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Are dynamic fluvial morphological unit assemblages statistically stationary through floods of less than ten times bankfull discharge?

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ABSTRACT

The morphological unit (MU) characterizes river landforms at the scale of ~0.5–5 channel widths. Geomorphic theory posits that ceteris paribus under a stationary flow and sediment regime, a river's channel pattern and its MU assemblage will also be stationary. This study tested that conjecture for the dynamic, gravel/cobble lower Yuba River. The MU assemblage consisting of eight in-channel bed types (i.e., chute, fast glide, pool/forced pool, riffle, riffle transition, run, slackwater, and slow glide) was mapped in 2006/2008 and 2014 for a ~34 km long by 100 m wide alluvial segment at ~1-m resolution using the Wyrick et al. (2014) methodology. Between these two surveys there were four brief floods of 6–9 times bankfull discharge and a total of 163 days above bankfull discharge, yielding an estimated 638,539 and 507,743 m^3 of erosion and deposition, respectively. Bulk statistical change tests (e.g., MU area, count, spacing, diversity, lateral diversity, and adjacency), MU temporal transition analysis, and MU individual polygon tracking analysis were used to answer the scientific question. Even though the river has an abundant internal sediment supply and dynamic flow regime, the river's in-channel bed shifted toward a lower-relief morphology, with a widespread and significant fragmentation of individual MU polygons, especially the large ones. The MU at each location in the river predominantly changed, except for pool, which tended to stay the same because of local topographic forcing. Overall, the predominance of evidence leads to the conclusion that the MU assemblage was not stationary over the period evaluated. This is hardly the final word, given the relatively short duration compared to geological time and considering only one cobble/gravel river, but this study points the way toward future investigation into MU stationarity in light of modern spatially explicit fluvial geomorphic mapping methods.

1. Introduction

Fluvial morphological units (MUs, aka geomorphic or channel units) are flow-independent landforms identifiable at the scale of ~0.5–5 channel widths (O'Neill and Abrahams, 1984; Grant et al., 1990). They are one of the fundamental delineations of river landforms and they play an important role in aquatic ecology (Gorman and Karr, 1978; Rashleigh et al., 2005; Moir and Pasternack, 2008) and river management (Gilvear, 1999; Brierley and Fryirs, 2005). New literature explores advancements for delineating them, taking advantage of detailed topo-bathymetric maps (e.g., Wyrick et al., 2014; Wheaton et al., 2015; Belletti et al., 2017; van Rooijen et al., 2021).

Rivers undergo morphodynamics in response to flow and/or sediment supply disturbance regimes. As a result, MUs change through time, especially during large floods. Or do they? Classic literature posits that channel pattern should remain the same as long as the driving forces and boundary conditions are consistent over time (Leopold and Wolman, 1957; Hack, 1960; Van den Berg, 1995; Kleinhans and Van den Berg, 2011). This systemic level understanding is believed to imply that the MU assemblage within a persistent channel pattern should also be statistically stationary. In other words, even if individual units change, aggregate attributes of the assemblage will not change, because the system is experiencing a consistent morphodynamic disturbance regime. This expectation is also tied to the concept of hierarchical nesting of landforms at different spatial scales (sensu Frissell et al., 1986), which also sets the expectation that the MU assemblage and its attributes are dictated by the higher scale controls (Thomson et al., 2004). However, the stationarity of MU assemblages over time has hardly been tested because of a lack of morphodynamic data spanning spatial scales but retaining high resolution. Methods are also lacking for evaluating MU changes. In any case, almost nothing is known about MU changes at the scales of individual MUs and MU assemblages.

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Compared to the classic approach of monitoring rivers with cross sections and longitudinal profiles, the advent and growing use of meter-resolution digital elevation models built from spatially explicit point cloud data collection methods (e.g., lidar, multibeam sonar, structure-from motion, etc.) has fundamentally advanced the ability to map landforms repeatedly over time and quantify landform changes mindful of morphodynamic processes (e.g., see comparison Fig. 5.4 of Vericat et al., 2017). MUs are spatial explicit landform objects (sensu Blaschke et al., 2000) that undergo planform object change as well as 3D volumetric change. A few studies have investigated volumetric change by MU, land surface type, inundation zone, geomorphic reach or other spatial objects (Wheaton et al., 2013; Tamminga et al., 2015; Pasternack and Wyrick, 2016; Weber and Pasternack, 2017), but relatively little is known about planform MU object change patterns and associated impacts on MU longitudinal sequencing.

The purpose of this study was to develop new methods of quantifying MU object change resulting from morphodynamics and apply those methods to gain new insights into fluvial geomorphology for one river type. After introducing MU mapping concepts and new concepts for MU change analysis, a set of specific scientific questions are presented to get at the fundamental question of stationarity of MU assemblages. Although the river test segment is long compared to previous studies at this resolution, scientific conclusions may be constrained by river type, flow and sediment supply regimes, landscape position, anthropogenic history, climate, and other factors.

1.1. MU mapping concepts

Classic, field-based morphological unit mapping usually entails the use of visual assessment of topographic and hydraulic indicators during a summer baseflow when people can wade a river to draw polygons on paper maps or navigate rivers to create polygons using Geographic Positioning System devices. Properly locating transitions between units is very difficult in the field, yielding high uncertainty. While MU mapping has benefited society and helped answer scientific questions, nobody knows how effective and accurate the methods are, because there is no independent gold standard to compare to. Drawbacks to field mapping MUs include yielding results that are highly opaque, subjective, difficult to replicate, and almost impossible to review or challenge years later. In the twenty-first century scientific advances have sought to rectify these problems.

With the growing availability of modern meter-scale digital terrain models of river corridors, automated MU mapping now exists. The common strategy for automated mapping involves replacing opaque field-worker subjectivity with a transparent, explicit, expert-based rule set designed by a multidisciplinary team and implemented with an algorithm applied to landform and hydraulic indicators evident in either a digital terrain model or two-dimensional hydrodynamic (2D) model output rasters (e.g., Wyrick et al., 2014; Wheaton et al., 2015; Belletti et al., 2017; van Rooijen et al., 2021). These methods are not to be confused with mesohabitat mapping methods that are similar in strategy but delineate patterns of discharge-dependent hydraulically homogenous patches (e.g., Newson and Newson, 2000; Borsányi et al., 2004; Hauer et al., 2009).

This study of MU change as a result of fluvial morphodynamics used a well-established, six-step MU mapping algorithm for in-channel riverbed landforms (Fig. 1) (Pasternack, 2011; Wyrick et al., 2014). This method requires two primary inputs. First, an expert geomorphologist, potentially working with local stakeholders, carries out field reconnaissance to determine what MU types compose the riverbed. Local knowledge and expert judgement are used to identify discrete combinations of depth and velocity at a representative steady baseflow that delineate each MU type's presence. Wyrick et al. (2014) performed sensitivity analysis to evaluate the best non-dimensional discharge to achieve this and found that typically ~0.2 times bankfull discharge works best. As a result, the MUs identifiable in the decision tree only include those inundated by this discharge. Riverbank and overbank MUs are not covered by this strategy and are not included in this study. The hydraulic decision tree is a transparent, expert-based product that can be reviewed and changed without impacting the ability to generate MU maps. A hydraulic decision tree is superior to a bottom-up, data-driven classification procedure, because the latter usually fails when rare but important MUs are not captured in the data. Data-driven methods are also highly sensitive to the sampling scheme.

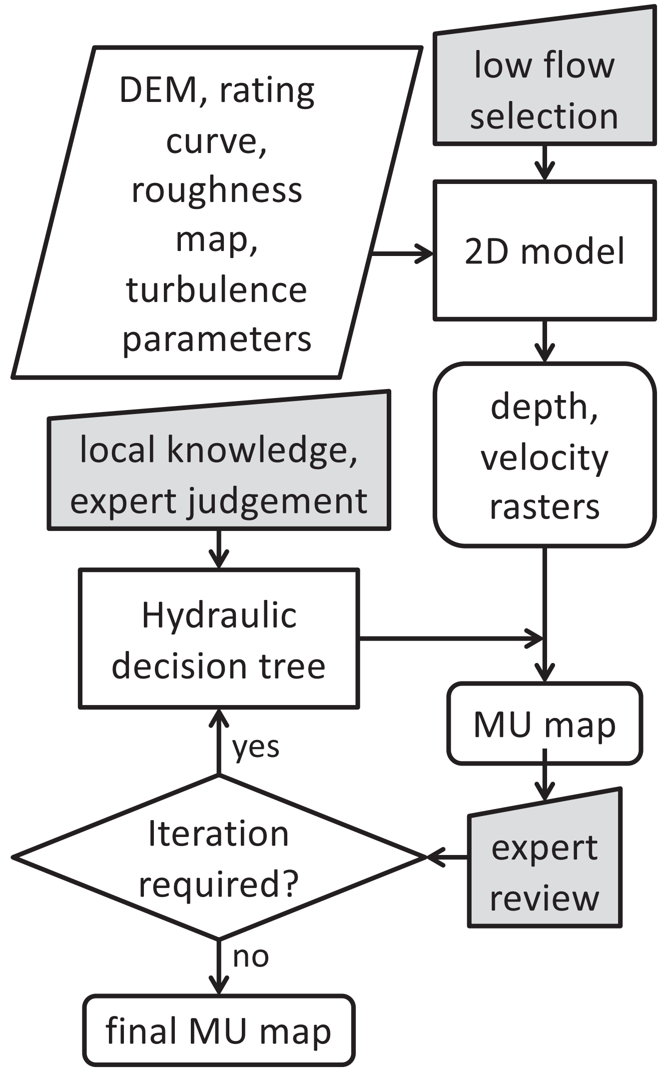

Fig. 1. Flowchart of MU delineation procedure. Parallelogram lists data inputs; trapezoids list subjective steps; Squares are objective algorithms; diamond is a subjective decision. Modified after Wyrick et al. (2014).

Second, spatially explicit, high-resolution maps of baseflow water depth and velocity are needed. It is increasingly feasible to explicitly map meter-resolution depth and surface velocity at baseflow using remote sensing (e.g., Feurer et al., 2008; Kinzel and Legleiter, 2019). It is also feasible to perform 2D hydrodynamic modeling with a wide range of accurate modeling software given increasingly available topo-bathymetric digital elevation models (DEMs) (Pasternack, 2011). Depth and velocity decision tree criteria are applied to spatially explicit depth and velocity rasters at the representative baseflow using GIS workflows or existing software with MU delineation tools, such as River Architect (https://riverarchitect.github.io). Adjacent aggregates of individually classified pixels sharing the same MU type are grouped to make one polygonal MU object. Further steps to cope with data uncertainty and isolated, small MUs, such as application of spatial rule sets, are available and under further research (e.g., van Rooijen et al., 2021). While this methodology has assumptions and limitations, as all such methods do, it is vetted and used in practice today.

1.2. MU change concepts

However a set of polygonal MU objects is obtained, a conceptual framework and associated standard analytical methods are needed to analyze how MUs change through time in response to morphodynamics. Given other kinds of geospatial data from before, during, and/or after morphodynamics, one may use MU polygons to segregate that data and analyze metrics of that data on a MU-stratified basis. The obvious example of such data to aid understanding morphodynamic processes is a topographic change raster. For example, given a raster of topographic changes caused by short, moderate magnitude floods during a six year drought period after MU's were mapped, Weber and Pasternack (2017) found that all in-channel riverbed MUs filled in, but at substantially different volumetric rates, causing a general decrease in bed relief. Alternately, using a map of in-channel riverbed MUs produced after a large flood, Pasternack and Wyrick (2016) found that the morphodynamics that created those riverbed MUs were all net erosional, including a strong differentiation in volumetric change between MUs that significantly enhanced bed relief. Putting the two studies of the same river together, the implication is that floods on a dynamic gravel/cobble river fill in existing MUs and carve out new MUs in different locations through processes such as lateral and knickpoint migration. This is very informative, but what it misses is any characterization of the patterns of the MU polygonal changes.

To evaluate how MUs change over time using repeat MU mapping, there are three broadly different ways to quantify change. First, one can establish a set of bulk statistical metrics characterizing each MU map and then compare how the metrics change over time. Wyrick and Pasternack (2014) proposed specific metrics and geospatial analytical methods for MU abundance, diversity, longitudinal distribution, longitudinal spacing, adjacency, and lateral variability. These can be used to evaluate change through time.

Second, one can perform a transition analysis to see what MU type a location has after versus before morphodynamics (Fig. 2). This is a bulk statistical analysis of an entire map dataset that produces a transition probability matrix. When performed using MU polygons from time 1 before change (Fig. 2, top polygon) and time 2 after change (Fig. 2, middle polygons), the resulting polygon union (Fig. 2, bottom polygons) reveals the percent of area of each MU type that either remained that type (Fig. 2, bottom, blue) or transitioned to a different in-channel riverbed MU type (Fig. 2, bottom, green). This analysis must also account for processes such as avulsion and lateral migration that cause areas outside of the riverbed to become in-channel riverbed MUs (Fig. 2, bottom, orange) or cause riverbed areas to be left out of it after change (Fig. 2, bottom, gray).

Third, one can identify an individual MU and investigate what happens to it through time by tracking it through the maps. This is a tricky and arguably more subjective procedure because it is often not obvious whether a MU polygon in one map corresponds to one or more MU polygons in a previous or successive map. This makes it difficult to automate such a procedure, though graph theory is the mathematical foundation for any such automation. However, one can establish rules to guide decision making for tracking and do as well as possible in a manual procedure using GIS.

Pursuing the concept of MU tracking further, it is possible to conceptualize the full range of alternative MU change "behaviors". Building on the conceptual work of Strom et al. (2016), which tracked peak-velocity polygons with increasing discharge, there are broadly three sets of behavior types: movement, growth, and combination. Movement is defined as the shifting (or lack thereof) of the coordinates of the centroid of a MU polygon. Growth is defined as a change in the area of a MU polygon (including shrinkage as negative growth).

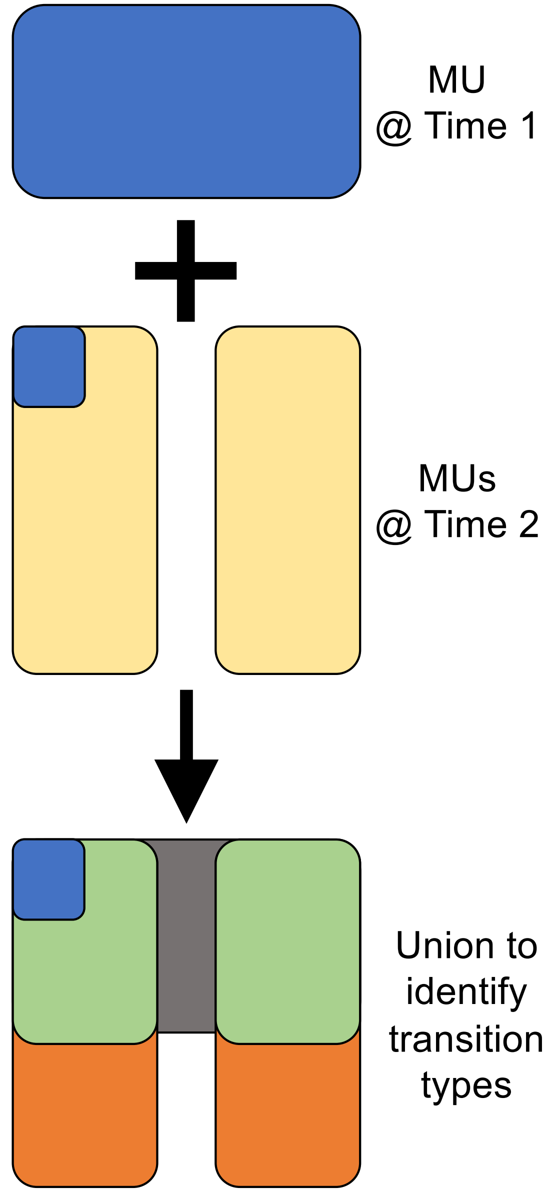

Fig. 2. Conceptual illustration of MU transition analysis. Top blue polygon is a MU of one type at time 1. Middle yellow polygons show the MU type present at the same location in time 2 after morphodynamics, with yellow indicating a type change. Bottom "union" set of MU polygons shows the different transitions that result, where blue indicates no change between times, green indicates transitions between MU types, gray indicates the area that was originally in the channel and is not in the channel at time 2, and orange indicates areas that were not in the channel originally but now are. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Combination is defined as the joining/splitting of polygons. Each of these types of behaviors is composed of a set of specific behaviors that reflect either the options for direction of change or degrees of magnitude of change. Growth and combination both have opposite directions available. Growth can be getting larger, smaller, or having no change. In the extreme limits, growth also includes full disappearance of a MU or an MU taking over a whole domain. Combination can be joining multiple polygons together to make one large polygon or splitting a polygon into many smaller bits. Shifting can also be directional if one tracks a shift relative to a streamwise coordinate system, such as upstream, downstream, river left or river right. Alternately, shifting can be divided into groupings on the basis of distance shifted, with a partial or complete shifting reflecting the presence or absence of any overlap from before to after change, respectively.

1.3. Study questions

In light of the above theoretical developments the opportunity now exists to address the basic scientific topic of MU assemblage stationarity associated with fluvial morphodynamics. To address the overall topic, this study to evaluate MU changes may be divided into a set of specific, tractable scientific questions relating to MU status after versus before flood-induced morphodynamics. (1) Do bulk statistical metrics of an MU assemblage in a river remain similar? (2) Does the spatial structure of MU adjacency remain similar? (3) Do individual MUs tend to remain in the same place and about the same size?

These questions are very important to fluvial geomorphology yet have hardly been investigated. At first, individual rivers require investigation to fine-tune methods and gain knowledge in individual settings. A more sophisticated set of questions would go beyond yes/no answers for one river and ask under what range of conditions would MU assemblages remain stationary in all these metrics, but such a study would require the availability of many individual studies of a diversity of rivers and that is not close to possible yet. However, with the new concepts and methods presented herein, the way is open for this new line of fluvial geomorphic research.

2. Testbed river

No one river can answer the fundamental question about MU stationarity alone, but science needs to start somewhere. A dynamic gravel/cobble river with a number of different MU types that experiences a range of floods, which in turn cause a range of MU changes is scientifically preferable. This study uses a thoroughly researched (>25 hydrogeomorphic journal articles), reasonably long river segment for which meter-resolution topo-bathymetry has been periodically resurveyed and that is dynamic enough to yield significant, observable changes well beyond statistical uncertainty. This section presents the setting to help readers properly constrain the applicability of the results to similar settings globally.

2.1. Setting

The Yuba River is a tributary of the Feather River in north-central California, USA, that drains 3480 km^2 of the western Sierra Nevada range (Fig. 3). The dry-summer subtropical watershed is subjected to atmospheric rivers and rain-on-snow events that trigger large floods on a roughly decadal cycle for recorded history (Guinn, 1890). Further, seasonally distinct weather patterns yield a heterogenous range of instream flows and small to moderate magnitude floods (Senter et al., 2017).

The Yuba River has a history of hydraulic mining that supplied a vast abundance of alluvium still present in the river valley. The total estimated volume of hydraulic mining sediment delivered into the Yuba River 1853–1884 is ~344 million m^3 (Gilbert, 1917). James (2005) estimated that an additional ~3 million m^3 was delivered 1893–1950.

Like most California rivers of its size, the Yuba River has experienced flow regulation and other management activities affecting the flow and sediment supply regime. Englebright Dam was built in 1940 to block any more sediment flux to the valley and promote downstream geomorphic recovery. Its reservoir is kept nearly full, so it has almost no flood abatement capacity. A large water supply reservoir in the North Yuba subcatchment significantly alters the flow regime for that tributary, but the other two large subcatchments (Middle and South Yuba Rivers) only have small reservoirs with minimal flood storage capacity. The combination of partial flood regulation and vast valley floor sediment storage

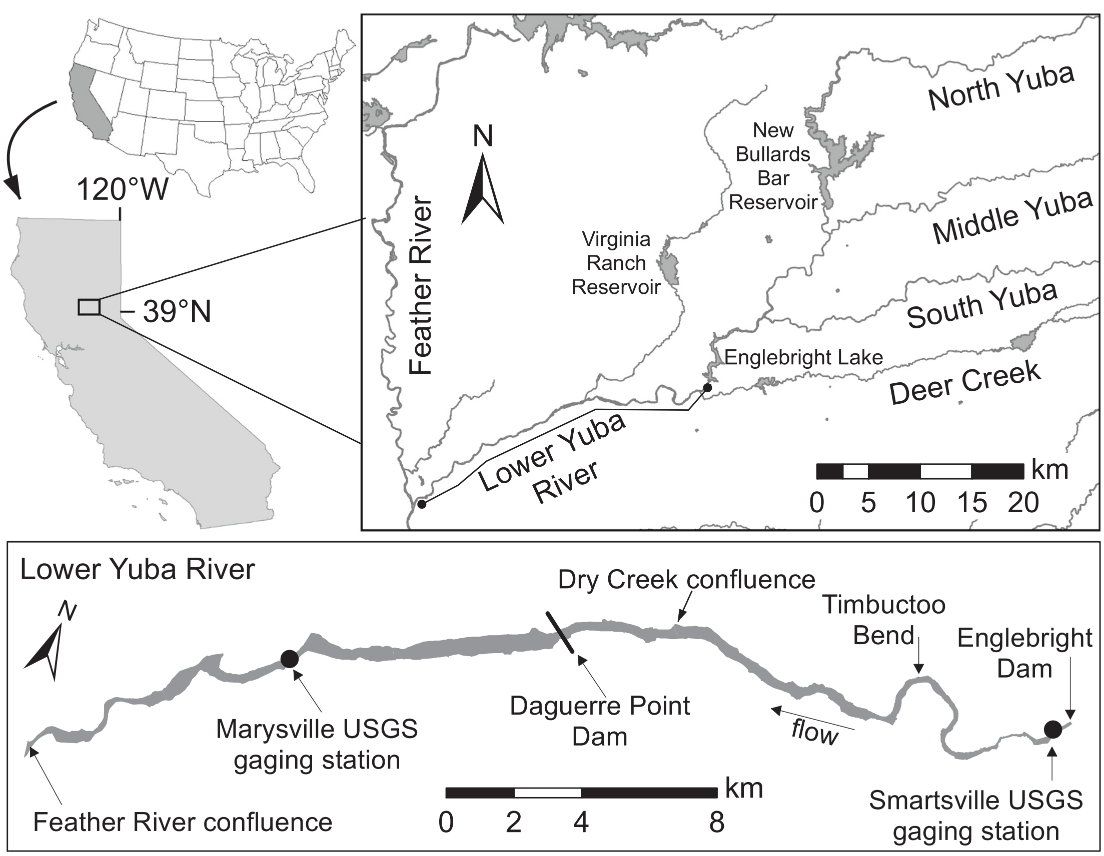

Fig. 3. Location map of the lower Yuba River showing key landmarks.

results in a persistent (multi-decadal), relatively dynamic flood regime and highly dynamic morphodynamic regime downstream of Englebright Dam (Gervasi et al., 2021).

2.2. Lower Yuba River

The 37.1-km river segment between Englebright Dam and the confluence with the Feather River is defined as the lower Yuba River (LYR). The LYR is a single-thread channel (~20 emergent bars/islands at bankfull) with low sinuosity, high width-to-depth ratio, and slight to no entrenchment. The river corridor is confined in a steep-walled bedrock canyon for the upper 3.1 river kilometers (RKM), then transitions first into a wider bedrock valley with some meandering through Timbuctoo Bend (RKM 28.3–34.0; Fig. 3), then into a wide, alluvial valley downstream to the mouth. Daguerre Point Dam (DPD) is an 8-m high irrigation diversion structure located at RKM 17.8 that creates a slope break and partial sediment barrier. During 1930–1950, hydraulic mining sediment was used to train the active river corridor in the wide lowlands to isolate it from the ~4000 ha Yuba Goldfields. Mean bed slope is 0.185%, with four major slope breaks. The segment-scale mean diameter of the channel sediment is 97 mm (i.e., small cobble).

Stage and discharge have been continuously recorded at the USGS gages at Smartsville near Englebright Dam (#11418000), at Marysville near the mouth (#11421000), and on the regulated tributary Deer Creek (#11418500). The geomorphically determined bankfull discharge of 141.6 m^3/s has ~82% annual exceedance probability. A floodplain-filling discharge has also been identified for the LYR as 597.5 m^3/s. In the bedrock canyon just below Englebright Dam, mean wetted width at baseflow discharge is 36.4 m (all width values from 2008 data). The remainder of the baseflow channel upstream of DPD widens to a mean wetted width of 64.6 m, and then the channel below DPD narrows slightly to a mean wetted width of 56.4 m. At bankfull, the mean widths are 51.4, 99.4, and 98.4 m, respectively, for those same regions. Though there are differences by reach, the LYR is broadly classified as a C3 channel by the Stream Type classification method (Rosgen, 1996) and as transitional between straight and meandering by the flow instability method (Parker, 1976).

2.3. Historical LYR morphodynamics

When discussing morphodynamics in this article, "net" is used to refer to quantitative topographic changes between any time 1 and time 2 at any specified spatial scale. No data is available to resolve the sequence of events within the period between times 1 and 2, which may have included episodes of erosion and/or deposition at any location and averaged to any spatial scale. Therefore, the term "net" expresses the observed overall change evident by subtracting the elevation at time 1 from that at time 2, while also applying spatially explicit uncertainty methods to remove changes below the local detection threshold (Weber and Pasternack, 2017).

As a result of the combination of vast sediment storage and a significant annual flooding regime, the LYR valley has undergone dramatic geomorphic dynamism that continues today. Adler (1980) investigated the history of the Yuba's morphodynamic post hydraulic mining. Based on available information and her own field studies, she theorized that the river experienced an initially intense period of extreme morphodynamics in the late 1800s followed by a steady decline in morphodynamic intensity through the twentieth century as the system adjusted to the post-Englebright state of system controls. Consistent with her work, the LYR has been net erosional since Englebright Dam was built, because it is evacuating historic mining sediments and has minimal sediment supply from its dammed catchment.

Nevertheless, historical aerial photo research by White et al. (2010) reported that a large reach of the LYR has existed in the same channel type for decades and it has substantial freedom to adjust itself by changing many available variables. This finding is in line with the precepts of dynamic equilibrium articulated by Hack (1960). Specifically, White et al. (2010) investigated the presence and positioning of riffles in 5.8-km Timbuctoo Bend from 1937 to 2006 and found that despite rapid, significant valley incision, most riffles persisted in the same locations, which coincided with the locally wide areas of the valley. Historical aerial photos are not detailed enough to enable evaluation of MU sizes, shapes, and patterns.

Research into LYR hydro-morphodynamic processes has found that the observed stability of riffle positioning is explained by flow convergence routing. Sawyer et al. (2010) was the first to report the presence of this process and the concomitant rejuvenation of riffle-pool relief at one pool-riffle-run sequence in the river. Strom et al. (2016) used 2D hydrodynamic modeling to reveal the ubiquitous occurrence of stage-dependent shifts in the locations and behaviors of the patches of highest velocities throughout the river, driven by flow convergence routing. Pasternack et al. (2018) directly demonstrated that the LYR has stage-dependent topographic patterning dominated by landforms that drive flow convergence routing.

The first modern topo-bathymetric map of the LYR was surveyed in 1999, which was after the larger flood of 1997. That map has a few data gaps making it unsuitable for systemic 2D hydrodynamic modeling and MU mapping. Since then, a new era of systemic, spatially explicit monitoring and analysis has revealed that the LYR is still highly dynamic. Dry summer subtropical rivers have the advantage of very low flows and clear water in late summer enabling excellent airborne lidar mapping performance. Newer LYR topo-bathymetric maps were produced in 2006/2008, 2014, and most recently in 2017. Large floods occurred on New Year's Eve into 2006 and in January 2017, continuing the long history with a roughly decadal large-flood cycle.

Carley et al. (2012) reported LYR gross scour and fill of ~$3.26 \cdot 10^6$ and ~$2.97 \cdot 10^6$ m^3 for 1999 to 2006/2008. When annualized the net export was ~17,000 m^3/yr. These are large sedimentary redistributions for a river of this size, yet with remarkably little export (because of the unique approach to river corridor training; James et al., 2009).

Despite the presence of a dam driving net erosion through decades, the LYR's channel remains well-connected to its floodplain (Wyrick and Pasternack, 2014) and flood events renew topographic relief preserving a diversity of MUs (Pasternack and Wyrick, 2016; Weber and Pasternack, 2017; Gervasi et al., 2021). Thus, numerous studies of hydro-morphodynamic processes, historical aerial photos, and modern topographic changes all agree that the LYR undergoes frequent topographic changes while retaining the same reach-scale channel pattern. With stable sediment supply and hydrologic regimes over the last 20 yr, the Yuba is an ideal testbed for investigating MU assemblage dynamism.

2.4. LYR topographic change, 2006/2008–2014

The study focuses on one period for which MUs were mapped at the outset (2006/2008) and at the end (2014), enabling a study of their changes. The first map has a mixed "time 1" because Timbuctoo Bend was surveyed in 2006 and the rest of the river was surveyed in 2008. The time between 2006 and 2008 was calm, so only local changes involving sediment redistribution from over-steepened riffle crests likely occurred while surveys were on-going.

Although the study period was categorically a severe drought for the region, the LYR experienced four floodplain-filling floods, ranging from 838.2 to 1246 m^3/s instantaneous flow, which correspond to ~3–5 yr recurrence interval events and 6–9 times bankfull discharge (Fig. 4). These floods were short-duration events spread over three years. Four of six years were classified as below average water years, one was a dry water year, and one was a wet water year. In all, there were 163 days above bankfull discharge and four days above floodplain-filling discharge. According to geomorphic theory, this scope of flooding ought to be more than enough to test questions about MU stationarity through morphodynamics. However, it may very well be that a significantly larger flood and a significantly longer period of flood duration

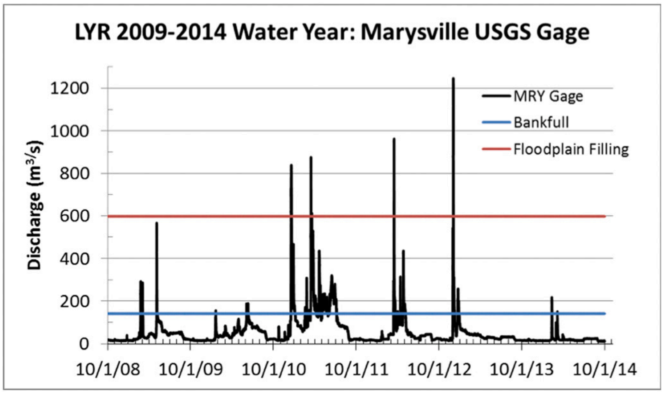

Fig. 4. Hydrograph during the morphodynamic change period between MU maps.

(Gervasi et al., 2021) would yield a different outcome. This will be testable in the future by repeating this study after a larger, longer-duration flood.

Weber and Pasternack (2017) performed topographic change detection and analysis for this study period. They reported that the LYR river corridor had an estimated 638,539 m^3 of erosion and 507,743 m^3 of deposition. This yielded a net annualized riverbed sediment export of ~22,200 m^3/yr given zero input because of Englebright Dam. Further, there was substantial net deposition in the channel and erosion of the overbank region. These metrics further demonstrate that even during a severe drought the LYR is an especially dynamic river suitable for an investigation of MU changes.

Thus, even though the Yuba was perturbed by mining sediment and river training, it is very plausible that its MU assemblage could be statistically stationary, because such stationarity could be forced by topographic controls on flow convergence routing (Brown and Pasternack, 2017; Pasternack et al., 2018). On the other hand, it is also possible that internal free modes of geomorphic dynamism acting on such an immense volume of stored sediment could render the river highly stochastic in its MU assemblage.

2.5. LYR MU mapping

2.5.1. 2006/2008 MU mapping

Wyrick and Pasternack (2012, 2014) previously delineated and published in-channel riverbed MUs using a meter-resolution LYR 2006/2008 DEM (Carley et al., 2012), validated baseflow 2D hydrodynamic model (Abu-Aly et al., 2013; Barker et al., 2018), and hydraulic decision tree produced as a collaboration among expert stakeholder participants of the Yuba Accord River Management Team, including the senior author of this article. All data characterizing the 2006/2008 LYR condition were previously vetted through peer reviewed journal articles. A summary is provided below, with more details available in the supplementary materials file and as published extensively in past articles.

Topo-bathymetric data used to produce the LYR DEM was obtained by airborne lidar, boat-based single-beam echosounding, robotic total stationing, and RTK GPS. After vertical calibration among survey methods, final differences were typically within ~3–5 cm, which is better than the class 1 standard (±0.15 m vertical accuracy; U.S. Army Corps of Engineers, 2002). For Timbuctoo Bend (surveyed in 2006 using ground methods and echosounding), the baseflow (24.92 m^3/s) wetted area had an average of 28 points per 100 m^2, while that area for the rest of the river (surveyed in 2008 primarily with airborne lidar and echosounding) had an average of 59.8 points per 100 m^2.

The surface-water modeling system (SMS; Aquaveo, LLC, Provo, UT) user interface and sedimentation and river hydraulics–two-dimensional (SRH-2D) algorithm (Lai, 2008) were used to produce LYR 2D hydrodynamic models. The LYR was divided into five domains whose computational meshes had an internodal mesh spacing of 0.91–1.5 m according to the procedures of Pasternack (2011). Discharge and water surface elevation data inputs were directly measured for each domain. Baseflow Manning's n bed roughness values were calibrated by domain using observed water surface elevation values at various locations along the river. Extremely thorough model validation was performed (Barker et al., 2018) to evaluate mass conservation, water surface elevation, depth, velocity magnitude, and velocity direction. All validation performance metrics exceeded common hydraulic and hydrology standards reported in peer reviewed journals.

An iterative process of consensus- and expert- based adjustment to MU names, definitions, and thresholds led to the final set of baseflow depth and velocity threshold values (Fig. 5) used to map eight in-channel riverbed MU types: riffle, pool, fast glide, slow glide, run, chute, slack water and riffle transition. Geomorphic descriptions of MU types from Wyrick and Pasternack (2014) are reproduced in the supplementary materials file.

Wyrick and Pasternack (2012, 2014) reported little sensitivity to the exact baseflow discharge chosen for mapping MUs using 2D hydrodynamic model output and discussed the issues around this matter. A typical LYR baseflow regime consists of ~24.92 m^3/s (0.18 times bankfull) out of Englebright Dam, no discharge out of either of the two tributaries, and a societal withdrawal of 9.91 m^3/s of water at DPD, yielding a Marysville gage flow of 15.01 m^3/s. Because of this withdrawal, a paired discharge regime is appropriate for MU mapping to account for the diversion, instead of using a theoretical constant discharge for the whole river. The selected baseflow discharges are equivalent to ~75% daily exceedance probability. This is appropriate for MU delineation in a regulated river.

2.5.2. 2014 MU mapping

For this study, the same MU mapping procedure was repeated but using a 2014 DEM and different 2D model. A summary of these data and models is provided herein. Details are in the supplementary materials file, technical reports, and peer-reviewed journal articles (e.g., Weber and Pasternack, 2017; Moniz et al., 2019).

Weber and Pasternack (2017) detailed the 2014 meter-resolution topo-bathymetric surveys and DEM production. This time, the vast majority (~85%) of the LYR was mapped by airborne topo-bathymetric lidar, supplemented with boat-based multi- and single-beam echosounding, and very limited ground surveys (total stationing and RTK GPS). After vertical calibration among survey methods, final differences were typically within 0.3–5 cm, which is better than the class 1 standard (±0.15 m vertical accuracy; U.S. Army Corps of Engineers, 2002). The baseflow (24.92 m^3/s) wetted area had an average of 512 points per 100 m^2.

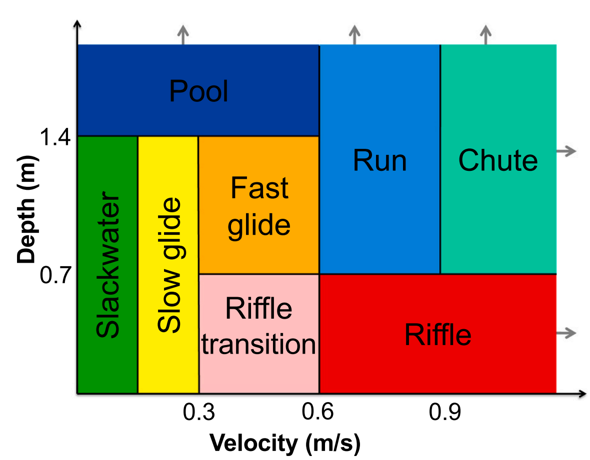

Fig. 5. Hydraulic thresholds for delineating MUs within the LYR at the selected baseflow discharge. Modified after Wyrick et al. (2014).

The 2D models for the 2014 LYR baseflow discharge were made using TUFLOW GPU (Huxley and Syme, 2016; WBM Pty Ltd, 2016). The change from SRH-2D to TUFLOW GPU was made because TUFLOW GPU is parallelized and performed 20–100 times faster than SRH-2D for the LYR. A thorough model comparison study of SRH-2D versus TUFLOW GPU for 2014 LYR conditions found minimal difference in hydraulic results between these solvers for this river (Pasternack and Hopkins, 2017).

The LYR was divided into four domains, each with a fixed 0.9144-m-resolution computational square grid. Discharge and water surface elevation data inputs were directly measured for each domain. Baseflow Manning's n bed roughness values were calibrated by domain using a subset of observed water surface elevation values at various locations along the river. Extremely thorough model validation was performed to evaluate mass conservation, water surface elevation, depth, velocity magnitude, and velocity direction (Hopkins and Pasternack, 2017). All validation performance metrics exceeded common hydraulic and hydrology standards reported in peer reviewed journals. For example, modeled versus observed wading depth and velocity regressions yielded r^2 values of 0.90 and 0.85, respectively.

Inevitably, there are methodological differences in topographic mapping and 2D modeling as technology progresses, but various mapping and modeling methodological intercomparisons and sensitivity analyses found that these did not impact MU map comparison between 2006/2008 and 2014. First, low sensitivity arises from the fact that use of a baseflow hydraulics decision tree to classify MUs is essentially a large smoothing function that takes precise hydraulic values and converts them into broad, simple groupings over large depth and velocity bin ranges. Thus, methodological differences can only affect outcomes if individual raster cell values are close to bin threshold values and a methodological difference moved the values across the threshold. Second, the LYR experienced significant topographic changes 2008–2014, so the majority of differences in MU polygons are caused by real changes, not MU mapping methodological uncertainties.

3. MU change analysis

All data in the study were collected or generated in American customary units consistent with regulatory requirements and then converted to SI units for this article. Most analyses involve a multiple of the fundamental raster pixel resolution of 3 ft, hence the appearance of some unusual values in SI units (e.g., 0.9144 m = 3 ft; 92.81 m^2 = 999 ft^2). Polygons for each MU type in each year were analyzed in ArcGIS 10.6 to extract area, count, size, spacing, diversity, lateral diversity, adjacency and transition metrics. Then percent change was computed between the start and end datasets; positive values indicate increases through time.

3.1. Bulk statistical change metrics

One approach for testing MU pattern stationarity is to quantify a variety of attributes and then test if those changed from time 1 to time 2. As individual MUs are 2D objects on a plan-view map, this study employed a wide range of concepts from the object-oriented literature to quantify such attributes. The first set of attributes quantified individual MU types. The second set quantified the statistical diversity of the set of all MU types. The third set quantified the spatial diversity of MU type patterning.

Total area, polygon count, and fraction of wetted area were calculated for each MU type, once considering all polygons of that type and again limiting analysis to only those of that type with an area > 92.18 m^2. In addition, the maximum, median, and mean size for each MU type was computed for each year based on the individual MUs using a minimum size of 0.9144^2 m^2 area. The longitudinal spacing of individual morphological units of the same type was determined by calculating the distance between centroids of laterally successive units of the same type.

This analysis was restricted to only those MU polygons with a meaningful area > 92.81 m^2, per reasoning explained in Wyrick and Pasternack (2014).

The Shannon Diversity Index is a common method utilized to quantify the spatial complexity and heterogeneity of habitat but has also been applied to MUs (Maddock et al., 2008; Wyrick and Pasternack, 2014). Assessments of diversity (*H*), evenness (*J*), and dominance (*D*) of the total MU areas were calculated with the following equations:

$$\mathrm{H} = -\Sigma(p_i \times \ln p_i) \tag{1}$$

$$\mathrm{J} = \mathrm{H}/\ln(\mathrm{N}) \tag{2}$$

$$\mathrm{D} = \ln(\mathrm{N}) - \mathrm{H} \tag{3}$$

where p_i is the fraction of total wetted area of the *i*-th MU type, and *N* is the total number of MU types. For the eight MU types in the LYR, a fully diverse composition would exhibit equal areas of each type (i.e., $p_i = 1/8 = 0.125$), a diversity index of 2.079, an evenness of 1.0, and a dominance factor of 0.0.

As another measure of MU diversity, the number of individual MUs aligned across the river were assessed for each survey and compared. In this analysis the river was delineated into 20-m long rectangles perpendicular to the valley centerline (Fig. 6a). Then, the number of individual MUs polygons present in each rectangle was counted using the method of Wyrick and Pasternack (2014). This analysis was conducted for MUs of all sizes and just those >92.81 m^2. Results were segregated for above and below Daguerre Point Dam. Because a wider channel could have more laterally adjacent MUs simply by being wider, it is also important to normalize all results by width using the method of Wyrick and Pasternack (2014).

Adjacency is defined as the percent occurrence that the boundary of each MU type abuts that of each other MU type (Fig. 6b). A MU cannot be adjacent to itself or else it would just be a larger MU by definition. If an individual MU is adjacent to more than one MU polygon of a second type, then the total number of adjacencies of that second MU type count, not just the occurrence of the type. As a result, adjacency analysis results

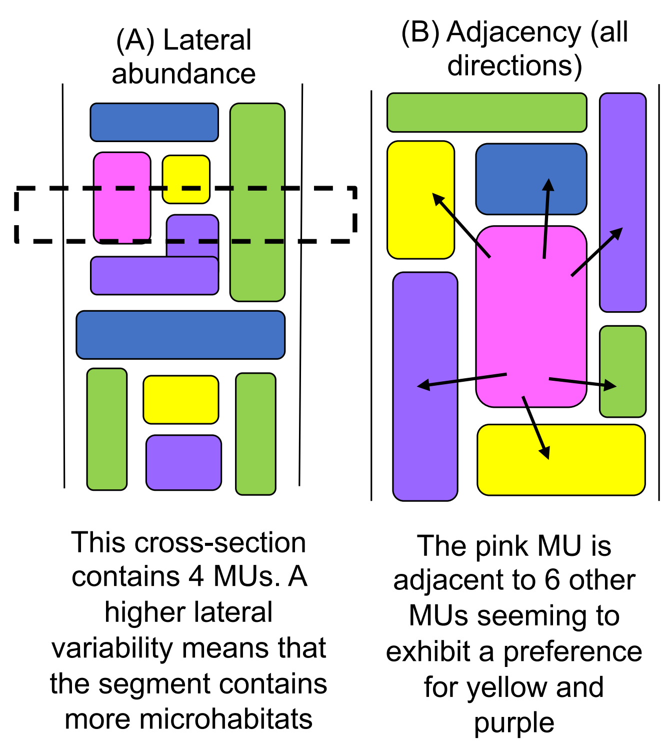

Fig. 6. Conceptual illustrations of MU (A) lateral diversity and (B) adjacency.

are not bi-directionally the same. One must specify the initial MU and then percent occurrence is relative to the total adjacencies for that starting MU type (Wyrick and Pasternack, 2014). This analysis was restricted to only those MU polygons with an area > 92.81 m^2.

For each survey in this study, there were eight MU types, so there is a 1/7 (14.5%) chance that a type randomly abuts another type, as a type cannot abut itself. Wyrick and Pasternack (2014) designated any adjacency value within 20% of the random value to be near-random. For this study, that means that the range 11.4–17.1% of adjacencies from any one MU type to any other indicates near-random, <11.4% indicates a lack of collocation (i.e., "avoidance", except MUs are not alive making decisions), and >17.1% indicates collocation (i.e., "preference"). These ranges were identified for each survey.

To characterize change in MU adjacency between two surveys, this study proposes and used two metrics. First, each adjacency was inspected to determine if the classification of near-random, avoidance, or preference changed. The direction/type of change was documented among the six possibilities. Second, the percent change in adjacency percent values was computed between each pair of MU types between 2006/2008 and 2014. Test metric results were interpreted to evaluate whether the structural pattern of adjacency as a whole changed from 2006/2008 to 2014.

3.2. Temporal transition analysis

Temporal transition analysis quantified the extent to which each MU typed changed into each of the other types. This was determined by computing the geospatial "union" of the individual MUs from 2008 with the individual MUs from 2014. With both years of data superimposed, it was possible to tally the percent of each MU type from 2008 that stayed as that type, transitioned to each other in-channel bed MU type, or left the channel in 2014, per concept shown in Fig. 2. For each MU type, percentages sum to 100% and indicate temporal transition probabilities when viewed as fractions instead of percentages. A Sankey diagram is a visualization that shows the connectivity among two sets of entities. Connection can be one-to-one, many-to-one, or one-to-many. Sankey diagrams were produced in this study to visualize temporal transitions among MU types as an aid to readers hand-in-hand with quantitative testing.

It was hypothesized that if an MU type was to transition to another type at all, then it would be most likely to transition to the MUs it was collocated with in 2006/2008 on the basis of the adjacency analysis. Further, because many LYR pools are forced by bedrock and valley constrictions (White et al., 2010), this type was anticipated to remain the most stable over time. To test the first part of the hypothesis, transition percentages were summed among the collocated MU types for each MU type as well as among the MU types that were not collocated. If the former sum is higher than the latter sum, then the hypothesis is corroborated.

3.3. Polygon tracking analysis

Given the vast number of individual MU polygons, a representative sampling strategy was needed to evaluate how individual MU polygons changed from 2006/2008 to 2014. The approach taken was to divide the wide range of MU sizes into ten logarithmically-scaled size classes and then randomly sample one individual polygon of each of the eight MU types per size class, yielding eighty total stratified-random individual MU polygons. The location of each MU polygon was visually inspected using the 2006/2008 and 2014 MU maps. Using the concepts from Section 1.2, author Woodworth performed expert-based assessment consistently for all 80 cases to identify what happened in terms of movement, growth/shrinkage, fragmentation/merging, and disappearance. Results were tallied by size regardless of MU type and by MU type regardless of size. Given six geomorphic change behaviors, a preference would be indicated by a value >20% (i.e., 1.2 × 16.67%). However, given the small number of samples possible with such an intensive manual effort, results focused on the largest deviations from random expectation.

4. Results

Before considering detailed statistical results of MU change analysis, it helps to view MU maps of two different types of sites to visually experience changes and get a sense of what is going on (Fig. 7). Given 34 km of river, it is not possible to represent all changes for the whole length at the native resolution on a single page. As one example, a site was selected far downstream in the backwater zone imposed by the Feather River (Fig. 7a). This section is highly constrained by engineered levees. In 2008 it was primarily composed of one long pool flanked by slackwater. From 2008 to 2014 it was predominantly depositional. As a result, the large pool MU was split up and the MUs changed to a more diverse mix, especially with the appearance of sizeable riffle and run MUs. The area and count of slow glides increased.

As a second example in a different fluvial setting, a section just downstream of the apex of Timbuctoo Bend was selected (Fig. 7b). This reach is less confined than the first example and its MU assemblage reflects the steeper slope and more undulating riverbed elevation. In 2006 the upstream end of the reach consisted of riffle and chute, but by 2014 riffle had predominantly been replaced by run and the chutes moved; these changes were caused by knickpoint migration. The middle of the section had its run-riffle-chute complex replaced by a fast glide-run complex. Just downstream of that the long central run unit in the lower half of the section was replaced in its upper half by a large forced pool that scoured on river left and a large fast glide unit. The downstream most MUs remained quite similar in both years.

These two site examples confirm that the LYR underwent significant MU change from 2006/2008 to 2014, and thus this is a meaningful testbed river to undertake full statistical analysis to further characterize what happened. Just considering these two sites, it is clear that there is no MU assemblage stationarity at the site scale. What is evident for the whole river?

4.1. Areal change results

As a whole, the baseflow wetted area of the Yuba River decreased about 2% (4.69 ha), though not every MU decreased as a result. Chute, pool, riffle, and slackwater all decreased in total area (Table 1a). Although fast glide, riffle transition, run and slow glide all increased in area, they did not increase enough to make up the difference. Notably, these changes imply a tendency for the whole river to shift toward a lower relief morphology. In other words, MUs with extremely high or low bed elevation and those with extremely high or low slope were replaced with moderate elevation, moderate slope units.

At the individual polygon level, the largest individual units of each MU type shrank, but otherwise size metrics showed divergent results by MU type. Because of study sampling methods, the median size of MUs was skewed small because many MUs are fragments as an individual pixel ($0.9144^2 = 0.8361$ m^2). The 2014 median size for all MUs except pool and chute was 1 or 2 pixels in 2014 (Table 1b). Even this was a decrease from 2008 when the smallest median size was 2 pixels. For all MU types except slackwater, the largest individual polygon decreased in area. For both chute and pool, the median and average sizes increased while the total area decreased, indicating growth and aggregation of polygons. The opposite occurred for slow glide and riffle transition, which increased in overall abundance while their median and mean sizes decreased, thus these types shrank and became more fragmented. Fast glide and run both increased in total area and mean (and median) individual polygon area, while riffle and slackwater both decreased in all of those metrics.

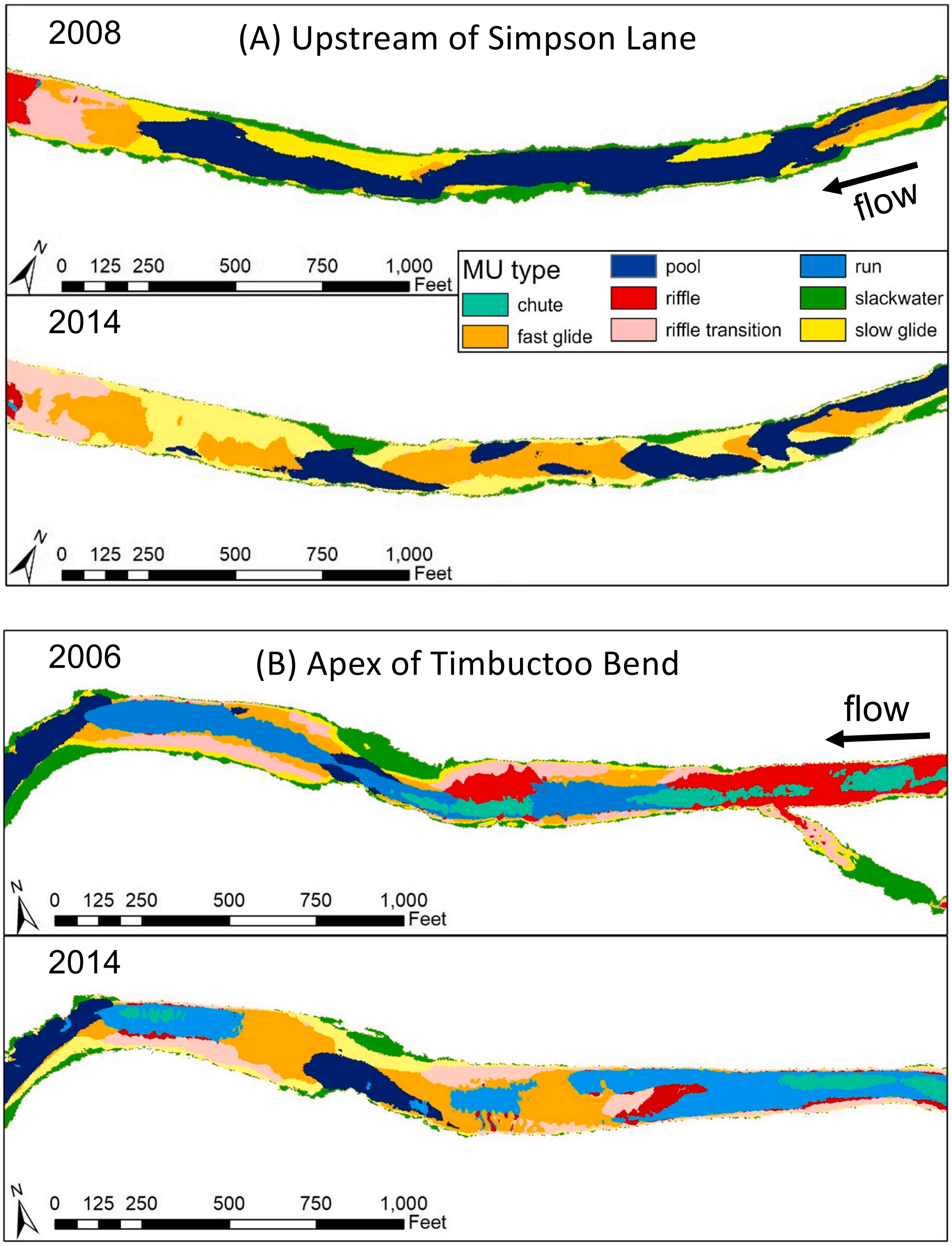

Fig. 7. Morphological unit maps for two sites showing significantly different MU assemblages before and after a period of morphodynamics, even during a severe drought.

4.2. Spacing and count change results

Considering only MU polygons >92.81 m^2, the average distance between MUs of the same type decreased universally for the six MUs studied (slackwater and slow glide were omitted because of their ubiquity as linear, peripheral landforms that are not spaced out). In contrast, the polygon count (>92.81 m^2) for each MU type did not show a universal change (Table 2). Instead, changes in count strongly, positively correlated with changes in total MU area ($r^2 = 0.63$, $p = 0.018$). For example, slackwater decreased in percent area and count by about a quarter and third, respectively. Fast glide polygons increased in percent area and count by 14.4 and 9.3%, respectively.

4.3. Diversity change results

When MUs of all sizes were accounted for, there was virtually no change in diversity, evenness, or the Simpson index for the river as a whole, while dominance increased by 8.8% from 2008 to 2014 (Table 3a). As the usage of single-pixel MUs has a significant impact on diversity analysis, these metrics were also calculated separately for MUs > 92.81 m^2. With this adjustment, the dominance metric doubled compared to using all MUs regardless of size. Otherwise, no significant differences were observed for the other metrics.

Another way to think about diversity for spatially explicit polygons is to consider the number of polygons fitting across the channel (Fig. 8). The average number of MUs across each cross section significantly increased (11%) between 2008 and 2014 (Table 3b). We found a

Table 1
Total and individual polygon area statistics for lower Yuba River morphological units.

(A) Total MU area	Area (m^2)			Relative area (%)[a]		
MU	2006/2008	2014	Change[c]	2006/2008	2014	Change[c]
Chute	8.86E+04	8.53E+04	−3.7	4.3	4.2	−1.5
Fast glide	2.94E+05	3.29E+05	12	14	16	14
Pool/forced pool	3.29E+05	3.07E+05	−6.7	16	15	−5
Riffle	2.72E+05	2.41E+05	−11	13	12	−9
Riffle transition	3.17E+05	3.70E+05	17	15	18	19
Run	1.79E+05	1.83E+05	2.6	8.7	9.1	5.0
Slackwater	3.38E+05	2.44E+05	−28	16	12	−26
Slow Glide	2.47E+05	2.58E+05	4.4	12	13	7

(B) Individual MU metrics	2014 polygon area (m^2)[b]			2006/2008–2014 area change (%)[c]		
MU	Max	Median	Mean	Max	Median	Mean
Chute	6.59E+03	5.85	210	−8.8	40	43
Fast glide	1.86E+04	1.67	117	−3.9	0.0	16
Pool/forced pool	4.63E+04	6.69	562	−35	167	39
Riffle	7.08E+03	1.67	106	−21	−33	−23
Riffle transition	2.07E+04	0.84	38	−26	−50	−20
Run	7.51E+03	1.67	144	−3.5	0.0	17
Slackwater	4.63E+04	0.84	15	149	−50	−41
Slow glide	7.19E+03	0.84	11	−43	−50	−42

[a] Percent of the total area summed for each MU out of total wetted area.
[b] Area metrics for individual MU polygons for each MU type. 2006/2008 values were published in Wyrick and Pasternack (2014).
[c] Percent change in metrics from 2006/2008 to 2014. Positive means it increased over time.

Table 2
Spacing and count metrics for lower Yuba River morphological units.

MU	Mean spacing (m)			Count[a]		
	2006/2008	2014	Change (%)	2006/2008	2014	Change (%)
Chute	424	402	−5.2	116	94	−19
Fast glide	292	215	−26	214	234	9
Pool/forced pool	416	319	−23	134	139	4
Riffle	323	267	−17	228	213	−7
Riffle transition	309	237	−23	301	311	3
Run	256	199	−22	194	214	10
Slackwater	N/A		N/A	445	338	−32
Slow glide	N/A		N/A	311	321	4.2

[a] Count of MU of each MU type greater than 92.81 m2.

significant difference in lateral diversity above versus below Daguerre Point Dam. In contrast, when the analysis was restricted to only polygons >92.81 m^2, then the average number of these larger MUs across each cross section decreased significantly (17%), and there was little difference above versus below Daguerre Point Dam. When results were adjusted for differences in width between cross sections, the same results were found with slight adjustments in the numbers (Table 3c). These results are all consistent with the overall finding of MU fragmentation in which large polygons gave way to a greater number of smaller polygons.

4.4. Adjacency change results

Adjacency analysis found that many changes took place, but that the changes did not result in a structural overhaul of how MUs connect to each other (Table 4). Out of 46 adjacency cases, 30 underwent more than 20% change from 2006/2008 to 2014, but only seven (15%) changed designation as near-random, lack of collocation, or collocation. Still, six out of eight MU types had one of their adjacencies change designation. The largest percent change values were associated with very small adjacency values in 2006/2008 changing to 0% in 2014, so their scientific meaning is relatively inconsequential. For example, pool-to-riffle adjacency went from 0.2% in 2006/2008 to 0% in 2014. An example of a highly meaningful change would be the slackwater-to-pool adjacency, which went from 18.2% of slackwater adjacencies to 46.2% of them. This came at the expense of slackwater-to-riffle transition adjacencies (Table 4). MUs tended to be adjacent to other MUs with a similar baseflow depth and velocity, rather than alternate from slow to fast or deep to shallow (though this did not follow for every MU type). The MUs whose adjacencies went down the most were the two at the bed elevation extremes – riffle and pool.

Table 3
Diversity metrics for lower Yuba River morphological units.

Test metric	All sizes			Only polygons >92.81 m^2		
	2006/2008	2014	Change (%)	2006/2008	2014	Change (%)
(A) Diversity metrics						
Diversity, H	2.022	2.017	−0.2	2.022	2.012	−0.5
Evenness, J	0.973	0.970	−0.2	0.972	0.968	−0.5
Dominance, D	0.057	0.062	8.8	0.057	0.067	17
(B) Lateral abundance counts						
Above DPD	18.7	19.1	2.1	5.9	4.9	−17
Below DPD	13.8	16.7	21	5.1	4.2	−18
Entire River	16.1	17.9	11	5.4	4.5	−17
(C) Lateral abundance counts normalized by width						
Above DPD	19.1	20.7	8	5.7	4.9	−14
Below DPD	15.7	20.1	28	5.8	4.8	−17
Entire River	17.9	20.4	14	5.7	4.9	−14

4.5. Temporal transition results

All MU types had the highest probability of undergoing no transition at all, but that probability tended to be only ~25–35%, so not particularly high (Table 5). Pool had the most stability (68% chance of no transition), consistent with the expectation based on known topographic forcing. The Sankey diagram helps visualize MU temporal transition tendencies and especially showcases how evenly riffle transitioned to all other MU types, except slackwater (Fig. 9). Transition analysis next tested the hypothesis that if an MU type was to transition to another type at all, then it was most likely to transition into 2006/2008 collocated MU types. The hypothesis was universally corroborated (Table 5). In every case, collocated MU types were preferentially transitioned to by a ratio 2.2–4.3 times more than non-collocated MU types. Notably, several MU types underwent a significant percent transition out of the in-channel bed, including slackwater, riffle, riffle transition, and slow glide. Of these, only slackwater preferentially transitions more to out-of-channel-bed than to collocated Mu type. This makes sense as slackwater is predominantly along the channel bank, so any small aggradation or lateral channel migration could shift slackwater out of the in-channel bed domain. Finally, of the areas that were not part of the in-channel bed in 2006/2008 but then became part of that domain in 2014, these preferentially became riffle transition, slackwater, and riffle, in that order (Table 5).

4.6. Polygon tracking

Of the 80 MU polygons tracked individually, more (64%) exhibited changes indicative of breaking down than staying the same and growing.

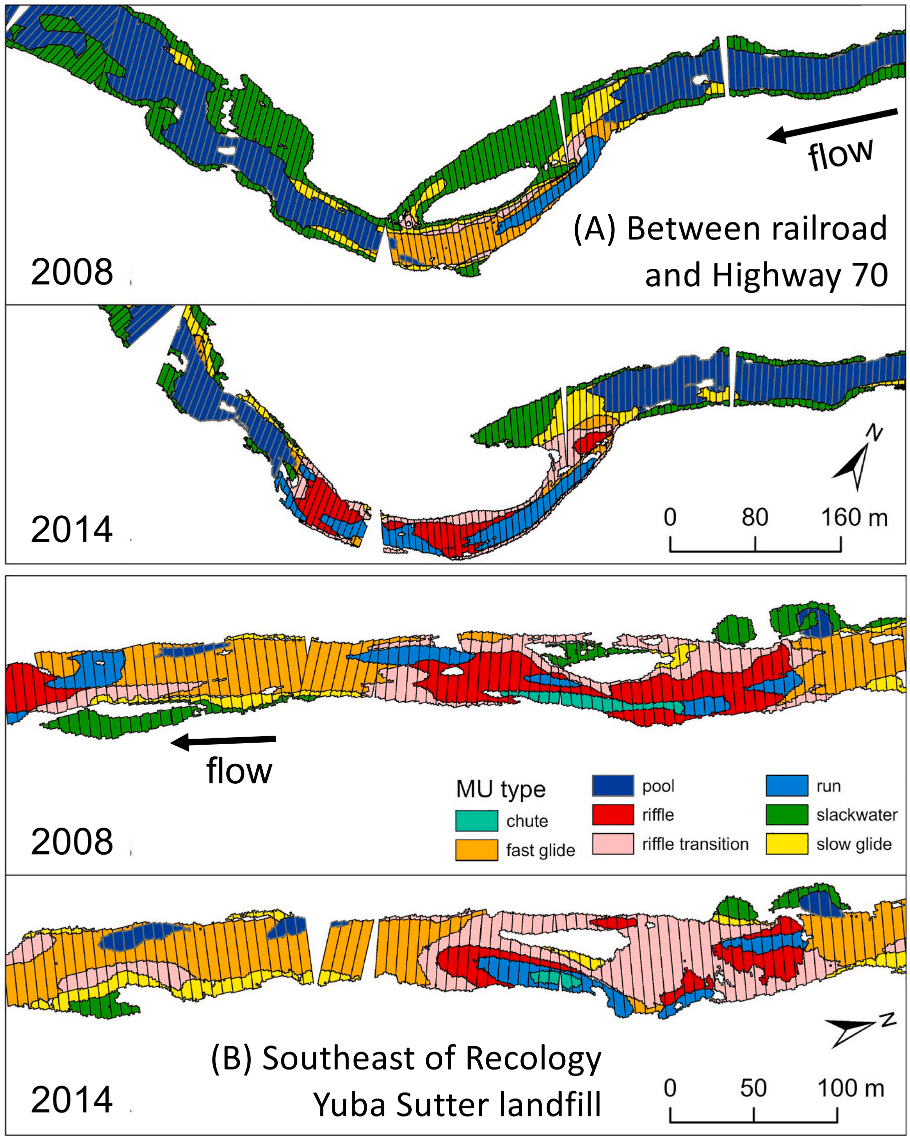

Fig. 8. Example maps for two sites showcasing changes in the lateral diversity of MUs across in-channel rectangular boxes.

Table 4
Percent change in MU adjacency. Bold font indicates values >20% change. Blue indicated change from random to preference, pink indicates random to avoidance, gray indicates preference to avoidance, and yellow indicates avoidance to preference.

	adjacent unit							
starting unit	chute	fast glide	pool	riffle	riffle transition	run	slack water	slow glide
chute		0[a]	**-51**	-5	0[a]	8	0[a]	0[a]
fast glide	0[a]		**45**	3	**-21**	**42**	**-69**	**-23**
pool	**-41**	15		**-100**[b]	**-100**[b]	**62**	**-23**	-13
riffle	6	-9	**-100**[b]		-5	10	**-100**[b]	**-20**
riffle transition	0[a]	**29**	**-100**[b]	19		45	-86	**-20**
run	**23**	3	-3	1	-15		0[a]	**-100**[b]
slackwater	0[a]	**-64**	**154**	**-100**[b]	**-78**	0[a]		-16
slow glide	0*	**32**	**97**	**-26**	9	**-100**[b]	**-46**	

[a]These adjacencies were 0% in 2006/2008 and in 2014.
[b]These adjacencies changed from an initial value in 2006/2008 to 0% in 2014.

Specifically, 24 fragmented, 15 shrank, and 12 disappeared completely. Of the remaining, 12 merged with other polygons of the same type, 15 grew, and 2 moved within the channel without significantly changing size.

Comparing among size classes, individual polygon changes showed size-dependent outcomes. Polygons among the largest three size classes tended to fragment and shrink. Those among the smallest three size classes tended to merge and disappear. The intermediate four size classes preferentially grew much more than the other size classes, but they also exhibited some shrinkage and fragmentation.

Differences were also evident between MU types (Fig. 10). Slackwater, slow glide, and fast glide polygons (types that tend to occur along the channel-bed periphery) exhibited a lot of fragmentation. Riffles preferentially merged. Chutes disappeared and shrank. Pool and riffle transition grew more than anything else, but also exhibited diverse behaviors. Run had the most uniform distribution among all behaviors.

5. Discussion

Most fluvial geomorphologists would probably expect that a lightly vegetated river predominantly composed of unconsolidated alluvium (e.g., the lower Yuba River) would undergo significant morphological

Table 5
Percent of 2006/2008-and-2014 MU polygon unions on the lower Yuba River that either stayed the same type (gray) or transitioned to a different type. Blue indicates preferred 2006/2008 adjacencies. Bold indicates most abundant transition.

	2014 MU											
2006/2008 MU	Chute	Fast Glide	Pool / Forced Pool	Riffle	Riffle Transition	Run	Slack water	Slow Glide	No 2014 MU[a]	Collocated	Avoided	Ratio
Chute	26.0	8.3	3.2	17.8	6.3	**23.2**	0.5	0.8	13.9	41.0	19.1	2.2
Fast Glide	0.8	44.2	6.1	6.9	**18.6**	7.1	0.9	8.1	7.3	33.8	14.6	2.3
Pool / Forced Pool	0.5	**9.9**	68.0	0.9	0.9	3.0	4.6	8.1	4.3	22.5	5.2	4.3
Riffle	8.4	6.7	0.7	30.7	**15.7**	11.2	0.8	1.8	24.1	35.3	9.9	3.6
Riffle Transition	0.9	**11.8**	0.8	11.5	40.2	3.5	1.9	6.3	23.1	29.6	7.1	4.1
Run	7.3	**19.3**	8.0	14.5	7.9	31.8	0.7	1.8	8.8	41.7	17.7	2.3
Slackwater	0.3	2.4	5.1	1.3	4.5	1.0	33.8	**10.2**	41.5	19.7	4.9	4.0
Slow Glide	0.2	12.6	4.6	2.4	**17.2**	1.6	8.7	30.3	22.3	38.5	8.9	4.3
No 2008 mu[b]	6.2	11.9	7.2	15.7	**21.5**	9.7	17.1	10.7	0.0	n/a	n/a	n/a

[a]Some in-channel bed MUs were no longer located on the in-channel bed in 2014, such as when the channel laterally migrated or avulsed away from these locations.
[b]Some locations that were not in the channel in 2006/2008 became part of the in-channel bed in 2014.

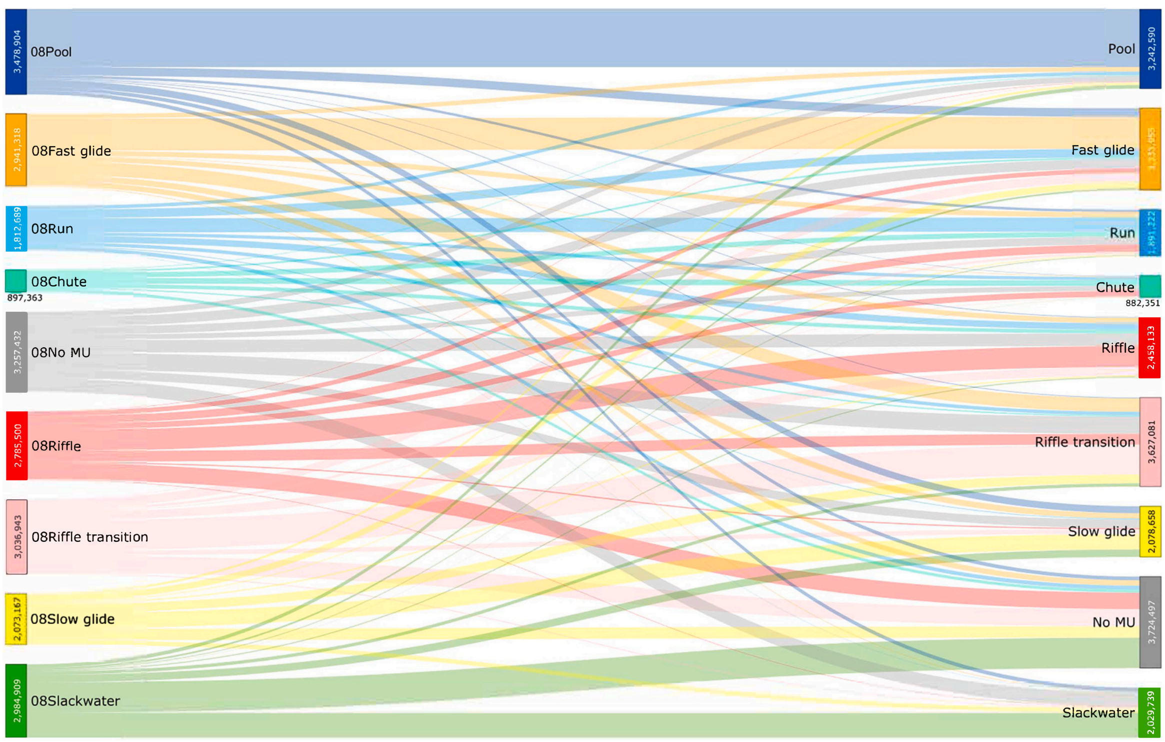

Fig. 9. Sankey diagram illustrating what 2006/2008 MUs (left) transitioned to in 2014 (right). Colors match those in previous map figures. Sizes of boxes on either side of the diagram are scaled to the number of MUs for each MU type.

change when subjected to a sequence of four brief floods of 6–9 times bankfull discharge and a total of 163 days above bankfull discharge over a 6–8 yr period. Indeed, Weber and Pasternack (2017) reported that the LYR underwent an estimated 638,539 m^3 of erosion and 507,743 m^3 of deposition. Yet it is also widely thought that such changes do not alter overall channel pattern, representative geometric variables, or morphological unit assemblage if the driving force regime of flow and sediment is itself statistically stationary. How much nonstationary geomorphic change would be considered insignificant is unarticulated. The time domain required to span to observe stationarity is also unclear and abstract.

This study is the first to test these concepts using modern, meter-resolution geomorphic datasets. Until now, morphodynamism has been primarily investigated in terms of volumetric change based on topographic change detection and analysis. Yet, that missed the opportunity to evaluate fundamental geomorphic questions, such as the one raised in this article. The next step beyond tabulating raw volumetric changes is to stratify landforms and changes to yield discrete objects using a decision tree or other classification method. Such objects may then be queried for their attributes and changes. The specific methods used in this study inevitably have caveats, assumptions, and limitations, but are reasonable and consistent with past literature on object extraction. Taking this step is important for both basic fluvial geomorphology and applied river management to gain an understanding of whether natural or artificial landforms should be expected to persist, even if just in their statistical aggregates.

5.1. LYR nonstationarity

This study of the lower Yuba River took the overall concept of MU assemblage stationarity and broke it into three specific, tractable questions (Section 1.3) applied to MU objects. First, the study found that bulk statistical metrics of a ~34 km long by 100 m wide MU assemblage changed significantly between 2006/2008–2014. Given the vast number

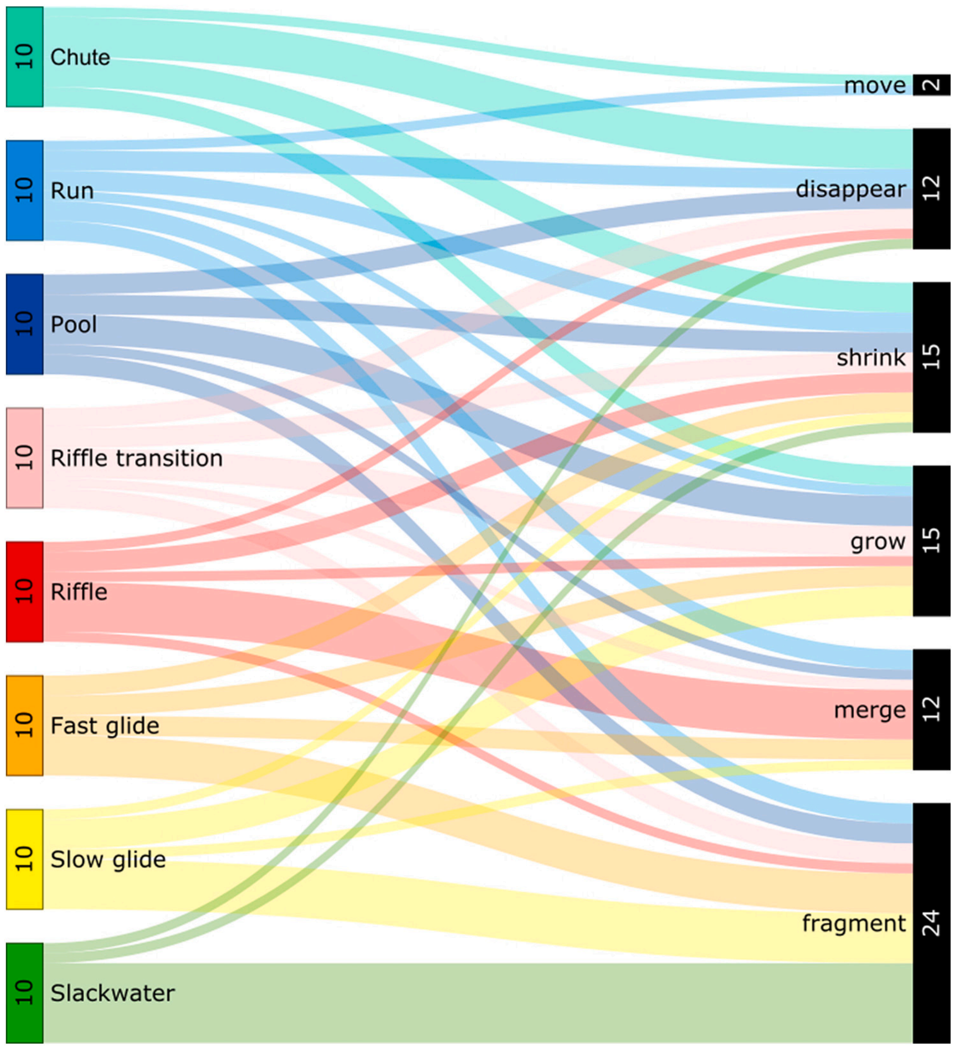

Fig. 10. Sankey diagram illustrating differences in geomorphic change behavior among MU types.

of MUs investigated, even very small changes would be statistically significant, so geomorphic significance needs a different standard than mere *p*-value. For example, if a 10% threshold was used to call change geomorphically significant and all 118% change values in Tables 1–4 are checked, then 68%, a strong majority, pass that test. If a 20% threshold is used, then 47%, nearly half, pass. The changes that took place broadly consisted of a systematic shift toward lower relief landforms with smaller, more fragmented MUs. As a result, these statistics lead to the general conclusion that the MU assemblage was not stationary and shifted in a geomorphically interpretable direction.

Second, MU types were evaluated for their spatial adjacency, a measure of spatial structure. Many individual adjacencies changed in their abundance by >20% and six out of eight MU types had one of their adjacencies change collocation designation. However, the structure as a whole (indicated by the overall distribution of preferential collocation, lack of collocation, or random adjacency) was arguably not significantly changed. This creates a challenge for interpretation. A reasonable basis exists to conclude that regardless of individual statistics and percent changes, if the overall structure of collations and lack of collocations is largely intact, then that affirms stationarity. Reasonable people can easily disagree over what to conclude from the adjacency analysis.

Third, individual MUs were evaluated for their tendency to remain in the same place and at about the same size. The MU at each location in the river predominantly changed, except for pool, which tended to stay the same. Many pools are forced by bedrock or local topography, and as these floods were not powerful to change the larger topographical structure of the entire floodway, then pools were relatively resilient. Strictly speaking, pools can be described as geomorphically static, not just statistically stationary. For all MU types, morphodynamism caused them to preferentially change to a different type that they tend to be collocated with, indicating incremental change. MU types typically along the bank were more likely to leave the in-channel bed, simply because of that spatial proximity, which makes sense. By tracking 80 individual polygons across all sizes and MU types, MUs were found to generally break down, consistent with bulk statistical tests, but the fate of MU polygons varied by MU type. Transition and polygon tracking analyses provide strong evidence in support of nonstationarity.

5.2. Why fragment?

This study introduced new methods for studying MU pattern stationarity and used them to find that the LYR's MU pattern fragmented from fewer, larger MUs to more, smaller ones. Why? While the study did not involve a direct investigation into MU fragmentation mechanisms, it was carried out within a larger program of hydro-geomorphic research that enables mechanistic conjecture involving two likely concurrent mechanisms. Both mechanisms are plausible to be occurring on the LYR, but there is insufficient analysis to characterize their relative importance.

One possible mechanism driving in-channel riverbed MU fragmentation could arise from the stage-dependent role of riverbed and bank forcing elements on hydraulics and morphodynamics. Bedrock outcrops, boulders, large wood, bank vegetation, knickpoints, and the MUs themselves are all capable of topographically steering complex flow patterns (Robert, 1990; Lacey and Roy, 2008), and this is most effective when water stage just inundates these features (Abu-Aly et al., 2013; Cooper et al., 2013). These forcing elements on and adjacent to riverbed MUs become inundated over a range of small floods such as those occurring in the study period, yielding wake, vortex, and peripheral convective acceleration dynamics (Shamloo et al., 2001). Hydraulic complexity yields morphodynamic heterogeneity, hence MU fragmentation. In contrast, a large flood deeply inundates these features and has such high momentum that the baseflow riverbed might experience relatively homogenous velocities and morphodynamics (Brown and Pasternack, 2008; Cooper et al., 2013). In such a large flood, morphodynamic heterogeneity shifts to the overbank flanks where inundation would just put forcing elements underwater there (Abu-Aly et al., 2013), but this does not affect the in-channel riverbed.

Another possible mechanism driving in-channel riverbed MU fragmentation could arise from forcing-free alluvial morphodynamics governed by antecedent conditions. Because rivers typically do not have a large in-channel accommodation space, it is likely that significant deposition at a location in one period will be followed by erosion in the next period, and vice versa. In fact, analysis of the patterns of LYR erosion and deposition during three epochs (1999–2006/2008, 2006/2008–2014, and 2014–2017) reveal just such switching in some geomorphic reaches (Weber and Pasternack, 2017; Gervasi et al., 2021). By analogous reasoning, if forcing-free morphodynamics yields MU aggregation and relatively large MUs in one period, then the odds could be that the subsequent change will tend toward disaggregation and smaller MUs in the next, in other words, the classic statistical regression toward a mean state. Whether forcing-free morphodynamics in non-cohesive alluvial rivers has such negative-feedback tendency or not is not known.

5.3. Contextualizing MU stationarity in channel change literature

The central question in this study wonders whether in-channel riverbed landforms are stationary as various disturbances of different magnitude and recurrence come and go. A large historical literature has investigated morphodynamics in a wide range of river types and "genetic" settings (i.e., climate, geology, topography, soils, land cover, and land use), but without a specific focus on morphodynamic pattern in light of modern spatially explicit mapping methods. One of the challenges of querying the past literature to gain insights on the scientific question arises from the fact that the literature is not well organized into a suitable, overarching meta-analysis framework. Studies span a wide range of river types, genetic settings, and event types, in terms of magnitude, frequency, and duration. Many possible controls and factors can be considered that might influence stationarity. How can we systematically decide whether a study's report of significant morphodynamic change (or lack thereof) is indicative of MU nonstationarity or not, let alone why?

A possible approach that could help frame the literature for use in considering stationarity better would be to focus on morphodynamic tempo. Tempo refers to the frequency of significant environmental changes, in general (Gupta and Fox, 1974; Scatena, 1995). Classic geomorphic theory posits that rivers have numerous, fast ways to adjust to accommodate changing forcings (Hack, 1960). For such accommodation to take place, change-inducing events need to occur more frequently than disturbances that kick the system out of a stable state (Wolman and Gerson, 1978). Consequently, the potential for MU stationarity is likely significantly influenced by morphodynamic tempo.

Rivers whose genetic setting establishes rapid morphodynamics driven by a stable flow and sediment supply regime may be more likely to not only adjust quickly but further settle into and maintain MU stationarity. Such settings might include (i) tropical and proglacial braided rivers and (ii) tropical and temperate, meandering, low width/depth, single-threaded sandy rivers with cohesive banks. Notably, these are the settings most amenable to investigation using 2D and 3D numerical morphodynamic models (Nicholas et al., 2013; Rousseau et al., 2016). Coding the MU mapping and stationarity analysis methods from this study into a morphodynamic modeling analytical framework would facilitate evaluating these conjectures.

Conversely, rivers whose genetic setting promotes positive-feedback morphodynamics are highly unlikely to exhibit MU stationarity, while those promoting punctuated morphodynamics with long recovery intervals may not exhibit it. Bedrock rivers whose morphodynamics are dominated by coarse-sediment-driven scouring mechanisms like potholing and riverbed grooving exhibit an evolving accentuation of features through time rather than a resetting back to earlier conditions (Whipple, 2004; Inoue and Nelson, 2020). Periglacial landscapes also tend to exhibit strong positive-feedback dynamism (French, 2017). Meanwhile, dryland rivers may lack sufficient water-driven incremental dynamism during normal period for MU pattern to recover (Tooth, 2000), and these systems are highly sensitive to the role of vegetation as a channel control (Camporeale et al., 2005). In turn, dryland riparian vegetation is governed by its own set of controls (Shaw and Cooper, 2008). The LYR is in a semiarid-type climate (dry summer subtropical) that could go either way in favor of or against MU stationarity. Robust decadal flood cyclicity and a moderate morphodynamic tempo could yield MU stationarity over a longer time period. Finally, tropical and temperate rivers disturbed by cyclones and/or debris flows experience such extreme fluxes and changes that MU stationarity is not likely (Gupta and Fox, 1974; Benda, 1990).

6. Conclusions

Stationarity of channel pattern and MU assemblage is one of the conjectures that arises from the theory that rivers can quickly adapt to changes by adjusting a subset of its many response variables, as long as the driving force regime remains stationary. If this conjecture were found to not hold, then it would have major ramifications for several theories, such as those addressing hierarchical nesting of landforms, flood geomorphic effectiveness, and geomorphic self-maintenance. This study found that the lower Yuba River underwent nonstationary changes to its MU assemblage from 2006/2008 to 2014. Even though this was a dry period, the flood regime and abundance of internal sediment supply enabled widespread and significant changes to numerous indicators of MU assemblage structure. As a result, the preponderance of evidence indicates a lack of stationarity during this period. While this study is hardly definitive for the LYR, let alone the world, it establishes a framework for investigating the topic and provides a baseline for comparisons for the LYR through time, among dynamic gravel/cobble rivers around the world, and between different river types.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2022.108135.

References

Abu-Aly, T.R., Pasternack, G.B., Wyrick, J.R., Barker, R., Massa, D., Johnson, T., 2013. Effects of LiDAR-derided, spatially-distributed vegetative roughness on 2D hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull. Geomorphology 206, 468–482. https://doi.org/10.1016/j.geomorph.2013.10.017.

Adler, L.L., 1980. Adjustment of the Yuba River, California, to the Influx of Hydraulic Mining Debris, 1849-1979. University of California, Los Angeles.

Barker, J., Pasternack, G.B., Bratovich, P., Duane, M., Wyrick, J.R., Johnson, T., 2018. Kayak drifter surface velocity observation for 2D hydraulic model validation. River Res. Appl. 34, 124–134. https://doi.org/10.1002/rra.3238.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P., 2017. Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. Geomorphology 283, 143–157.

Benda, L., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surf. Process. Landf. 15 (5), 457–466.

Blaschke, T., Lang, S., Lorup, E., Strobl, J., Zeil, P., 2000. Object-oriented image processing in an integrated GIS/remote sensing environment and perspectives for environmental applications. In: Environmental Information For Planning, Politics And The Public, 2, pp. 555–570.

Borsányi, P., Alfredsen, K., Harby, A., Ugedal, O., Kraxner, C., 2004. A meso-scale habitat classification method for production modelling of Atlantic salmon in Norway. Hydroécol. Appl. 14, 119–138.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Wiley-Blackwell.

Brown, R.A., Pasternack, G.B., 2008. Engineered channel controls limiting spawning habitat rehabilitation success on regulated gravel-bed rivers. Geomorphology 97, 631–654.

Brown, R.A., Pasternack, G.B., 2017. Bed and width oscillations form coherent patterns in a partially confined, regulated gravel–cobble-bedded river adjusting to anthropogenic disturbances. Earth Surf. Dyn. 5, 1–20. https://doi.org/10.5194/esurf-5-1-2017.

Camporeale, C., Perona, P., Ridolfi, L., 2005. Hydrological and geomorphological significance of riparian vegetation in arid regions. In: D'Odorico, P., Porporato, A. (Eds.), Dryland Ecohydrology. Springer, Dordrecht, Netherlands, pp. 161–180.

Carley, J.K., Pasternack, G.B., Wyrick, J.R., Barker, J.R., Bratovich, P.M., Massa, D.A., Reedy, G.D., Johnson, T.R., 2012. Significant decadal channel change 58–67 years post-dam accounting for uncertainty in topographic change detection between contour maps and point cloud models. Geomorphology 179, 71–88. https://doi.org/10.1016/j.geomorph.2012.08.001.

Cooper, J.R., Aberle, J., Koll, K., Tait, S.J., 2013. Influence of relative submergence on spatial variance and form-induced stress of gravel-bed flows. Water Resour. Res. 49 (9), 5765–5777.

Feurer, D., Bailly, J.S., Puech, C., Le Coarer, Y., Viau, A.A., 2008. Very-high-resolution mapping of river-immersed topography by remote sensing. Prog. Phys. Geogr. 32 (4), 403–419. https://doi.org/10.1177/0309133308096030.

French, H.M., 2017. The Periglacial Environment. In: John Wiley & Sons Ltd, Chichester, p. 458.

Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D., 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environ. Manag. 10, 199–214.

Gervasi, A.A., Pasternack, G.B., East, A.E., 2021. Flooding duration and volume more important than peak discharge in explaining 18 years of gravel–cobble river change. Earth Surf. Process. Landf. 46 (15), 3194–3212. https://doi.org/10.1002/esp.5230.

Gilbert, G.K., 1917. Hydraulic-mining debris in the Sierra Nevada. U.S. Geol. Survey Prof. Paper 105, 154 pp.

Gilvear, D.J., 1999. Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31, 229–245.

Gorman, O.T., Karr, J.R., 1978. Habitat structure and stream fish communities. Ecology 59 (3), 507–515.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, western Cascades, Oregon. Geol. Soc. Am. Bull. 102, 340–352.

Guinn, J.M., 1890. Exceptional years: a history of California floods and drought. In: Historical Society of Southern California, Los Angeles, 1, pp. 33–39, 5.

Gupta, A., Fox, H., 1974. Effects of high-magnitude floods on channel form: a case study in Maryland Piedmont. Water Resour. Res. 10 (3), 499–509.

Hack, J.T., 1960. Interpretation of erosional topography in humid temperate regions. Am. J. Sci. 258-A, 80–97.

Hauer, C., Mandlburger, G., Habersack, H., 2009. Hydraulically related hydro-morphological units: description based on a new conceptual mesohabitat evaluation model (MEM) using LiDAR data as geometric input. River Res. Appl. 25, 29–47.

Hopkins, C.E., Pasternack, G.B., 2017. Autumn 2014 Lower Yuba River TUFLOW GPU 2D Model Description and Validation. Prepared for Yuba County Water Agency. University of California, Davis, CA.

Huxley, C., Syme, B., 2016. TUFLOW GPU – best practice advice for hydrologic and hydraulic model simulations. In: Hydrology and Water Resources Symposium 2016, Queenstown, New Zealand.

Inoue, T., Nelson, J.M., 2020. An experimental study of longitudinal incisional grooves in a mixed bedrock–alluvial channel. Water Resources Research 56 (3), e2019WR025410.

James, L.A., 2005. Sediment from hydraulic mining detained by Englebright and small dams in the Yuba basin. Geomorphology 71 (1–2), 202–226.

James, L.A., Singer, M.B., Ghoshal, S., Megison, M., 2009. Historical channel changes in the lower Yuba and Feather Rivers, California: long-term effects of contrasting river-management strategies. In: James, L.A., Rathburn, S.L., Whittecar, G.R. (Eds.), Management and Restoration of Fluvial Systems With Broad Historical Changes and Human Impacts, Geological Society of America Special Paper 451, pp. 57–81. https://doi.org/10.1130/2008.2451(04).

Kinzel, P.J., Legleiter, C.J., 2019. sUAS-based remote sensing of river discharge using thermal particle image velocimetry and bathymetric lidar. Remote Sens. 11 (19), 2317. https://doi.org/10.3390/rs11192317.

Kleinhans, M.G., van den Berg, J.H., 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surf. Process. Landf. 36, 721–738.

Lacey, R.J., Roy, A.G., 2008. The spatial characterization of turbulence around large roughness elements in a gravel-bed river. Geomorphology 102 (3–4), 542–553.

Lai, Yong, 2008. SRH-2D Version 2: Theory and User's Manual. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO.

Leopold, L.B., Wolman, M.G., 1957. River Channel Patterns: Braided, Meandering, and Straight. US Government Printing Office, Washington, DC.

Ltd, W.B.M.Pty, 2016. TUFLOW Users Manual- build 2016-03-AE. WBM Oceanics, Australia.

Maddock, Ian, Smolar-Žvanut, Nataša, Hill, Graham, 2008. The effect of flow regulation on the distribution and dynamics of channel geomorphic units (CGUs) and implications for Marble Trout (*Salmo marmoratus*) spawning habitat in the Soča River, Slovenia. In (Vol. 4, No. 1, p.). IOP Conference Series: Earth and Environmental Science, , 1st4. IOP Publishing, p. 012026. https://doi.org/10.1088/1755-1307/4/1/012026. https://iopscience.iop.org/article/10.1088/1755-1307/4/1/012026. (Accessed 16 February 2022).

Moir, H.J., Pasternack, G.B., 2008. Relationships between mesoscale morphological units, stream hydraulics and Chinook salmon (Oncorhynchus tshawytscha) spawning habitat on the lower Yuba River, California. Geomorphology 100, 527–548.

Moniz, P.J., Pasternack, G.B., Massa, D.A., Stearman, L.W., Bratovich, P.M., 2019. Do rearing salmonids predictably occupy physical microhabitat? J. Ecohydraulics 1–19. https://doi.org/10.1080/24705357.2019.1696717.

Newson, M.D., Newson, C.L., 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Prog. Phys. Geogr. 24, 195–217.

Nicholas, A.P., Ashworth, P.J., Smith, G.S., Sandbach, S.D., 2013. Numerical simulation of bar and island morphodynamics in anabranching megarivers. J. Geophys. Res. Earth Surf. 118 (4), 2019–2044.

O'Neill, M.P., Abrahams, A.D., 1984. Objective identification of pools and riffles. Water Resour. Res. 20, 921–926.

Parker, G., 1976. On the cause and characteristic scales of meandering and braiding in rivers. J. Fluid Mech. 76, 457–480.

Pasternack, G.B., 2011. 2D Modeling and Ecohydraulic Analysis. Createspace, Seattle, WA.

Pasternack, G.B., Hopkins, C.E., 2017. Near-census 2D model comparison between SRH-2D and TUFLOW GPU for use in gravel/cobble rivers. In: Prepared for Yuba County Water Agency. University of California, Davis, CA.

Pasternack, G.B., Wyrick, J.R., 2016. Flood-driven topographic changes in a gravel-cobble river over segment, reach, and unit scales. Earth Surf. Process. Landf. 42, 487–502. https://doi.org/10.1002/esp.4064.

Pasternack, G.B., Baig, D., Webber, M., Brown, R., 2018. Hierarchically nested river landform sequences. Part 2: Bankfull channel morphodynamics governed by valley nesting structure. Earth Surf. Process. Landf. 3, 2519–2532. https://doi.org/10.1002/esp.4410.

Rashleigh, B., Parmar, R., Johnston, J.M., Barber, M.C., 2005. Predictive habitat models for the occurrence of stream fishes in the mid-Atlantic highlands. N. Am. J. Fish Manag. 25, 1353–1366.

Robert, A., 1990. Boundary roughness in coarse-grained channels. Prog. Phys. Geogr. 14 (1), 42–70.

Rosgen, D., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO, USA.

Rousseau, Y.Y., Biron, P.M., Van de Wiel, M.J., 2016. Sensitivity of simulated flow fields and bathymetries in meandering channels to the choice of a morphodynamic model. Earth Surf. Process. Landf. 41 (9), 1169–1184.

Sawyer, A.M., Pasternack, G.B., Moir, H.J., Fulton, A.A., 2010. Riffle-pool maintenance and flow convergence routing confirmed on a large gravel bed river. Geomorphology 114, 143–160. https://doi.org/10.1016/j.geomorph.2009.06.021.

Scatena, F.N., 1995. Relative scales of time and effectiveness of watershed processes in a tropical montane rain forest of Puerto Rico. In: Washington DC American Geophysical Union Geophysical Monograph Series, 89, pp. 103–111.

Senter, A.E., Pasternack, G.B., Piegay, H., Vaughan, M.C., Lehyan, J.S., 2017. Wood export varies among decadal, annual, seasonal, and daily scale hydrologic regimes in a large, Mediterranean climate, mountain river watershed. Geomorphology 276, 164–179.

Shamloo, H., Rajaratnam, N., Katopodis, C., 2001. Hydraulics of simple habitat structures. J. Hydraul. Res. 39 (4), 351–366.

Shaw, J.R., Cooper, D.J., 2008. Linkages among watersheds, stream reaches, and riparian vegetation in dryland ephemeral stream networks. J. Hydrol. 350 (1–2), 68–82.

Strom, M.A., Pasternack, G.B., Wyrick, J.R., 2016. Reenvisioning velocity reversal as a diversity of hydraulic patch behaviours. Hydrol. Process. 30, 2348–2365.

Tamminga, A.D., Eaton, B.C., Hugenholtz, C.H., 2015. UAS-based remote sensing of fluvial change following an extreme flood event. Earth Surf. Process. Landf. 40, 1464–1476.

Thomson, J.R., Taylor, M.P., Brierley, G.J., 2004. Are River Styles ecologically meaningful? A test of the ecological significance of a geomorphic river characterization scheme. Aquat. Conserv. Mar. Freshwat. Ecosyst. 14, 25–48.

Tooth, S., 2000. Process, form and change in dryland rivers: a review of recent research. Earth Sci. Rev. 51 (1–4), 67–107.

U.S. Army Corps of Engineers, 2002. Hydrographic Survey Manual. Engineering and Design Manual No. EM-1110–2–1003. U.S. Army Corps of Engineers, Washington, DC.

Van den Berg, J.H., 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology 12, 259–279.

van Rooijen, E., Vanzo, D., Vetsch, D.F., Boes, R.M., Siviglia, A., 2021. Enhancing an unsupervised clustering algorithm with a spatial contiguity constraint for river habitat analysis. Ecohydrology 14, e2285. https://doi.org/10.1002/eco.2285. (Accessed 16 February 2022).

Vericat, D., Wheaton, J.M., Brasington, J., 2017. Revisiting the morphological approach: opportunities and challenges with repeat high-resolution topography. In: Gravel-Bed Rivers: Process and Disasters, first edition. Wiley, Oxford, pp. 121–158.

Weber, M.D., Pasternack, G.B., 2017. Valley-scale morphology drives differences in fluvial sediment budgets and incision rates during contrasting flow regimes. Geomorphology 288, 39–51. https://doi.org/10.1016/j.geomorph.2017.03.018.

Wheaton, J.M., Brasington, J., Darby, S.E., Kasprak, A., Sear, D., Vericat, D., 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. J. Geophys. Res. Earth Surf. 118, 759–779.

Wheaton, J.M., Fryirs, K.A., Brierley, G., Bangen, S.G., Bouwes, N., O'Brien, G., 2015. Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248, 273–295.

Whipple, K.X., 2004. Bedrock rivers and the geomorphology of active orogens. Annu. Rev. Earth Planet. Sci. 32, 151–185.

White, J.Q., Pasternack, G.B., Moir, H.J., 2010. Valley width variation influences riffle-pool location and persistence on a rapidly incising gravel-bed river. Geomorphology 121, 206–221. https://doi.org/10.1016/j.geomorph.2010.04.012.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process. 3 (2), 189–208.

Wyrick, J.R., Pasternack, G.B., 2012. Landforms of the Lower Yuba River. University of California, Davis, Prepared for the Yuba Accord River Management Team.

Wyrick, J.R., Pasternack, G.B., 2014. Geospatial organization of fluvial landforms in a gravel-cobble river: beyond the riffle-pool couplet. Geomorphology 213, 48–65. https://doi.org/10.1016/j.geomorph.2013.12.040.

Wyrick, J.R., Senter, A.E., Pasternack, G.B., 2014. Revealing the natural complexity of fluvial morphology through 2D hydrodynamic delineation of river landforms. Geomorphology 210, 14–22. https://doi.org/10.1016/j.geomorph.2013.12.013.