributary Channel	0	0	0	633	0	0	0	**633**
Tributary Delta	0	0	0	0	0	101,832	0	**101,832**
Total	**11,555,950**	**28,275,388**	**26,175,513**	**12,563,952**	**23,316,086**	**10,971,913**	**1,626,761**	**114,485,564**

Area Statistics

ArcGIS produces a map of the in-channel MUs with a pixel resolution size of 3x3 ft^2. Clusters of adjacent pixels of the same unit classification are joined together to form large polygons. Therefore, the smallest morphological unit polygon that can result from this analysis has a size of 9 ft^2. The largest single polygon that was delineated in the LYR is a Pool unit in the Marysville reach that encompasses 772,263 ft^2 (17.7 ac). Overall, the mean polygon size of the in-channel bed and bar units is 923 ft^2 and the median size is 18 ft^2 (Table 18). Beyond the bankfull channel, the morphological units are mapped at a coarser scale; therefore, very few single-cell polygons exist for those classifications. In fact, the mean polygon size of the remaining MUs is 44,120 ft^2.

Table 18. Statistics of in-channel morphological unit polygon areas (ft^2)

Unit	Maximum Size	Median Size	Mean Size
Chute	77,715	45	1,575
Fast Glide	208,755	18	1,084
Pool	772,263	27	4,349
Riffle	96,849	27	1,474
Riffle Transition	302,031	18	517
Run	83,781	18	1,323
Slackwater	200,204	18	266
Slow Glide	135,603	18	205
Lateral Bar	280,095	151	15,567
Medial Bar	383,857	50	10,084
Point Bar	233,597	18,598	41,559
Swale	361,404	293	25,624
Bank	427,661	17,290	61,567
Hillside / Bedrock	384,975	45	28,591
Total	**772,263**	**18**	**923**

Individual polygons for each in-channel bed MU were binned by area then converted into a histogram to represent the extent and diversity of sizes (Figure 32). Histograms were not plotted for the Bar MU, however, because the manual method used in delineating the polygons created mostly uniquely-sized areas not at the pixel scale denomination. Most of the total numbers of polygons for in-channel MU are represented by the smallest possible size of 9 ft^2 (Figure 32), however these small polygons account for only a small percentage of the total area (Figure 33). In fact, *the greatest percentages of total area for each MU are made up of the largest polygon sizes, even though there are a relatively few number of them* (See Table 19 in next section).

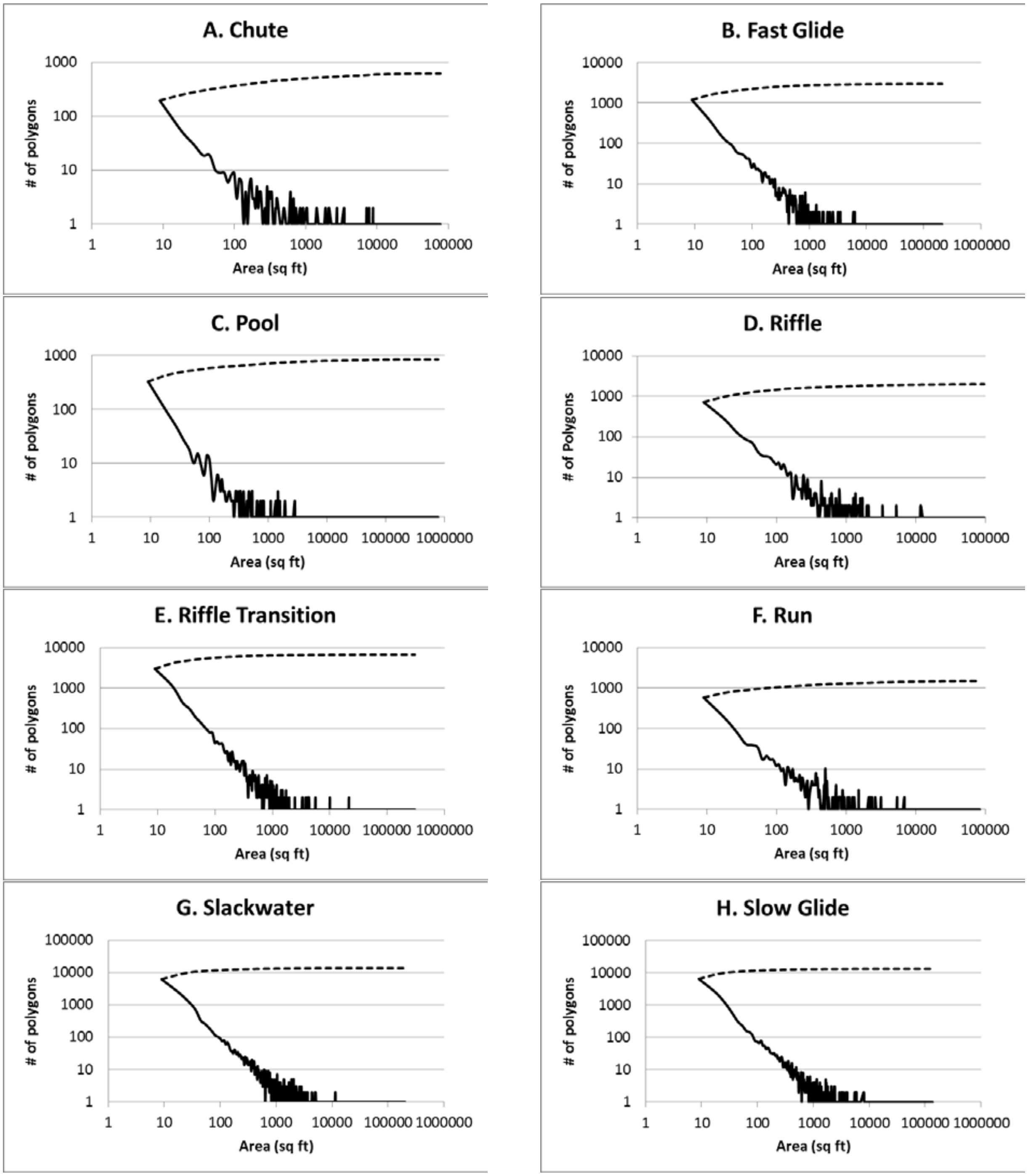

Figure 32. Histogram of polygon areas for in-channel morphological units. Solid lines represent number of discrete polygon areas. Dashed lines represent cumulative number.

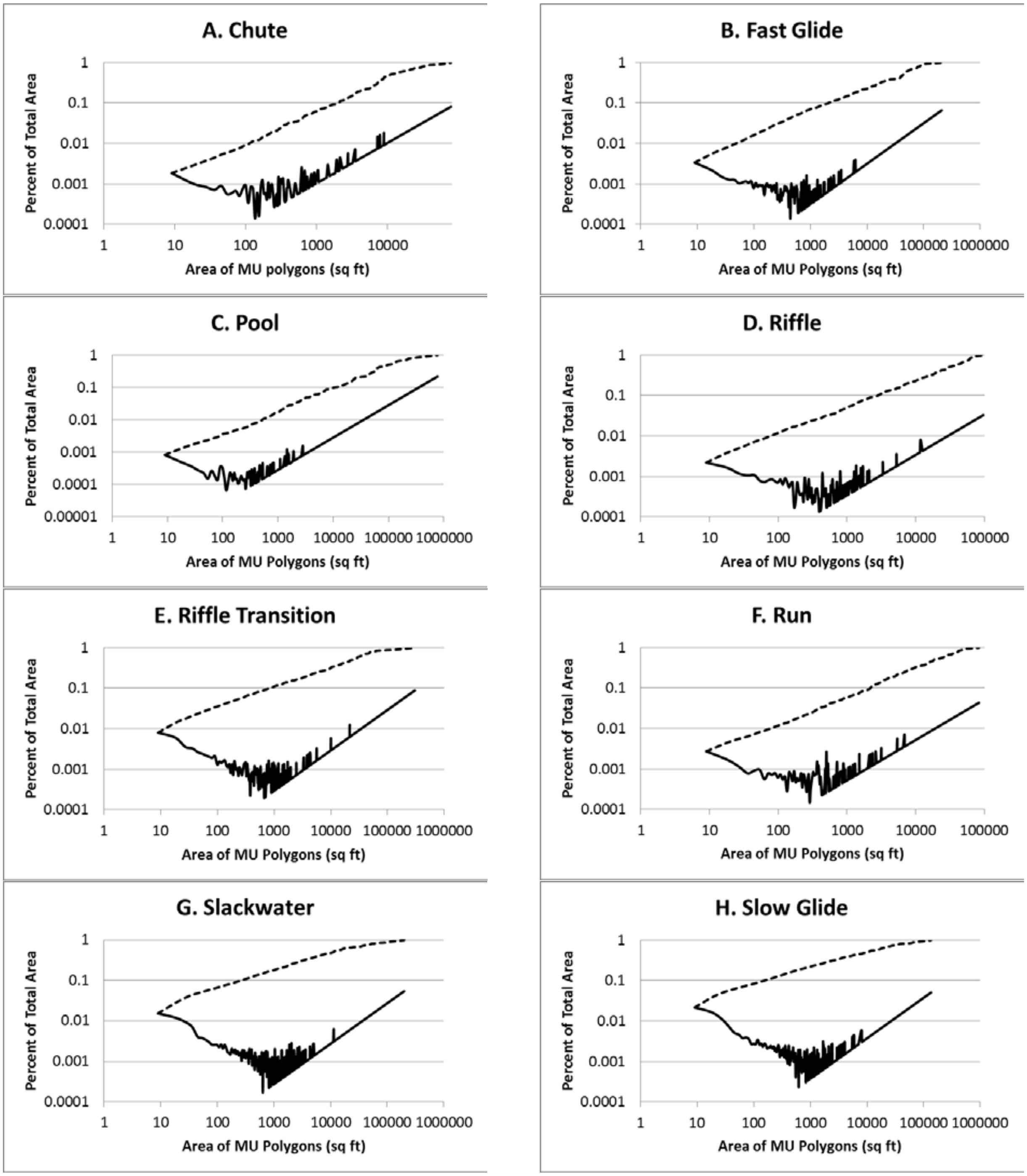

Figure 33. Histograms of fractional areas for in-channel morphological units. Solid lines represent fractions of discrete polygon areas. Dashed lines represent cumulative fractions.

Minimum Size of Morphological Units for Use in Geomorphic Analyses

Every unit classification includes some polygons of the smallest size (Figure 32), which may be difficult to accurately identify in the field. One option to overcome this would at first seem be to increase the minimum pixel size used in the algorithm, however this retains some of the same errors and introduces others (for more discussion and a sensitivity analysis on this, refer to the

Specific Sampling Protocols and Procedures for Delineating Morphological Units report (Wyrick and Pasternack, 2011)). Instead, this study keeps the minimum pixel size at 9 ft^2 to maintain a high resolution; however this small size would be considered more a discrete hydraulic unit rather than a geomorphic 'landform' unit. For this analysis, a geomorphic landform should be readily identifiable in the field. The in-channel bar units (Table 6b), floodway units (Table 6c), and the off-channel units (Table 6d) are not delineated at the pixel scale, and therefore no minimum size discrimination would be appropriate for these MU types. However, because the in-channel bed units (Table 6a) are discretized using assessments of depth/velocity combinations outputted from the 2D hydrodynamic model at the 3x3 ft^2 scale, an individual pixel whose depth/velocity combination forms a separate MU classification than all of its surrounding pixels may be considered a model relic based on this delineation method rather than a full MU landform. In fact, among all of the in-channel bed MU polygons, 45% are only one pixel in size (varying from 32%-49% for each MU type, Figure 28). The cumulative area of these one-pixel polygons, however, account for 0.76% of the total area for in-channel bed units (which decreases as the other MU types are included in the total channel area). An easy argument can be made, then, that eliminating these one-pixel polygons from the geomorphic analyses would have negligible effects on the results. What about excluding two-pixel polygons, or three-pixel polygons? At what minimum size can we mandate a threshold for our geomorphic analyses, but still maintain the integrity of the morphological map? With every increase in the minimum size threshold, more total area of the channel is also eliminated from the analyses. For example, setting the minimum size threshold at 252 ft^2 (28 pixels, or ~16x16 ft^2), the total percent of in-channel bed MU polygons excluded would be 90.1% and the total percent area excluded would be 5.1%. Increasing this threshold to 396 ft^2 (44 pixels, or ~20x20 ft^2) yields an exclusion of 92.3% of the number of polygons and 6.4% of the area. The minimum polygon size threshold that would retain at least ~90% of the channel's area is 999 ft^2 (111 pixels, or ~31x32 ft^2). This threshold would exclude ~95% of the total number of polygons (Table 19), however, the high percentage of remaining area validates the concept that morphological units are on the scale of 0.5-10 W in size and cover a majority of the channel. In addition to the minimum size of 999 ft^2 maintaining 90% of the channel area for the analyses, this size is also appropriately large enough for field surveyors to visually identify a morphological landform, and is consistent with sizes used in other delineation methods (e.g., Thomson et al., 2001). Therefore, from a statistical and visual standpoint, the minimum size threshold for the following analyses will be 999 ft^2; however, as a comparison the same analyses will also be performed using no size discrimination.

Using this minimum size threshold may only eliminate 10% of the total in-channel bed area, but this percentage is not consistent among the individual units (Table 19). This threshold has the least effect on the pool units (excluding 1.7% of the total pool area), but has more significant effects on the marginal units of slackwater and slow glide (18.0% and 22.1% of their respective areas). The reason those are so affected is that they are long and skinny, so it is easy to form chains of catercorner pixels in the raster, and these pixels become distinct units when the raster is converted to a polygon. Knowing that these multiple features are really parts of the same entity, it makes sense to not treat them as all distinct.

Table 19. Percent of number and area of in-channel bed morphological unit polygons below minimum field-identifiable landform size threshold of 999 ft^2. For total areas of each MU, refer to Table 11.

Unit	Total Number of Polygons	% of total number ≤ 999 ft^2	% of total area ≤ 999 ft^2
Chute	603	80.8	6.0
Fast Glide	2914	92.7	7.0
Pool	812	83.7	1.7
Riffle	1,984	88.5	4.9
Riffle Transition	6,587	95.5	10.9
Run	1,453	86.7	5.8
Slackwater	13,620	96.7	18.0
Slow Glide	12,952	97.6	22.1
Total	**40,925**	**95.3%**	**9.9%**

While the percentages of other MU types (i.e., those outside of the low-flow wetted area) are near zero for the one-pixel sized polygons, increasing the minimum size threshold to 999 ft^2 may have some effects on their analyses as well. For the other units, the total percent of the number of polygons ≤999 ft^2 is 68.0%, which equates to a mere 0.24% of the total units area (Table 20). Of the Bar units, Point Bar is the least affected unit with only 0.03% of its area excluded with this size threshold, while Pond and Tailings are also minimally affected with 0.02% or less. Overall, the Medial Bar and Island-Floodplain are the most affected at 0.89% and 0.62% of their respective areas excluded. Some morphological units are not listed in Table 20, because all of their polygons are > 999 ft^2 and would therefore be unaffected by the minimum size discrimination.

Table 20. Percent of number and area of morphological unit polygons below minimum field-identifiable landform size threshold of 999 ft^2. For total areas of each MU, refer to Table 13, Table 15, Table 16, and Table 17. Other MUs not listed here have no polygon < 999 ft^2.

Unit	Total Number of Polygons	% of total number ≤ 999 ft^2	% of total area ≤ 999 ft^2
Lateral Bar	356	62.2	0.41
Medial Bar	176	79.0	0.89
Point Bar	56	42.9	0.03
Swale	153	58.2	0.27
Hillside/Bedrock	64	71.9	0.23
Pond	16	43.8	0.02
Backswamp	43	48.8	0.15
Floodplain	642	77.3	0.18
Island Floodplain	112	79.5	0.62
Tailings	24	41.7	0.01
High Floodplain	600	66.2	0.41
Terrace	120	51.7	0.05
Island High Floodplain	35	62.9	0.47
Total	**2,374**	**68.0%**	**0.24%**

Longitudinal Distribution

The previous sections established that morphological units are geomorphologically differentiated, with some in greater abundance than random expectation and some notably absent. The next question is whether they are spatially organized or randomly located along the study segment. By definition, if they are randomly located, there is equal probability of them being located in any particular location. When that is the case, then the type of statistical distribution that is present is called a uniform distribution. The presence of a uniform distribution is indicated by having a horizontal discrete probability distribution function (PDF) and a diagonal straight-line cumulative distribution function (CDF) when probability of occurrence is plotted against distance upstream. In a CDF, deviations of the slope from a straight-line trajectory indicate a higher or lower occurrence in a region of channel relative to the uniform expectation, where a steeper slope would indicate a higher occurrence and a lower slope would indicate a lower occurrence.

For the in-channel morphological units (Figure 34, Figure 35), Chutes and Runs are more predominate in the upper reaches of the LYR (Figure 34A,F, Figure 35). Slackwater (Figure 34G) and Slow Glide (Figure 34H) units are distributed fairly uniform across the segment. Pools (Figure 34C) are unequally distributed between the upper and lower reaches but mostly lacking in the middle reaches except for the large scour hole downstream of Daguerre Point Dam. Riffles exhibit uniform probabilities through most of the reaches except for Englebright and Marysville (Figure 34D). Riffle Transitions trend generally upwards in occurrence probability from the Englebright to the DPD Reach, peaking in the Hallwood Reach, and then drastically declining into the Marysville Reach.

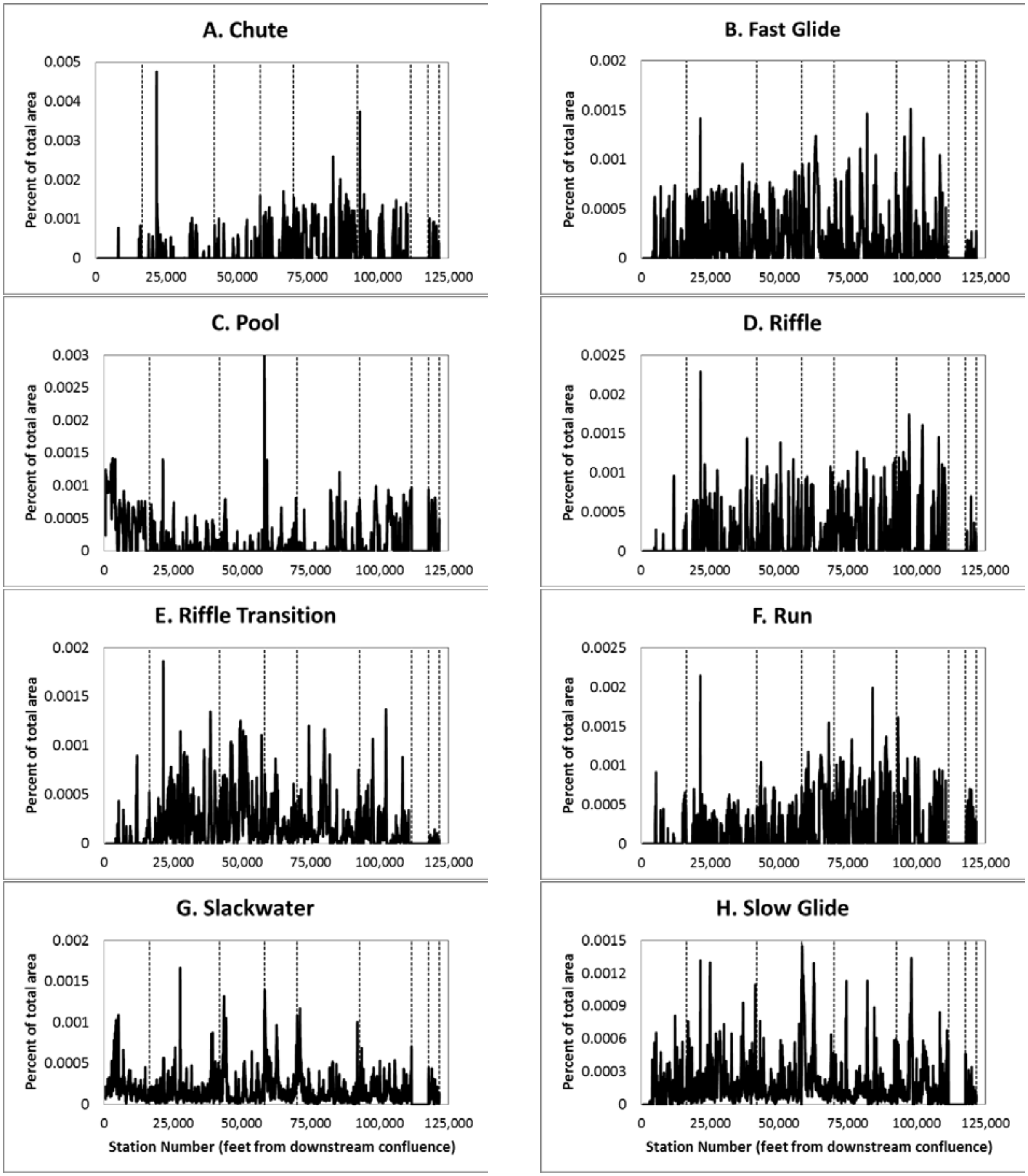

Figure 34. Probability distribution functions for areas of in-channel morphological units. Vertical dotted lines represent reach breaks. *Note: scales on ordinate axes are not consistent.*

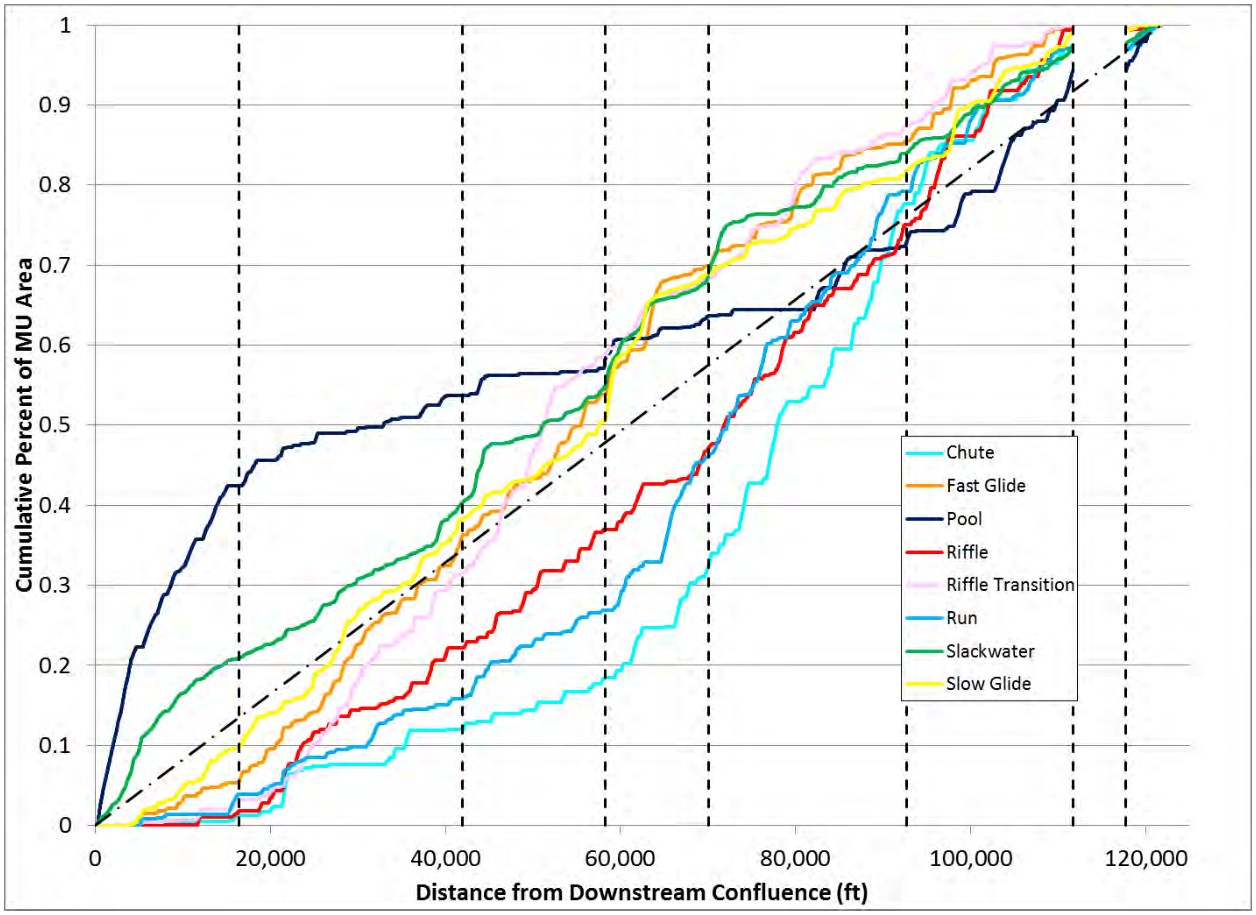

Figure 35. Cumulative distribution functions for areas of in-channel bed MUs. Vertical dotted lines represent reach breaks. Diagonal dash-dot lines represent uniform distribution.

The longitudinal-distribution analysis was calculated by using the previously describe dataset that consists of a longitudinally distributed set of rectangles that are stationed along the valley centerline and clipped to the valley boundary. To determine the longitudinal distribution of each MU type, the rectangles were used, because it is possible to use ArcGIS to calculate the area of each MU in each rectangle, and each rectangle has a longitudinal position. The distribution of MU area in rectangles down the river is the probability density function of MU area for the longitudinal profile. First, a decision has to be made whether to consider all polygons or just those whose size is > 999 ft^2. How much variation would there be in the PDFs if the minimum size discrimination was employed? To test this, the same analysis was performed both ways- with all polygons and using only those whose area is > 999 ft^2. Because the percent of each MU area at each cross-section is already such a small value and the size discrimination only removes ~10% of the area, the visual comparison of the PDFs do not reveal much to the average observer. However, subtracting the PDFs does reveal the differences (Figure 36). A positive value illustrates that the percent area of that particular MU at that cross-section is greater using no size discrimination, and a negative value shows the reverse. In general, the morphological units' areas that were most affected by the size discrimination (e.g., slackwater and slow glide, Table 15) exhibit the least changes in cross-sectional percentage residuals (Figure 37G, H). Chute, however, was nominally affected (6.0% omitted), and exhibits a wide range of difference residuals between the two size discrimination methods (Figure 37A).

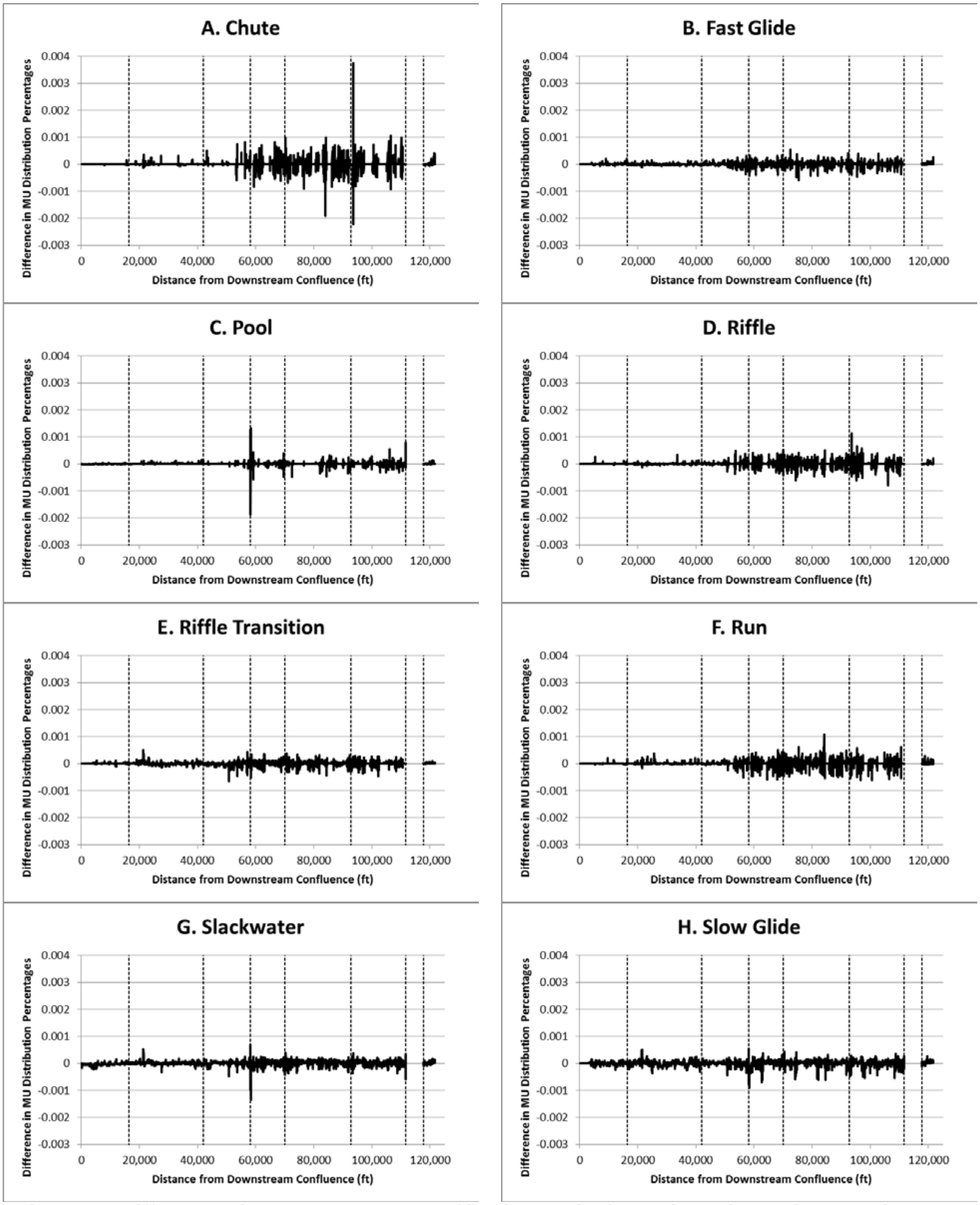

Figure 36. Differences in area percentages of in-channel bed morphological units at each cross-section. The differences represent those between using no minimum size discrimination and those of 999 ft^2. Each ordinate axis has the same scale. Vertical dotted lines represent reach breaks.

For the bar morphological units (Figure 37, Figure 38), Lateral Bars are ubiquitous throughout the segment (Figure 37A). Swales are almost non-existent in the upper confined reaches, but become prevalent in the lower, wider, meandering reaches (Figure 37D). The Hillside/Bedrock units are mostly present in the upper, confined reaches, while Bank is more dominant in the alluvial, lower reaches (Figure 37E, F).

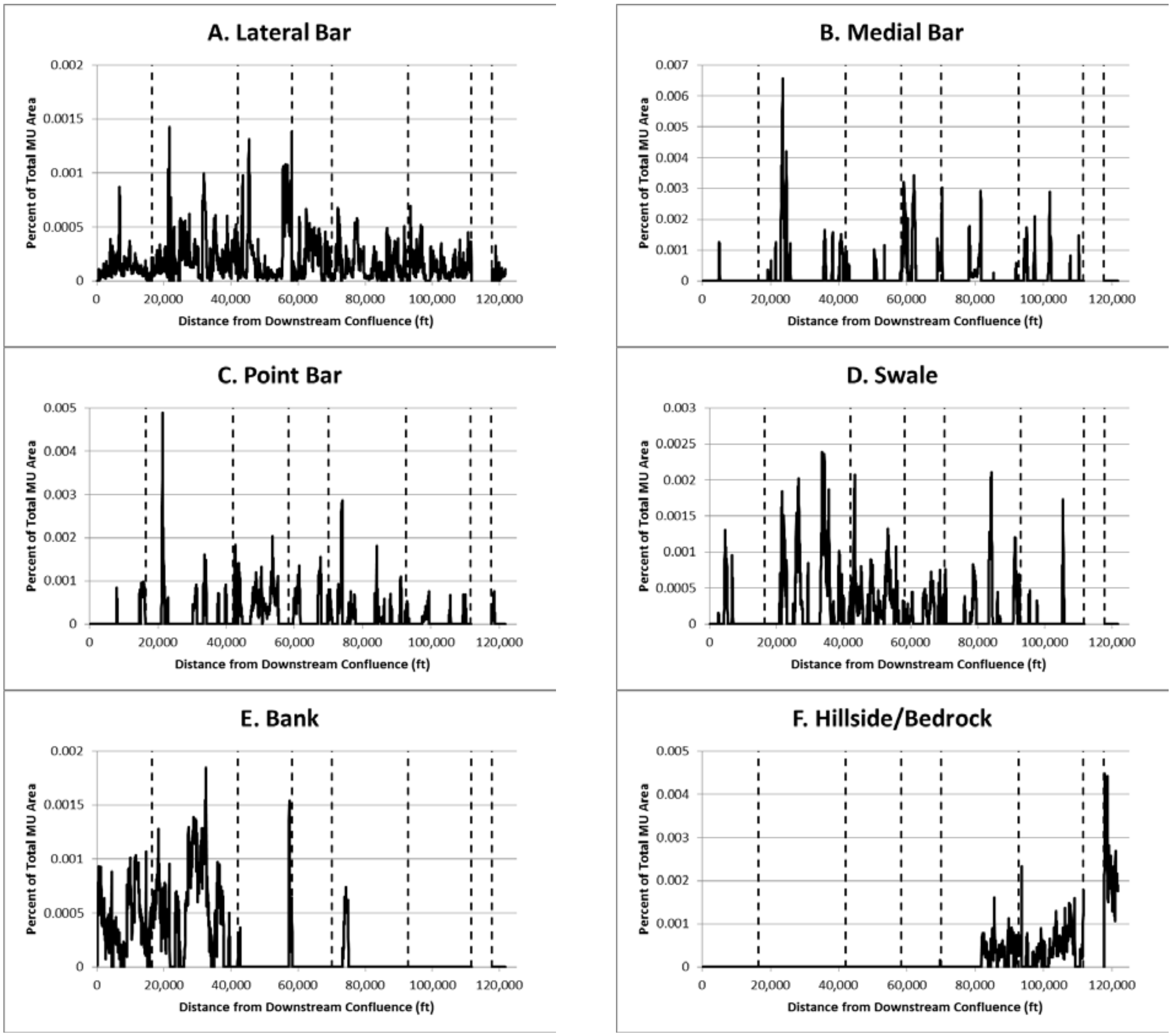

Figure 37. Probability distribution functions for areas of bar morphological units. Vertical dotted lines represent reach breaks. *Note: scales on ordinate axes are not consistent.*

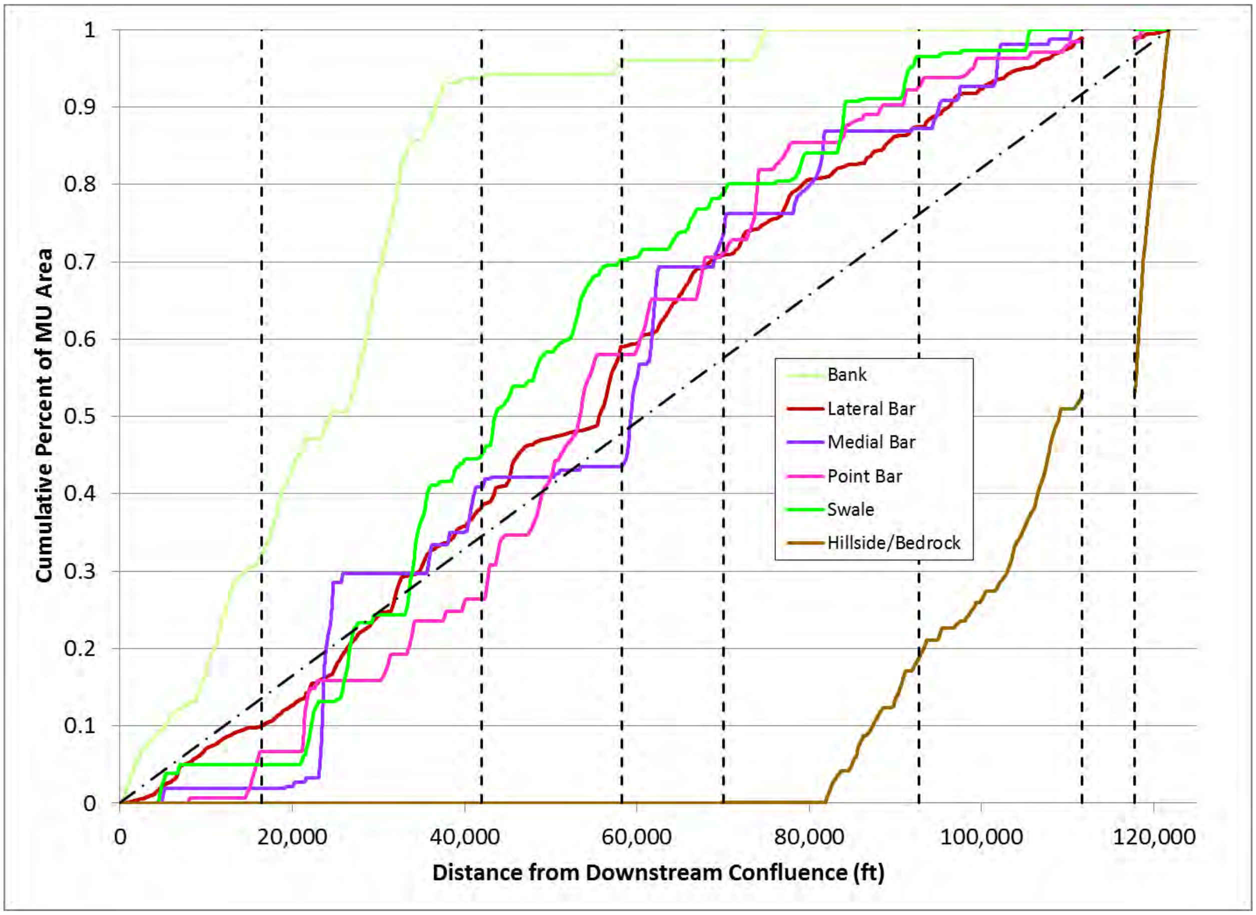

Figure 38. Cumulative distribution functions for areas of in-channel bar morphological units. Vertical dotted lines represent reach breaks. Diagonal dash-dot lines represent uniform distribution.

Longitudinal Spacing

According the definition of C3 Stream Type, pools and riffles tend to be spaced about 5-7 channel widths (W) downstream from each other (Rosgen, 1996). However, other analyses of alluvial channels similar to the LYR suggest a spacing of about 3W (Carling and Orr, 2000). To test this on the LYR, and to analyze the spacing between other relevant units, the centroid of each MU polygon was determined in ArcGIS and then located to the nearest perpendicular point along the channel thalweg. The route distance from the downstream end of the thalweg to each point was determined, and the differences between route distances for adjacent thalweg points of like morphological units were calculated (Figure 39), which yielded a spacing metric.

Some units, such as slackwater, slow glide, and lateral bar, are so ubiquitous (i.e., near-uniform longitudinal distribution) that this test is not viable. The procedure was therefore only performed for units that are primarily longitudinally distributed – chute, fast glide, pool, riffle, riffle transition, run, point bar, and swale. In the spacing analyses for these units, the relevant distances are not necessarily between every subsequent polygon of the same unit classification, but rather between complexes or assemblages of like polygons. Because there exists lateral variability in morphological units on the LYR, there could be situations in which a unit exists on either side of a channel, or in a secondary channel, along the same cross-section. To include both of those units in this metric would artificially shorten the average spacing. Therefore, some discretion was used to manually exempt some of the units from the calculations (Figure 39). To this end, the minimum size threshold of 999 ft^2 was also employed to focus on the major features.

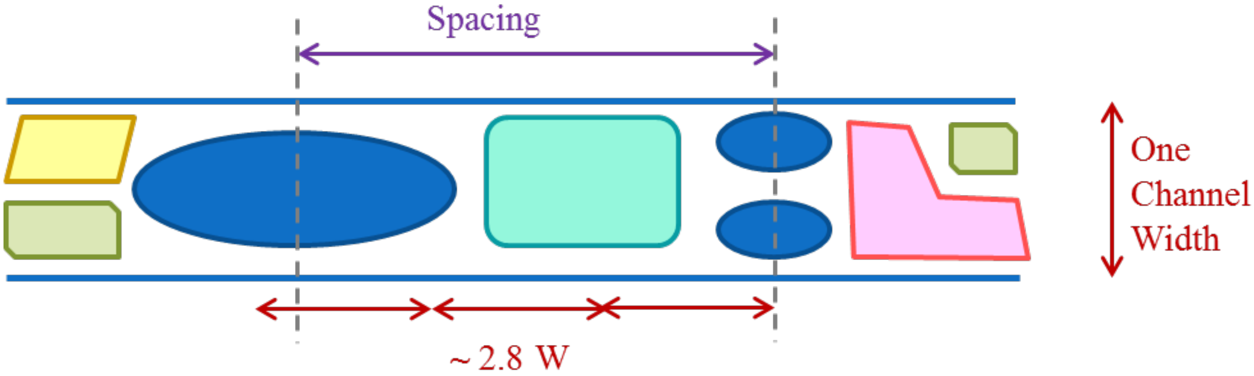

Figure 39. Schematic of method for measuring longitudinal spacing between morphological units. In this example, the spacing between the small blue ovals on the right would not be included in the analysis because they are on the same cross-section. Instead the distance is measured to next downstream blue oval, and the distance metric is normalized by the average channel width.

Once the absolute distances between each MU were calculated, they were then normalized by the bankfull channel widths listed in Table 4. *The key finding of this analysis is that none of the morphological units exhibit the classic 5-7 channel widths (W) spacing at the segment scale as suggested by Rosgen (1996), but do fit the expected 3W spacing of alluvial rivers as suggested by Carling and Orr (2000)* (Table 21). The in-channel unit spacings range from 3.1 – 4.4 W, while the bar unit spacings range from 7.7 – 11.7 W. Of the in-channel units, Runs are the most tightly spaced at 2.7 W, while Pools and Chutes have the longest spacing at 4.4 W. This deviation from classic concept should not be interpreted as good or bad in and of itself, because generic empirical relations have little accuracy or diagnostic value for any one river. Also, the accuracy and detail of the new method developed in this study may be incompatible to interpret relative to the crude methods used historically. Knowing that in-channel bed units are systematically spaced ~2.5-4.5 W indicates that there must be morphological controls at that spatial scale, so that is something to investigate in subsequent studies that focus on processes instead of landforms.

Some of the units, however, do exhibit the classic spacing at the reach scale, such as Riffles in Englebright Reach (6.4W) and Pools in Parks Bar Reach (5.3W). Across all the reach scales, Riffles range from 1.8 – 7.8 W, and Pools from 3.3 – 8.9 W. The Dry Creek Reach exhibits the shortest spacing among the in-channel units (1.8 – 3.7 W), while the Marysville Reach has the longest (4.6 – 12.6 W). The long distances between units in the Marysville Reach can be explained in part by the fact that the wetted area is made up of a smaller number of large units.

The average spacing for the Point Bar units are thought to be a proxy for meander wavelengths, since they are generally formed on the inside banks of meander bends. Through a variety of fluvial environments, meander wavelengths tend to be about 10-14 W (Knighton, 1998). Ackers and Charlton (1970) suggest an equation to calculate meander wavelength (λ) as a function of bankfull discharge (Q_b) as: $\lambda = 62 \cdot Q_b^{0.47}$. For a Q_b of 5,620 cfs, the meander wavelength for the LYR should be 11.2 W. For the river segment, the actual point bar/meander spacing is 11.7 W (varying from ~7 – 17 W at the reach scale), and is therefore in good agreement with expectations. There are no Point Bars in the Englebright Reach, however, due to the system being confined in a bedrock valley.

Swales are usually associated with backwater effects of channel-spanning riffles. At the segment scale, the Swale spacing is more than double that for Riffle spacing. At the reach scale, Swale spacing is consistently greater than Riffle spacing, except for the Marysville Reach where backwater effects are also caused by the deep pools and low slopes. That means that about every other riffle has a low-lying Swale associated with it.

Table 21. Mean longitudinal spacing of morphological units by absolute distance (ft) and normalized distance (channel widths) at the segment and reach scales.

	Chute	Fast glide	Pool	Riffle	Riffle Trans.	Run	Point bar	Swale
Total LYR	1,390	959	1,365	1,059	1,014	840	3,651	2,423
# widths	**4.4**	**3.1**	**4.4**	**3.4**	**3.2**	**2.7**	**11.7**	**7.7**
# of spacings	82	121	91	106	111	139	30	36
Englebright	820	621	554	1,072	1,628	442	n/a	n/a
# widths	**4.9**	**3.7**	**3.3**	**6.4**	**9.7**	**2.6**	**n/a**	**n/a**
# of spacings	3	2	7	3	1	8	n/a	n/a
Timbuctoo Bend	1,064	966	1,125	1,172	867	936	3,830	5,509
# widths	**3.9**	**3.5**	**4.1**	**4.3**	**3.2**	**3.4**	**14.0**	**20.1**
# of spacings	19	21	18	17	22	22	5	2
Parks Bar	1,208	1,084	1,643	851	859	793	2,726	4,952
# widths	**3.9**	**3.5**	**5.3**	**2.8**	**2.8**	**2.6**	**8.9**	**16.1**
# of spacings	21	24	16	30	28	33	8	5
Dry Creek	940	935	1,563	751	909	717	6,994	3,311
# widths	**2.2**	**2.2**	**3.7**	**1.8**	**2.2**	**1.7**	**17.0**	**7.9**
# of spacings	12	12	8	15	13	14	2	2
DPD	1,617	1,010	1,847	1,173	1,380	985	2,652	1,492
# widths	**4.3**	**2.7**	**4.9**	**3.1**	**3.6**	**2.6**	**7.0**	**3.9**
# of spacings	11	18	10	15	12	18	5	11
Hallwood	2,169	812	1,101	1,246	992	745	4,156	1,990
# widths	**6.6**	**2.5**	**3.3**	**3.8**	**3.0**	**2.3**	**12.6**	**6.0**
# of spacings	13	32	24	21	28	37	7	11
Marysville	2,899	1,052	2,049	1,798	1,661	1,687	3,995	1,308
# widths	**12.6**	**4.6**	**8.9**	**7.8**	**7.2**	**7.3**	**17.3**	**5.7**
# of spacings	3	12	8	5	7	7	3	5

Adjacency Probability

An underutilized approach to investigating morphological unit organization is the Markov chain or transition probability analysis method used for 1D morphological units by Grant et al. (1990). This approach evaluates the frequency that any type of item (morphological unit types in this case) is adjacent to any other type of item, and then compares that against the expectation associated with a random system that has equal probability of adjacent. Markov chains are used throughout science and technology, but could be especially useful for understanding fluvial landforms now that a method exists to describe then laterally as well as longitudinally, yielding more opportunity for adjacencies. As a result of lack of use of Markov chains in river science so far, there is no baseline as to what constitutes a "normal" transition probability matrix, so an important first step is to apply the method for diverse natural and regulated streams and derive that. At a minimum, this tool can be used to establish whether the river the river is spatially structured, and if so, which units tend to be co-located or avoid co-location.

Because the morphological unit framework used in this study involve both lateral and longitudinal adjacency of units, a new procedure had to be developed to calculate transition probabilities. The new metric involves determining non-directional adjacency probabilities. To determine how many units of one morphologic type were adjacent in any direction to another type, the Select by Location ArcGIS selection tool was used. This tool allows the user to specify criteria for selection. This led to the selection of all polygons of the specified unit type (from the morphologic unit shapefile containing all polygons of that particular unit type) that shared a common boundary with another individual morphologic unit type shapefile. For instance, a Riffle unit was adjacent to a Chute unit 673 times and to a Pool only 3 times, so 12.6% of the entire Riffle adjacency is associated with Chutes and only 0.06 % associated with Pools (Table 22, Table 23). This type of adjacency is not one-to-one. That is, unit type A will have a number of adjacencies to unit type B, while unit B will have a different number of adjacencies to unit type A (Figure 40). That happens because a single type-A polygon can be long and touches multiple type-B polygons, whereas in the inverse, all those B polygons are only touching the one type-A polygon. In other words, there is no way to count each individual transition, which would have to be one-to-one, and instead the metric that is counted is the number of unique adjacencies. If five unit A polygons touch the same unit B polygon, then that counts as one adjacency, but in the inverse it counts as five adjacencies.

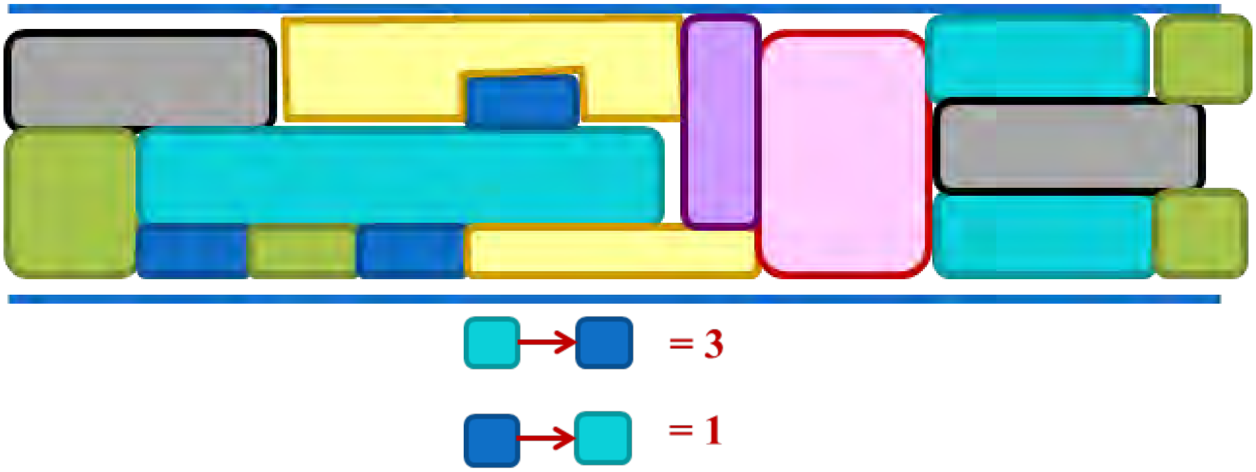

Figure 40. Schematic of method for measuring MU adjacency. In this example, the light blue units are touching to three unique dark blue units; therefore, the adjacency from light blue to dark blue would be three. However, the dark blue units are only touching one unique light blue unit; therefore, the adjacency from dark blue to light blue would be one.

The way Grant et al. (1990) evaluated the likelihood that the transition probabilities were nonrandom was to randomly generate a sequence of units (with each unit equally likely to occur next in order of selection), calculate the random transition probabilities, and then compare the real transition probabilities to those. A possible issue with that method is that the outcome is sensitive to the specific sequence created at random. Conceivably, one could repeat the step several times and compare the real transition probabilities to the average of random ones. Taking that idea to the limit, if one was to use a near infinite number of random sequences, then by definition, the transition probabilities available for this analysis must converge on the uniform distribution of transitions among all unit types. Just considering the units within the baseflow inundation region, this convergence value would be 1/8, or 12.5%, since there is equal probability of any unit type randomly going to any of the other eight unit types. As a result, it is possible to designate a “preference” or “avoidance” to adjacency to a unit type on the basis of whether the percent of adjacencies to it are notably higher or lower than 12.5%. Adjacencies that are within a couple percentage points (i.e., ~10-15%) of this random value will be considered as “near-random”.

The results show that there is a strong organizational structure evident in the adjacency probabilities (Table 22, Table 23). A majority of the units exhibit greater-than-random preferences to Riffle Transition and Slow Glide. Conversely, the Riffle Transition and Slow Glide units exhibit few preferential connections towards other units besides each other and Slackwater; however they do exhibit the highest total number of adjacencies. Adjacency probabilities that are near-random include the Pool-Slackwater, Riffle-Run, and Riffle-Slackwater connections.

Also of note in these results are the avoidances between some units. Both the Riffle-Pool and Pool-Riffle adjacencies are greater-than-random avoidance (Table 23), which differs from traditional, simplistic methods for identifying pool and riffle MUs in a channel. The units Riffle Transition and Fast Glide were envisioned as entrances and exits to the pools and riffles, which the adjacency probabilities corroborate (Pool-Fast Glide = 34.9%; Riffle-Riffle Transition = 39.2%).

Table 22. Total number of unit types adjacent to starting unit (left column) for all in-channel bed MU polygons.

Starting Unit	Chute	Fast Glide	Pool	Riffle	Riffle Transition	Run	Slack-Water	Slow Glide	Total
Chute		114	24	661	131	918	10	38	1896
Fast Glide	52		677	481	3208	687	671	2352	8128
Pool	23	1280		2	132	258	534	1438	3667
Riffle	575	567	2		4095	1248	1394	2577	10458
Riffle Transition	44	2158	73	1506		603	9345	11458	25187
Run	369	1714	411	1600	1140		64	235	5533
Slackwater	9	533	229	372	4143	48		12144	17478
Slow Glide	22	1570	329	544	5476	174	13013		21128
Total	2188	15872	3490	10332	36650	7872	50062	60484	186950

Table 23. Percent of unit types adjacent to starting unit (left column) for all in-channel bed MU polygons. Green highlighted boxes represent greater-than-random preference probabilities (> 20%); Yellow boxes represent near-random adjacency probabilities (~12.5%); Pink boxes represent greater-than-random avoidances (< 5%).

Starting Unit	Chute	Fast Glide	Pool	Riffle	Riffle Transition	Run	Slack-Water	Slow Glide
Chute		6.0%	1.3%	34.9%	6.9%	48.4%	0.5%	2.0%
Fast Glide	0.6%		8.3%	5.9%	39.5%	8.5%	8.3%	28.9%
Pool	0.6%	34.9%		0.1%	3.6%	7.0%	14.6%	39.2%
Riffle	5.5%	5.4%	0.0%		39.2%	11.9%	13.3%	24.6%
Riffle Transition	0.2%	8.6%	0.3%	6.0%		2.4%	37.1%	45.5%
Run	6.7%	31.0%	7.4%	28.9%	20.6%		1.2%	4.2%
Slackwater	0.1%	3.0%	1.3%	2.1%	23.7%	0.3%		69.5%
Slow Glide	0.1%	7.4%	1.6%	2.6%	25.9%	0.8%	61.6%	

The results in Table 22 and Table 23 include all in-channel bed MU polygons, regardless of size. To evaluate whether adopting the field-identifiable minimum size affects these results, the same analysis was performed for just those MU polygons with areas > 999 ft^2 (Table 24, Table 25). The total number of adjacencies in the segment corridor is reduced to ~2.5% of the original count (Table 24). Most of the connections that were considered as preference remained so. The two exceptions are Riffle-Slow Glide and Riffle Transition-Slackwater, which changed to avoidance and near-random, respectively. Two of the previously near-random adjacencies changed to preference (Pool-Slackwater and Riffle-Run), while the third changed to avoidance (Riffle-Slackwater). Six previous avoidance probabilities changed to greater-than-random preference: Riffle-Chute; Fast Glide-Run; Riffle Transition-Fast Glide; Riffle Transition-Riffle; Slackwater-Pool; and Slow Glide-Fast Glide. Eight other adjacent combinations also increased from avoidance to near-random (yellow boxes in Table 25).

Table 24. Total number of unit types adjacent to starting unit (left column) for in-channel bed MU polygons greater than 999 ft^2.

Starting Unit	Chute	Fast Glide	Pool	Riffle	Riffle Transition	Run	Slack-Water	Slow Glide	Total
Chute		0	6	126	0	113	0	0	245
Fast Glide	0		96	71	221	124	10	191	713
Pool	5	131		1	1	65	158	149	510
Riffle	110	71	1		205	165	3	4	559
Riffle Transition	0	161	1	191		122	111	215	801
Run	88	144	72	175	164		0	1	644
Slackwater	0	10	81	3	95	0		257	446
Slow Glide	0	145	78	4	203	1	298		729
Total	203	662	335	571	889	590	580	817	4647

Table 25. Percent of unit types adjacent to starting unit (left column) for in-channel bed MU polygons greater than 999 sq ft. Green highlighted boxes represent the adjacency probabilities that remained as preference (> 20%). Light green represents those that changed from avoidance to preference. Dark green represents those that changed from near-random to preference. White represents those that changed from preference to near-random (~12.5%). Orange represents those that changed from preference to avoidance. Pink represents those that remained as avoidance (< 5%). Yellow represents those that changed from avoidance to near-random. Maroon represents those that changed from near-random to avoidance.

Starting Unit	Chute	Fast Glide	Pool	Riffle	Riffle Transition	Run	Slack-Water	Slow Glide
Chute		0.0%	2.4%	51.4%	0.0%	46.1%	0.0%	0.0%
Fast Glide	0.0%		13.5%	10.0%	31.0%	17.4%	1.4%	26.8%
Pool	1.0%	25.7%		0.2%	0.2%	12.7%	31.0%	29.2%
Riffle	19.7%	12.7%	0.2%		36.7%	29.5%	0.5%	0.7%
Riffle Transition	0.0%	20.1%	0.1%	23.8%		15.2%	13.9%	26.8%
Run	13.7%	22.4%	11.2%	27.2%	25.5%		0.0%	0.2%
Slackwater	0.0%	2.2%	18.2%	0.7%	21.3%	0.0%		57.6%
Slow Glide	0.0%	19.9%	10.7%	0.5%	27.8%	0.1%	40.9%	

If we now just consider the adjacency probabilities that exist between the units within the bankfull inundation region, there are four major units to include in the analysis based on their abundances (Table 14); however, the Medial Bar units are uniquely located in the middle of the channel, fully separated from the other bankfull units. Therefore, including those units would improperly skew the results. The next most abundant and relevant unit to use as a replacement is Hillside/Bedrock. Considering just these four units within this region, the random probability of adjacency would be 25%. Point Bar, Hillside/Bedrock, and Swale all exhibit greater-than-random preferences to Lateral Bar (Table 26). Other notable spatial preferences are Lateral Bar-Swale and Point-Swale. Notable avoidances include those between Hillside/Bedrock and Swale, and between Hillside/Bedrock and Point Bar.

Table 26. Percent of unit types adjacent to starting unit (left column) for MUs in the bankfull inundation region. Green highlighted boxes represent adjacency probabilities that exhibit a greater-than-random preference (>> 25%). Pink boxes represent avoidance (<< 25%). Yellow boxes represent near-random adjacencies (~ 25%).

Starting Unit	Lateral Bar	Point Bar	Hillside/Bedrock	Swale
Lateral Bar		28.0%	17.2%	54.8%
Point Bar	66.1%		0.0%	33.9%
Hillside/Bedrock	88.2%	0.0%		11.8%
Swale	74.4%	20.5%	5.1%	

Because the in-channel bar units inhabit the bankfull inundation region which envelops the baseflow inundation region, there will be adjacency probabilities between the MU sets. For comparing the adjacencies of the five main in-channel bar units (now including Medial Bar) to the eight in-channel bed units, the random probability would be 1/8 (12.5%). All five in-channel bar units exhibit a greater-than-random adjacency preference to the Slackwater units (Table 27). Other greater-than-random transitions include Lateral, Medial, and Point Bars to Slow Glide, and Lateral and Medial Bars to Riffle Transition. Near-random probabilities exist for the Medial Bar-Riffle, Point Bar-Riffle Transition, Hillside-Riffle, Hillside-Slow Glide, and Swale-Slow Glide (Table 27). All other transitional probabilities exhibit a greater-than-random avoidance.

Table 27. Percent of in-channel bar MUs adjacent to in-channel bed MUs. Green boxes represent adjacency probabilities that exhibit a greater-than-random preference (>> 12.5%). Pink boxes represent avoidance (<< 12.5%). Yellow boxes represent near-random probabilities (~ 12.5%).

Starting Unit	Chute	Fast Glide	Pool	Riffle	Riffle Transition	Run	Slack-water	Slow Glide
Lateral Bar	0.0%	0.3%	0.6%	7.9%	19.2%	0.2%	43.3%	28.5%
Medial Bar	0.0%	0.0%	0.0%	14.7%	28.2%	0.0%	35.0%	22.0%
Point Bar	0.0%	0.6%	0.0%	8.9%	14.9%	0.0%	46.4%	29.2%
Hillside/ Bedrock	1.2%	1.2%	7.1%	11.8%	2.4%	3.5%	60.0%	12.9%
Swale	0.0%	0.0%	0.0%	1.4%	4.2%	0.0%	81.9%	12.5%

Within the transition boundaries from in-channel bed units to in-channel bar units, most bed units exhibit a greater-than-random adjacency probability (20%) to Lateral Bar (Table 28). Chute has only one transition, to Hillside/Bedrock, therefore the adjacency probability between those units is inflated. For this analysis, no in-channel bed units exhibit a greater-than-random adjacency probability for either Medial Bar or Swale units; however, several do exhibit near-random probabilities (Table 28).

Table 28. Percent of in-channel bed MUs adjacent to in-channel bar MUs. Green boxes represent adjacency probabilities that exhibit a greater-than-random preference (>> 20%). Pink boxes represent avoidance (<< 20%). Yellow boxes represent near-random probabilities (~ 20%).

Starting Unit	Lateral Bar	Medial Bar	Point Bar	Hillside/ Bedrock	Swale
Chute	0.0%	0.0%	0.0%	100.0%	0.0%
Fast Glide	33.3%	0.0%	33.3%	33.3%	0.0%
Pool	33.3%	0.0%	0.0%	66.7%	0.0%
Riffle	51.9%	22.2%	14.8%	9.9%	1.2%
Riffle Transition	55.5%	21.8%	18.2%	1.8%	2.7%
Run	25.0%	0.0%	0.0%	75.0%	0.0%
Slackwater	51.5%	12.0%	13.3%	5.8%	17.4%
Slow Glide	55.2%	16.8%	17.5%	4.9%	5.6%

Lateral Distribution

Classic research predominantly considered spatial organization in 1-D, i.e., one morphological unit per cross-section. Wide, diverse rivers, such as the LYR, could exhibit lateral variability in its form-process associations (Figure 41). It is widely believed that high channel heterogeneity promotes biological diversity by providing multiple closely located but different niches. To test whether the LYR has lateral heterogeneity, the number of distinct morphological units at each cross-section were counted and compared for the segment and reach scales.

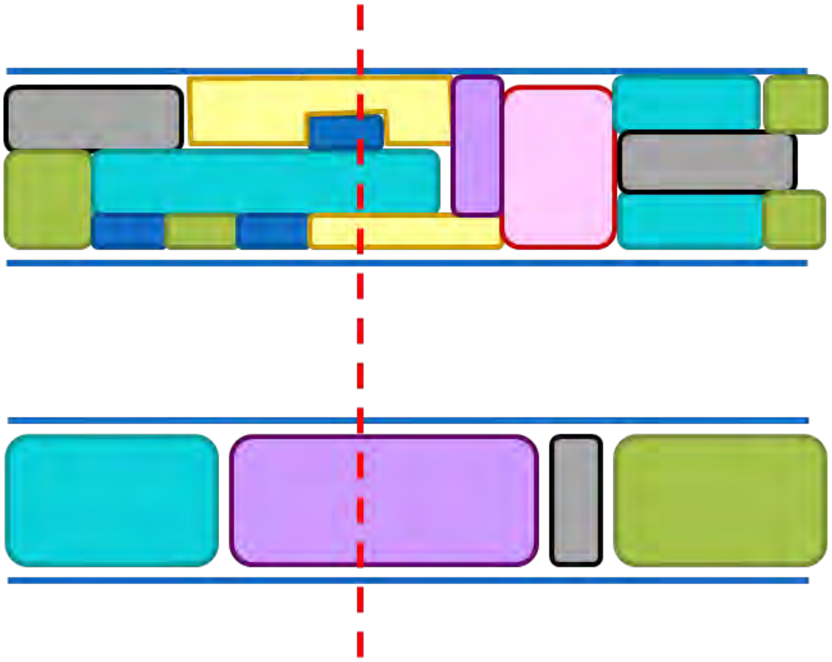

Figure 41. Conceptual schematic of difference between 2-D spatial organization (top) and 1-D spatial organization (bottom). In this example, the red dashed line illustrates a cross-section that exhibits lateral variability only in the top channel.

This method utilized the longitudinally stationed rectangles on the valley centerline as the domain within which to count the number of MU polygons across the channel. First, the MU polygons were cut with the rectangles. Within an individual rectangle, unusually shaped polygons that were once part of one larger MU but now cut into multiple pieces in the same rectangle were merged back into a single multi-part MU polygon, but the other pieces of that MU polygon outside of the rectangle were not included. If a cross-section contains many small MU polygon bits, then its lateral variability value will be high. However, this variability may not be as apparent to the field observer, which is exactly why it is important to have an objectively defined method of delineating and analyzing MUs. The previous discussion of what the minimum size of a MU polygon that would constitute a recognizable landform is relevant for this analysis as well. Many small MUs may have real meaning in terms of local habitat heterogeneity, but this analysis aimed to capture the lateral abundance of visually discernible MUs as well. Therefore, the rectangles were also used to dissect only those MUs with an area > 999 ft^2. What was relevant was to determine which cross sections morphological units of sufficient size intersect.

Including all MU polygon bits, the LYR segment exhibits ~19 morphological units per 20-ft long bankfull cross-section. The Dry Creek reach exhibits the highest average number of morphological units per cross-section at ~29, while Marysville exhibited the lowest at ~11 (Table 29, Figure 42). Minimum size discriminations 999 ft^2 reveal averages of ~ 9 MU per cross-section, ranging from ~6-12 at the reach scale (Table 29).

Table 29. Reach-averaged cross-sectional variability of morphological units, including sensitivity analysis on minimum size considerations for included polygon bits (square feet)

		All bits	Bits ≥ 999
Segment Scale	**Total Count**	112,532	51,047
	% Count Decr		54.6%
	Average #/W	19.3	8.8
	Max	96	24
	Min	1	1
	Sum Area (ft^2)	39,656,593	37,338,199
	% Area Decr		5.8%
Reach Average Counts per Width	**Englebright**	19.0	6.4
	Timbuctoo	17.7	7.4
	Parks Bar	21.5	8.7
	Dry Creek	28.6	11.8
	DPD	18.8	9.0
	Hallwood	19.9	9.6
	Marysville	11.1	7.7

Regardless of the size of MU polygons included in the analyses, the Dry Creek reach still exhibits the greatest lateral variability throughout the LYR segment (Table 29). The Marysville reach exhibits the lowest average lateral variability in the analysis that includes all the polygon bits, while the Englebright reach exhibited the lowest average lateral variability for the large minimum-size polygon analysis. Regardless of the size discrimination, the adjacent reaches of DPD and Hallwood tend to exhibit similar reach-averaged lateral variability that is also near the segment-scale average.

Using no size discrimination, the analysis shows that the middle, unconfined reaches (Parks Bar, Dry Creek, DPD, and Hallwood) have the greatest lateral variability (Figure 42). The reach-scale average variability ranges from ~19 to 29 MU per cross-section (Table 29). Setting a minimum MU size of 999 ft^2 does little to change the overall pattern of lateral variability at the segment or reach scale (Figure 43). The highest local peaks in each of the reaches tend to be spatially aligned, albeit muted in value.

As the minimum MU size discrimination is assessed, the lateral variability is still at its greatest within the middle reaches (Figure 43). The values within the Englebright reach, however, decrease at a faster rate with increased minimum sizes because of the smaller widths associated with this region. It is also interesting to note that several of the peaks in lateral variability tend to occur near the reach transitions, especially the transitions from Parks Bar to Dry Creek and Dry Creek to DPD (Figure 43).

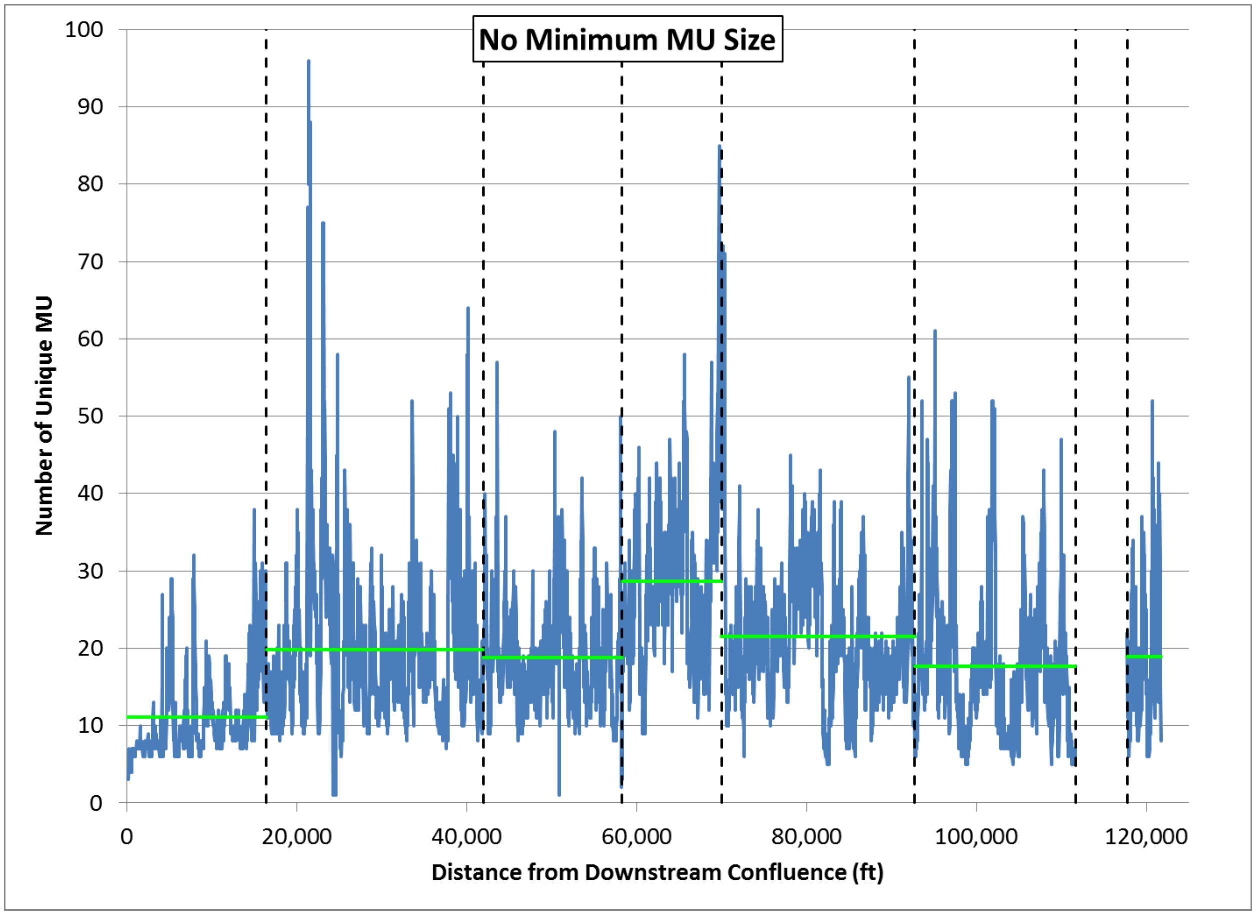

Figure 42. Lateral variability of morphological units per 20-ft long cross-sections. Analysis includes all MU polygon bits (no minimum size discrimination). Vertical dash-dot lines represent reach breaks. Green line represents average per reach.

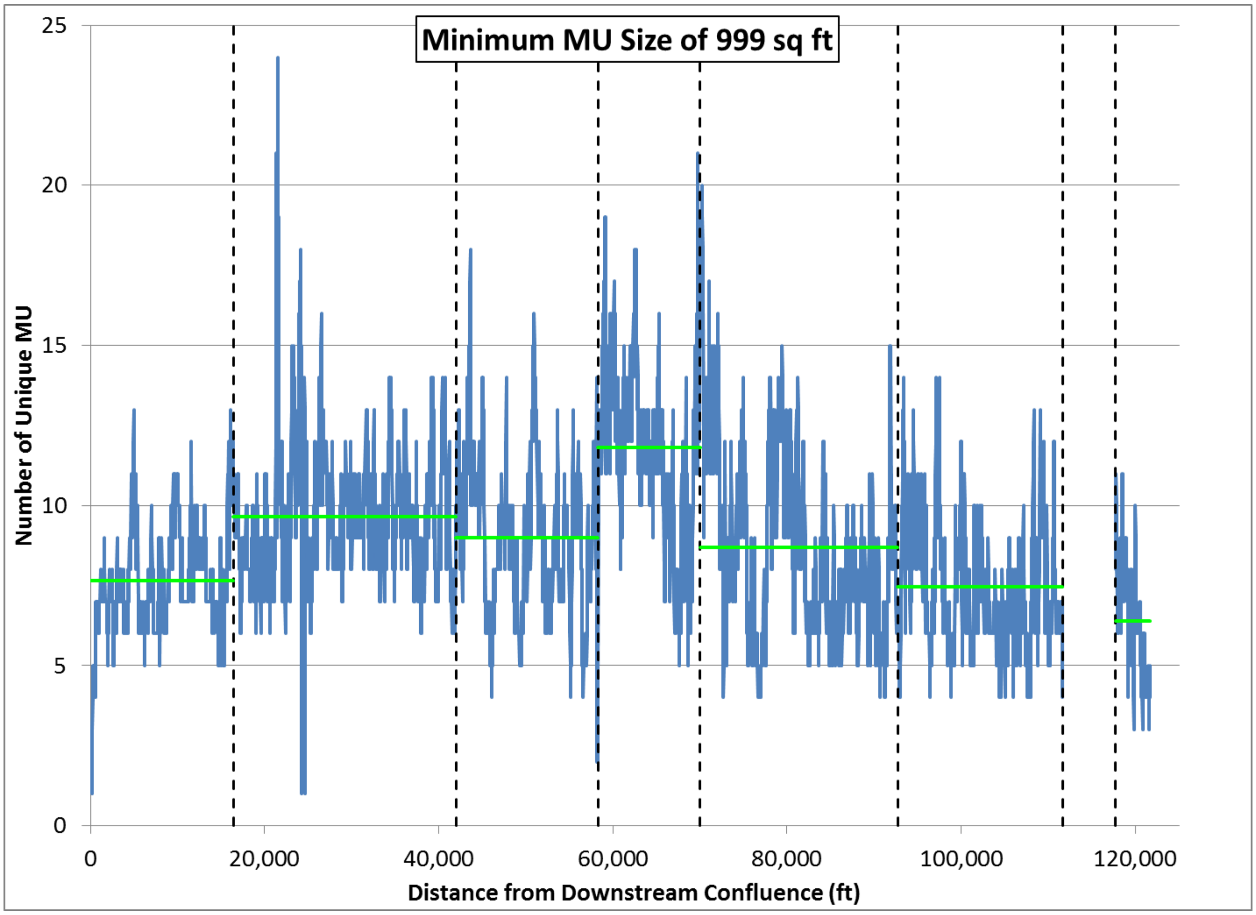

Figure 43. Lateral variability of morphological units per 20-ft long cross-sections. Analysis includes only those MU polygon bits larger than 999 ft^2. Vertical dash-dot lines represent reach breaks. Green line represents average per reach.

The high values of lateral variability within the middle reaches of Parks Bar, Dry Creek, DPD, and Hallwood may be explained by their high widths. The wider a channel section is, the more space there is for laterally adjacent morphological units. To determine the influence of channel width on this parameter, the individual lateral variability values for the 999 ft^2 analysis were normalized by their associated channel widths (Figure 44). By eliminating width as a factor, the river segment becomes much more uniform in lateral variability, especially through the Timbuctoo-Parks Bar-Dry Creek reaches. Using this metric, the narrow Englebright and Marysville reaches exhibit the highest width-normalized reach-scale averages, whereas the rest of the reaches all exhibit about the same variability value with the wide DPD reach having the lowest normalized variability.

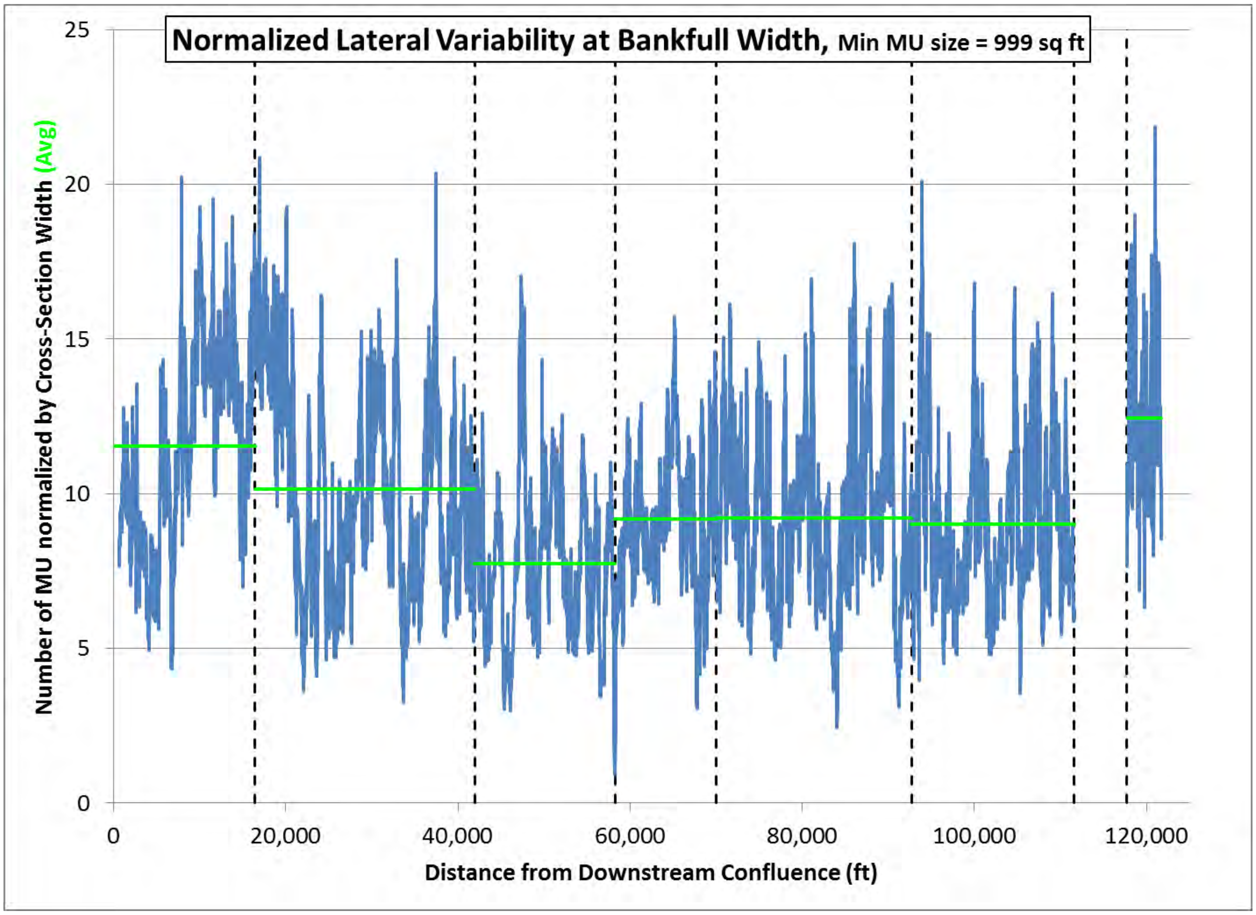

Figure 44. Lateral variability of morphological units normalized by the ratio of average reach width to local cross-sectional width, using a minimum polygon size of 999 ft^2. Green line represents reach-scale averages and vertical dashed lines represent reach breaks.

Overall, *this analysis shows that the LYR exhibits a high degree of lateral variability, regardless of the minimum size discrimination implemented for MU landform identification.* Even incorporating the minimum size analysis (Figure 43), all of the reaches exhibit an average of more than one MU per discrete cross-section. Applying a minimum size of 999 ft^2 scale, the average reach-scale lateral variability ranges from ~6-12 MUs per cross-section, with discrete local variability of up to 24 MU per cross-section.

Conclusions and Recommendations

The primary goal of this project was to comprehensively and transparently characterize and delineate the morphology of the LYR at several spatial scales. A combination of novel technologies, data-processing methods, mechanistic models, and GIS-based spatial and 3D analyses were utilized to achieve this goal. Thorough geomorphic analysis is often neglected in instream flow analyses in favor of 1D habitat analyses or reconnaissance-based visual assessments, thus neglecting the inherent spatial variability in the channel's geomorphology and physical processes. In contrast, this study used a "near-census" approach for collecting topographic and hydrologic data that resulted in a far more detailed characterization of the river corridor and is accurate at multiple spatial scales (Pasternack, 2011). 2D model results were used to thoroughly demonstrate a new way to characterize the geomorphology of a river at a moment in time as well as to infer key physical processes for sustaining physical habitat. New methods were developed to characterize the spatial structure of the morphology, which revealed that the fluvial landforms in the study segment are spatially organized, not randomly located. This spatial organization has a strong influence on physical meso- and micro-habitat conditions.

Methodological Outcomes

A primary methodological question was whether a 2D hydraulic model could be used as the focal lens through which instream flow assessment could be conducted. The answer is that a 2D hydraulic model proved extremely versatile in what it could lend insight into. The geomorphic analysis section in this study is almost completely based on 2D model results and includes several new discoveries about scale-dependent geomorphic patterns and processes that would not have been possible without the use of a 2D model. In order to accurately map the channel morphology at the MU spatial scale, a new methodology initially tested by Pasternack and Senter (2010) on the upper South Fork Yuba River was implemented for the LYR, thus creating a comprehensive and objective delineation of landforms. This methodology is easily applicable to any stream system, even if the new channel would exhibit different hydraulics and morphological units.

Another methodological question was how to analyze the natural spatial organization of the channel landforms. Spatial Analyst and 3D Analyst tools within ArcGIS enabled the characterization of morphological units by abundance, size, longitudinal distribution and spacing, adjacency probabilities, and lateral variability. While some of these methods were pioneered by Pasternack and Senter (2010), the computation of the lateral variability of MUs and many other metrics used in this report represent a significant step for fluvial geomorphic analysis.

Scientific Outcomes

The hydrology and land-use history of the LYR are well documented; however, how those factors have combined with geology, land cover and topography to shape the present-day morphology is not well known. The results and analyses presented in this report provide a clear morphological characterization of the LYR as a baseline for current and future assessments.

Using major changes within the geomorphic variables as a guide, the ~25-mi segment was delineated into eight distinct reaches. The key geomorphic indicators of reach breaks were presence of tributary confluences, presence of dams, valley width, riverbed slope breaks, and substrate. The segment was also delineated in the streamwise direction by identifying key inundation regions for baseflow, bankfull, and flood discharges.

Starting from the 3-ft resolution 2D hydrodynamic model outputs, it was possible to identify laterally varying, flow-independent “morphological units” that serve as the basic building blocks of geomorphic processes at reach and segment scales. Discovery of laterally explicit morphological units and the geomorphic characterization of their specific spatial organization is a major scientific advance. The exact terminology used for some of the morphological units is somewhat different from other studies, but is not particularly important. What is scientifically novel is the new methods implemented to map these units. Some units are preferentially located further upstream or downstream within the segment. Each unit has a statistically significant higher likelihood (i.e., “preference”) of occurrence adjacent to a subset of other unit types.

Management Outcomes

The results presented herein represent a static view at a single time circa 2008 for the LYR. Therefore, it is not recommended that these results be used to infer past temporal variability within the channel corridor. Subsequent process-related studies are pending. However, it is possible to make some general morphologic characterizations of the present LYR channel. Namely:

1. Despite some flow regulation, the channel and floodplain in the LYR are highly connected, with floods spilling out onto the floodplain more frequently than commonly occurs for unregulated semiarid rivers. Some location exhibit overbank flow well below 5,000 cfs, while others require somewhat more than that. In any given year, there is an 82% chance the river will spill out of its bankfull channel and a 40% chance that the floodway will be fully inundated.
2. The bars and floodplains outside of the baseflow channel are hydraulically well-connected. The floodplain areas up to the floodway wetted area have an inundation frequency of about once every 2.5 years.
3. In the areas of the training berms (DPD Reach), the geomorphically-active valley corridor is at its widest.
4. The valley corridor is on average ~5 times as wide as the baseflow channel (ranging from ~3-8 times at the reach scale), thus allowing for sufficient meandering. Downstream where meandering intersects berms, the berms are rapidly being cut through. Left to its own action, the river will naturally meander through the berms and divert into the wasteland of the Yuba Goldfields.
5. The classification of the LYR by Rosgen Stream Type shows that its morphology and functional processes are in accordance with other similar alluvial channels (C3). Pristine rivers are not all meandering with a forested floodway. It useful to use channel classification as one of many guides to gain insight into the suitable palette of geomorphic processes and ecological functions consistent with what a river can achieve. Any decision to switch the morphology of a river to a different class type should be based on a clear understanding of the viability and resilience of the proposed alternative state.
6. The LYR exhibits low to moderate sinuosity at the segment and reach scales, which is typical of river corridors whose alluvium consists of a similar mixture for its bed and banks.
7. On average, the LYR is not entrenched at the segment or reach scales. There do exist short stretches of entrenchment in all reaches, but there also exist more and longer stretches that are not.

8. The presence of slackwater morphological units at the baseflow discharge represents areas of low velocity that are ideal for juvenile refugia habitat. In fact, slackwater represents the highest areal percentage within the baseflow inundation region (~16%).
9. The presence of medial bars and islands throughout the segment represent sections of split flow and multiple channels. There are ~20 flow-splitting islands in the segment.
10. The presence of swales in the bankfull wetted area represents areas of detached flow paths through the floodplain. There are ~60 swales in the segment with a spacing frequency of ~8 channel widths.
11. The presence of backswamp and pond morphological units represents backwater areas at the bankfull and higher discharges. There are ~30 of these units in the segment.
12. The non-random organization of the MU landforms shows that there is a natural structure to the channel morphology at multiple spatial scales.
13. The LYR exhibits significant lateral and longitudinal variability in its morphology, thereby enabling a spectrum of hydraulics and habitat across its breadth and length.

Recommendations for Application of Results

The morphological data presented in this report can be and has been used as a baseline for the stratification at different spatial scales of any relevant biological data, e.g., redd locations and distributions, vegetation and cover, and juvenile salmonid refugia. The present channel characterization can be used as a context for historic and future comparisons.

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