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Revealing the natural complexity of fluvial morphology through 2D hydrodynamic delineation of river landforms

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Abstract

Fluvial landforms at the morphological-unit scale (~ 1-10 channel widths) are typically delineated and mapped either by breaking up the one-dimensional longitudinal profile with no accounting of lateral variations or by manually classifying surface water patterns and two-dimensional areal extents *in situ* or with aerial imagery. Mapping errors arise from user subjectivity, varying surface water patterns when the same area is observed at different discharges and viewpoints, and difficulty in creating a complete map with no gaps or overlaps in delineated polygons. This study presents a new theory for delineating and mapping channel landforms at the morphological-unit scale that eliminates in-field subjective decision making, adds full transparency for map users, and enables future systemic alterations without having to remap in the field. Delineation is accomplished through a few basic steps. First, near-census topographic and bathymetric data are used in a two-dimensional hydrodynamic model to create meter-scale depth and velocity rasters for a representative base flow. Second, expert judgment and local knowledge determine the number and nomenclature of landform types as well as the range of base flow depth and velocity over each type. This step does require subjectivity, but it is transparent and adjustable at any time. Third, the hydraulic landform classification is applied to hydraulic rasters to quickly, completely, and objectively map the planform pattern of laterally explicit landforms. Application of this theory will reveal the true natural complexity, yet systematic organization, of channel morphology.

Keywords: morphological units; fluvial landforms; fluvial geomorphology; 2D modeling

1. Introduction

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 morphologic changes. A common practice in fluvial geomorphology involves focusing on specific spatial scales at which landforms have characteristic features (Grant et al., 1990; Rosgen, 1996; Thomson et al., 2001). These scales are often thought of as dimensionless (i.e., exhibiting similarity of forms and processes among systems of different absolute size) and proportional to channel width (W), with common names such as catchment (entire watershed scale), subcatchment, segment (~ 10^3-10^4 W), reach (~ 10^2-10^3 W), morphological (alternately channel or geomorphic) unit (~ 10^0-10^1 W), and hydraulic unit (~ 10^{-1}-10^0 W) (Frissell et al., 1986; Grant et al., 1990; Bisson et al., 1996; McDowell, 2001). This study presents a new theory and methodology for delineating and mapping channel landforms at the morphological-unit scale that eliminates in-field subjective decision making, adds full transparency for map users, and enables future systemic alterations without having to remap in the field.

1.1. MU definition

There are several terms for discernible units of channel morphology at the ~ 1-10 W scale, such as *channel unit* (e.g., Grant et al., 1990; Bisson et al., 1996), *channel geomorphic unit* (e.g., Hawkins et al., 1993), *geomorphic unit* (e.g., Thomson et al., 2001), *morphological unit* (e.g., Wadeson, 1994; Moir and Pasternack, 2008), and *physical biotope* (e.g., Newson and Newson, 2000). The terms that begin with *channel* preclude their usage for overbank landforms, which therefore can be more specific than desired when considering the river corridor as a continuum. *Biotope* imposes a biological requirement that may not be applicable or necessary for geomorphic analysis. *Geomorphic unit* is a likely term, but is broadly used across all spatial scales and is not limited to landform geometry. The term of choice for this study is *morphological unit* (MU), which provides an appropriately descriptive term for topographic forms within the river corridor that represent distinct form-process associations.

River topography is a continuous form, so to an extent the idea of breaking it down into discrete units may seem artificial and arbitrary (Kondolf, 1995). However, we have long understood that different landscape elements are responsible for different physical processes and biological functions, so it is worthwhile to explore MUs in more detail and with more objectivity than has been attempted before.

At the scale of ~ 1-10 W, MUs are conjectured to be a basic unit for understanding physical processes and assessing instream habitat considering that ecohydraulic variables such as depth, velocity, shear stress, and substrate are closely controlled by the shape and structure of the landform over which they occur (Whiting and Dietrich, 1991; Newson and Newson, 2000; Thompson, 2006; Sawyer et al., 2010). The MU scale therefore provides a relatively high degree of resolution of analysis that balances scientific detail with the potential for segment-scale application (Padmore et al., 1998). Since many studies have subjectively defined MUs and/or habitat types and then used those classifications to make important geomorphic and ecological observations, river scientists obviously find this spatial-scale delineation a valuable tool.

Notably an MU is not a habitat or biotic object or concept. Habitat at the mesoscale is defined as the interdependent set of the ecohydraulic variables over an MU that attracts organisms to reside there for a significant part of the day (e.g., Beisel et al., 1998; Parasiewicz, 2007). The MUs can be revealed by their overlying hydraulics (see section 1.2), but they are not an assemblage of flow-dependent hydraulic conditions; thus, they do not change their spatial pattern as discharge changes (excluding scour and fill). The MUs constitute a classification of the *landforms* that create key environmental requirements of an aquatic community.

A key advancement for MU mapping is the trend toward performing spatially explicit, detailed, planform mapping. Traditional sampling of rivers with a small number of cross sections suffers from many problems (Pasternack and Senter, 2011), including biased preconceptions as to which locations are more important, stable, accessible, or representative. A census is a complete accounting of a population; but when considering a continuous spatial variable like topography, there are ever-finer scales of variability precluding a true census. Pasternack (2011) coined the term *near-census* to refer to comprehensive, spatially explicit observation of the landscape emphasizing the ~ 1-m scale as the basic building block for characterizing geomorphic processes and ecological functions.

1.2. Hydraulic MU delineation

The morphology of channel beds and banks impacts overlying flow hydraulics (e.g., Whiting and Dietrich, 1991; Clifford and French, 1998; MacWilliams et al., 2006; Pasternack et al., 2006), so hydraulics can in turn be used as a proxy for identifying underlying MUs. In fact, most recent methods for delineating MUs are based on categorizing a suite of local hydraulic combinations between fast or slow velocity with deep or shallow depths (e.g., Hawkins et al., 1993; Borsanyi et al., 2004; Zimmer and Power, 2006; Hauer et al., 2009; Klaar et al., 2009). The main differences among these methods arise from how they determine local hydraulics, at what spatial area to apply them, and how to locate MU boundaries. Most of these studies focused on qualitative observations of surface flow patterns, surface water slope, and/or localized point measurements or estimations of depth and velocity. A similar pattern of hierarchical decisions about the use of flow hydraulics has emerged. Typically, the user decides in the field whether some area exhibits fast or slow velocity, then whether the water column is deep or shallow, which then leads to a mesohabitat unit description. The user also subjectively delineates the unit boundaries. Mapping subjectivity is accepted in peer review for lack of any objective methodology.

This subjective MU delineation method, however, has several deficiencies. First, a field observer at ground level may have limited and insufficient vantage points to observe the necessary hydraulics. Second, decisions may be improperly influenced by conditions at time of measurement. Hydraulic thresholds for MU boundaries are often not visible to the human eye. Third, visual qualitative observation of the magnitudes of depth and velocity suffers from the same types of problems reported for visual substrate and other classifications (Jowett, 1993; Marcus et al., 1995; Bunte and Abt, 2001; Faustini and Kaufmann, 2007) in that: (i) individual observers may visually distinguish areas with dramatically different hydraulics, but are unlikely to visually distinguish less dramatic differences, (ii) individual observers tend to overvalue large magnitudes, (iii) individual observers looking at the same magnitude but in different surrounding contexts may experience optical illusions that lead to mischaracterizing the same magnitudes as different, and (iv) different observers may look at the same location and report different magnitudes. Fourth, the subjective delineation of spatial patterns will suffer from the same types of problems as enumerated for estimating magnitudes, yielding unreliable, nonrepeatable interpretations. Fifth, spatial patterns are commonly mapped as polygons with a handheld GPS (with real-time or post-processed differential positions) whose nominal precision is submeter, but whose true accuracy when operated while moving (lacking repeated counts at each vertex) is often unchecked and actually poor (~ 2-5 m). The accuracy of GPS polygon delineation is poor enough that lines may cross over and thus requires that individual polygons be corrected later. Finally, field-delineated polygons are not snapped, leaving gaps and overlaps that are difficult to reconcile.

Several researchers have enhanced the hydraulic delineation of MUs through the use of digital elevation models (DEMs), which serve to reduce field subjectivity and allow for repeatability of morphologic delineation methods. Near-census topographic and bathymetric data collected using light detection and ranging (LiDAR) and echosounding provide more robust data sets and quantitative terrain and hydraulic metrics for mapping MUs. For example, Milne and Sear (1997) used ArcGIS to detrend river DEMs based on cross-sectional surveys of several upland rivers and then used elevational variations of the bed surfaces to differentiate between pools and riffles, i.e., using depth as the sole MU indicator. However, depth is an inadequate indicator when used alone because it cannot distinguish between two landforms with the same depth but significantly different bed slopes and bed roughnesses that yield different velocities and shear stresses. Moir and Pasternack (2008) mapped a suite of laterally and longitudinally explicit MUs based on expert judgment of hydraulics and substrate using site visits as well as a 1-m resolution topographic map to hand-delineate MU polygons in ArcGIS. Hauer et al. (2009) combined LiDAR and terrestrial survey data to create a DEM of a gravel-bed river and simulated a range of discharges using a two-dimensional (2D) hydrodynamic model. They then used an algorithm to map six types of mesohabitat regions within this range of discharges based on binned values of velocity, depth, and shear stress. Their study provides a template for repeatability but is focused on flow-dependent mesohabitats, not MUs.

1.3. Topographic MU delineation

Ideally, both MUs and flow-dependent mesohabitats should be delineated objectively without spatial interpretation by observers. Some studies have argued that the way to achieve this is to forgo flow-based indicators and only use terrain. O'Neill and Abrahams (1984) determined riffle crests and pool troughs using the one-dimensional channel-bed longitudinal profile. They argued that any method involving depth and velocity would be inherently dependent on discharge, and therefore proposed the use of variances along the topographic slope for MU delineation. However, this method is not without subjectivity either. The geomorphic community generally accepts longitudinal profiles without questioning the process of obtaining them, but in fact this method of one-dimensional MU mapping involves a process of picking and sampling pathways that includes several opaque assumptions and choices lacking objectivity, transparency, or justification. Most importantly, the geometry of a channel's fastest, deepest pathway and the means by which geomorphologists locate it are both flow-dependent; so too is the geometry of the centerline of the wetted area. In theory, a pathway connecting the deepest points down a channel might not be flow dependent, but its location in the field is difficult to identify without being influenced by the hydraulics on the day of observation. Yet the longitudinal profile and subsequent MU delineation are determined for a single discharge, which is often arbitrarily the one that happens to occur on the day of summer field work, which in turn is usually chosen to be a wadable low flow or picked for other logistic reasons instead of scientific ones. Further, the choice of variance thresholds is subjective as to how much topographic high or low makes a riffle or pool (as admitted in O'Neill and Abrahams (1984)), but once the flow, profile, and criteria are set, the mapping algorithm to locate riffles and pools is objective. Additionally, there are more MUs than just riffles and pools, and most rivers contain significant lateral and oblique terrain variability that cannot accurately be captured by cross sections and profiles (e.g., Borsanyi et al., 2004; Milan et al., 2010).

The greatest degree of objectivity and accuracy could be achieved if near-census river corridor DEMs were objectively analyzed to delineate a full suite of individual MUs. Terrain segmentation based on topographic slopes, aspects, and/or curvatures is not a new concept in geomorphology (e.g., Waters, 1958; Brandli, 1996). In fact, MU-scale mapping can be considered similar to the elementary forms concept proposed by Minar and Evans (2008), in which units were defined by third-order slope equations. However, analytical terrain segmentation does not include flow direction, and flow direction at any given point in a river is not necessarily parallel to the downvalley channel slope. Hence, the use of these topographic equations to delineate MUs could result in incorrectly assigning an MU classification based on the assumption of linear, longitudinal flow. Another significant hurdle in topographic delineation of MUs arises from the fact that different MUs may have very similar nondimensional geometry, but they have subtly or significantly different dimensional scales. Depending on the native resolution of the data and different approaches to detrending and filtering, MUs may be revealed or obscured, necessitating subjective interpretation and manipulation. New technologies may solve these challenges in the future, but a strong basis still exists for taking advantage of the innate connection between landforms and their overflowing hydraulics as an objective method to map MUs.

1.4. Study objectives

Pure topographic analysis of landforms remains problematic, and past efforts at hydraulic-based MU delineation have either lacked enough detail to capture meaningful variations or emphasized mesohabitat instead of MU delineation. However, the previous studies have provided templates and guidelines for this next logical step in creating a complete MU coverage map. In this study, an objective map of MUs was found to be obtainable from two inputs: (i) spatial grids of depth and velocity at a low discharge (when topography is the primary control on hydraulics) estimated using a 2D hydrodynamic model, and (ii) an expert-specified MU classification scheme using depth and velocity values. With these inputs, one can objectively classify any location in a river into an MU type and then identify coherent MUs as adjacent aggregates of individually classified points. This study introduces a theory and methodology that removes much of the subjectivity in mapping river MUs and presents the concepts and justifications for spatially explicit delineation of MUs aided by 2D hydrodynamic modeling. Near-census data and model results enable representation of all areas of the wetted channel with equal emphasis and objectivity, and as such will yield unambiguous and comprehensive MU results.

2. MU mapping methodology

A six-step procedure for mapping river MUs was developed in this study (Fig. 1), with basic steps outlined in this paragraph followed by detailed information for each step in the following subsections. First, obtain near-census topographic and bathymetric data of the river corridor of interest and produce a DEM. Second, use expert judgment and local knowledge (perhaps guided from observations during data collection) to predetermine the number and nomenclature of MU types to be mapped, and then estimate the range of each hydraulic variable for each MU type. Codify hydraulic thresholds into an algorithm for classifying individual raster cells. Third, use hydrogeomorphic processes and/or ecologic functions to determine an appropriate low flow regime at which to identify the MUs. Fourth, develop, run, and validate a 2D hydrodynamic model at the flow of relevance for MU delineation of the inundation zone to be mapped. Fifth, create rasters of the key delineation variables (presently taken to be depth and velocity, but future developments could also draw on Froude number, Shields stress, or other derivative variables) consistent with the resolution of the 2D model. Sixth, apply the MU delineation algorithm to obtain a preliminary MU map. Finally, we recommend a review of the map to evaluate if the predetermined MU types and thresholds yield meaningful patterns. Tests exist that can be used to evaluate the spatial organization of MUs (Pasternack and Senter, 2011; Wyrick and Pasternack, 2012), but there is also a risk of circularity if the existence or nonexistence of coherent MU spatial organization is used to modify the MU algorithm, and in turn, the same tests are used to subsequently demonstrate the existence of spatial organization. Overall, the proposed methodology eliminates subjectivity in assessing the magnitude of hydraulics and the resulting spatial pattern, leaving the choice of number and nomenclature of MU types as well as the ranges of joint depth and velocity magnitudes for each MU type as the only subjective aspects. Any remaining subjectivity may be considered as a flaw, yet so far no existing method is devoid of subjectivity. This new approach represents a significant step forward in using 2D modeling results to develop objective criteria for understanding the underlying landforms within a river corridor.

2.1. Channel topography

Looking beyond the era of fluvial geomorphology based on cross sections, a near-census river corridor digital terrain model is the most important input for diverse geomorphic, engineering, and ecological applications, including MU delineation (Wheaton et al., 2004; Pasternack, 2011). Near-census data sets are obtained at reasonable cost and are increasingly available for free (e.g., http://www.opentopography.org). The preferred methods at this time are airborne LiDAR mapping of the terrestrial river corridor (Lane and Chandler, 2003; Hilldale and Raff, 2007) and boat-based echosounding of the subaqueous riverbed (single- or multi-beam depending on depth). These methods typically have high point densities (~ 0.5 to 3 points per m^2). Where remote methods are ineffective (e.g., shallow, wadable, submerged areas; submerged areas with excessive bubbles; and terrestrial forests with inadequate canopy openings), a combination of Real-Time Kinematic Global Positioning System (RTK GPS) and Total Station (TS) surveys are recommended. Spatial sampling may aim for maximal point density commensurate with channel type (Brasington et al., 2000; Valle and Pasternack, 2006), emphasize key features and slope breaks (e.g., Bouwes et al., 2011), or do both (e.g., Pasternack, 2011). Each method and interpolation scheme has unique, inherent uncertainties that need to be assessed and reported (Milan et al., 2011) in order to provide full disclosure of steps taken to apply high standards for quality of data used for all other analyses.

2.2. Discharge selection

A choice that must be made is the discharge to use in the 2D model for an accurate MU delineation. Such a choice is inherent in almost every MU delineation method, including those only analyzing the topography of the thalweg profile or wetted area centerline, but this choice is often hidden and denied. If the flow is too low, especially for a channel with gently sloping banks, then too little of the channel will have identifiable hydraulics. If the flow becomes too high, then the momentum of the water will increase enough that some topographic controls will be effectively drowned out (Pasternack et al., 2006; Wyrick and Pasternack, 2008), and the resulting hydraulics will have decreased spatial variation. The inherent self-maintenance of most channels results in a morphology that is at quasi-equilibrium for all but flood flows, but manifests most clearly at the low flows (Langbein and Leopold, 1962).

The choice of which low flow to use in the model is not that sensitive and is aided by available discharge records along with flow indicators of hydrogeomorphic processes and/or ecological functions. One option is to rely on a hydrological process, such as base flow. Base flow is generally defined as the average annual low flow discharge that exists for some measurable extended time period (i.e., not an instantaneous measurement). Another option is to reference against a flow responsible for channel maintenance, such as bankfull discharge. Based on experience thus far, a flow of ~ 1/10 to 1/5 of bankfull discharge is recommended. A third option is to identify key low flows for ecological functions such as anadromous salmonid migration or spawning. Finally, an iterative process with sensitivity analyses may be used to compare and contrast alternatives and quantify uncertainty (Wyrick and Pasternack, 2012).

The hydraulics over an MU change with discharge, but it is important to keep in mind that the landform is what is being mapped with this method. Therefore, selection of the 'ideal' discharge to model is ultimately less important because for any selected discharge a particular MU will have a specific depth-velocity combination (see section 2.4 for more details) that must be recognized and implemented into the methodology. In other words, use of a lower or higher flow for MU mapping yields virtually no difference in MUs because the hydraulic thresholds are adjusted down or up, respectively (Wyrick and Pasternack, 2012). The resilience of MU delineations across discharges by adjusting hydraulic thresholds is key evidence that this methodology is revealing underlying landforms that are independent of discharge.

2.3. 2D hydrodynamic modeling

Two-dimensional (depth-averaged) hydrodynamic models have existed for decades and are increasingly used to study a variety of hydrogeomorphic processes (Bates et al., 1992; Leclerc et al., 1995; Miller and Cluer, 1998; Cao et al., 2003; Brown and Pasternack, 2008; Sawyer et al., 2010) and to perform quantitative habitat assessments (e.g., Leclerc et al., 1995; Elkins et al., 2007; Moir and Pasternack, 2010; Bouwes et al., 2011). Notably, these previous studies were generally limited to short river areas, ~ 50 to 2000 m of channel length. While such distances may be adequate to reveal local processes and test site-scale project designs, it is not adequate for comprehensive instream flow analysis of a river segment (i.e., 10^3-10^4 W). As mapping and modeling technology has progressed, 2D modeling is emerging as a preferred tool for near-census river analysis. A recent textbook on 2D modeling presents the requisite inputs, methods, and some applications of simulation outputs for fluvial geomorphology and habitat assessment (Pasternack, 2011). The selection of a specific algorithm is not important for the MU methodology reported in this study, as long as the model can discern the hydraulic phenomena present in the study segment.

Results from any 2D model need to be converted to raster format for use with this methodology. The output from a 2D model is often a point-based text or binary file with point coordinates and the values of hydraulic variables at those coordinates. Depending on the 2D model procedure used and point density, the user should select an appropriate method (e.g., Delaunay triangulation, kriging, or nearest neighbor) for converting the point results to a raster (Moore et al., 1991; Pasternack, 2011).

2.4. MU classification

Given a 2D model simulation of the spatial pattern of base-flow depth and velocity in a river, the key step in MU delineation involves assigning each point's joint velocity and depth combination to an MU type. To do this, one must already have a basic knowledge of which MU types are relevant to the study region and what range of hydraulics are likely to be associated with each MU type for the selected flow. This knowledge can come from the literature on channel types and MUs, past regional studies, and/or experience with the study area. Ideally, experts with different fluvial educations and experiences would reach a consensus as to what fluvial landforms are potentially present at the ~ 1-10 W scale. A strength of this new theory and methodology is that it forces this key step into public discourse with transparency, whereas traditional methods rely on experts to make these decisions *in situ* on the river with no chance for future adjustment or adequate explanation.

A spectrum of MU and/or mesohabitat terminology and definitions exists that can guide users in assessing what is relevant and meaningful for MU delineation for a new study region (e.g., Grant et al., 1990; Hawkins et al., 1993; Brierly and Fryirs, 2000; Milan et al., 2010). Existing terminologies have qualitative definitions that are generally consistent throughout geomorphic literature, so quantitative delineations of MUs should be appropriately grounded to these broadly accepted qualitative definitions. For example, countless articles have been published assessing forms and processes of the MU types known as *pool* (i.e., topographic low with deep, slow, subcritical hydraulics) and *riffle* (i.e., topographic high with shallow, fast, near-critical hydraulics). Classically, some fluvial geomorphologists only recognized pools and riffles, especially when relying on a longitudinal profile for MU delineation. In the last ~ 20 years, however, a growing number of studies have defined an increasingly large number of MU or mesohabitat types. For example, McCain et al. (1990) listed 22 in-channel habitat types. Hawkins et al. (1993) identified 18 channel unit types (seven fast water units and eleven slow water ones). Brierly and Fryirs (2000) catalogued 12 different types of bank-attached morphological units alone. Brown (1997) described 17 different types of floodplain features. Although these diverse schemes have received limited objective scrutiny or comparison, their application in river management has yielded significant statistical associations with physical variables and biological observations. The purpose of this study is not to question or justify any specific number of MUs for any particular purpose, but instead to present a method for mapping diverse landforms as objectively as possible for those who already accept that such diversity exists.

For an example of how to use classic definitions to classify MUs, consider some common in-channel morphological units such as: pool, riffle, glide, and run (see more comprehensive compilations in Grant et al. (1990), Newson and Newson (2000), or Milan et al. (2010)). Descriptive and relevant definitions of each can be gleaned from literature (Table 1). From these qualitative definitions, they can be sorted by ranges of associated hydraulics relevant to the applied river system as a starting point. Typically the topographic endmembers, pool and riffle, are succinctly defined for low flow hydraulics as *deep and slow* and *shallow and fast*, respectively. Glides tend to be defined as shallow and slow, while runs tend to be defined as deep and fast. Therefore, a simple four-type classification can be created with the subjective choice being exactly which depth and velocity values to use as hydraulic thresholds. From there, the number of MU types and their respective hydraulic thresholds can be tailored to be more specific to the river of interest and may include additional MU types with their own depth–velocity ranges, such as chute, cascade, riffle transition, etc. The nomenclature is less important than the ability to identify coherent landforms that exhibit similar hydraulics.

Once the number and definitions of MU types are set, the next step is to assign quantitative depth and velocity thresholds to delineate them at the relevant discharge of the 2D model run. For those who prefer considering rivers as a continuum rather than an assemblage of discrete MUs, the threshold uncertainty may optionally be addressed using a fuzzy inference system in which a lower probability of being in an MU is assigned on the basis of higher proximity to a threshold (e.g., Legleiter and Goodchild, 2005). Such a fuzzy inference system could also be used to cope with the effect of uncertainty in 2D model estimation accuracy on MU designation.

Initial estimates of hydraulic thresholds for MU delineation come from the literature on channel types and MUs, past regional studies, and experience with the study area. Like the numerical thresholds in any landform classification, these thresholds are arguably subjectively chosen, but the resulting map is objective because neither the spatial pattern nor assignment of MU types to points is subjective. Further, this scheme means that the subjective aspects still inherent to the methodology are fully transparent and adjustable, whereas the suite of individual field-based choices cannot be fully explained nor adjusted later without a high degree of uncertainty.

By way of comparison, this approach of assigning thresholds has some similarity to supervised cluster analysis used to classify and interpret spatial patterns (e.g., Johnson, 1967; Maxwell et al., 2002). In that method, the number of units and an initial estimate (seed) of the middle of each unit's hydraulic domain (strictly speaking, the centroid of each *n*-dimensional phase-space unit where depth and velocity constitute a 2D phase space) are selected by the user. All points are then assigned to the nearest seed and the centroid of points in each unit is computed to yield an adjusted middle. This process is repeated until the centroid value no longer changes. Then the points are assigned to each unit centroid and boundaries delineating final units are inferred based on the point classification.

The use of supervised cluster analysis for MU delineation suffers from two significant drawbacks relative to the method developed in this study. First, the outcome would be an array of units based on clusters that were biased by design to have a large abundance and density of points, which is different from having units based on the uniqueness of the joint distribution of individual, disparate hydraulics values associated with underlying landforms. Second, the number of raster cells in an MU delineation would be proportional to the total area of each MU type in the study domain, and this would impact MU delineation. For example, one MU type with a lot of cells might draw the attention of multiple seeds and be subdivided unnecessarily; whereas a rare MU type with a distinct joint distribution of depth and velocity may be real and meaningful, but might end up subsumed into one or more other clusters and not be revealed because of low numbers of points. In other words, sub-MU scale features may possibly yield complex joint distributions of depth and velocity distributions that are meaningful at the smaller hydraulic unit scale but are not similarly appropriate for MU-scale landform delineation. This is an example where the topographic detail of near-census data could confound proper landform mapping. Classifying by boundary values instead of centroids guarantees that the hydraulic domain of each MU matches a distinct signature of each landform.

This methodology was implemented on a lowland, gravel–cobble river (Wyrick and Pasternack, 2012) and an upland, cobble–boulder river (Pasternack and Senter, 2011). In each case the set of MUs was unique to the landscape setting on the basis of local knowledge and geomorphic theory (Fig. 2). For more details on the river settings, MU type definitions, and classification selection choices, please refer to the referenced reports. These examples should not be adopted in future studies without mindful consideration of their suitability in each case, but are presented here simply as visual representations of hydraulic classification.

2.5. MU mapping

Given 2D model rasters for depth and velocity, a specified number of MU types, and the hydraulic threshold values for each MU type, the last step is to objectively map individual MUs. This is accomplished using a computer program, such as the raster calculator in ArcGIS Spatial Analyst (see workflow in Pasternack, 2011). This calculation automatically assigns each raster pixel to a particular MU type based on its discrete values of depth and velocity. All contiguous pixels with the same classification coalesce into a single MU polygon, thus providing automatic spatial delineation for the river. As an additional step, one may choose to limit an individual MU to a minimum size on the basis of spatial coherence testing, for which procedures already exist (e.g., Wheaton et al., 2010; Carley et al., 2012). Alternatively, size discrimination could be applied after the fact for any subsequent MU analyses.

After inspection of the initial MU map, the number of MU types and their hydraulic thresholds may be individually manipulated based on expert knowledge to assess the sensitivity of the map to different choices. A visual review of the MU map will reveal qualitative patterns that can be assessed for realism. The MUs should be organized in a somewhat expected manner — in the longitudinal direction and within contiguous nondirectional clusters. For example, the geometrically steepest and flattest landforms would be expected to be separated by some transitionally sloped landforms. If submeter-scale color aerial imagery is available, then one could visually compare the MU map to the imagery to check the delineation of easily observed MUs. No formal evaluation or improvement procedure exists at this time, but it would be feasible to run optimization tests to determine the scheme that yields the MU map with the most significant spatial organization metrics. In the meantime, user judgment based on local experience, expert group consensus, and independent peer review are the best aids to final selection, just as they are for traditional approaches to MU mapping.

Following the example application of hydraulic thresholds (Fig. 2), examples of how the depth and velocity rasters can be used in concert with the hydraulic thresholds to create detailed MU maps are illustrated for a lowland, gravel–cobble river (Fig. 3) and an upland, cobble–boulder river (Fig. 4). While detailed analyses of these MU maps are beyond the scope of this article, some basic results can be evaluated to highlight the methodology's veracity and relevance. First, the maps show that the suite of landforms completely covers the wetted area of the selected base flow, i.e., no overlaps or gaps exist within the mesh of polygons as might occur with field-delineated maps. Second, MU shapes are highly irregular, as might be expected from intricacies of channel morphology. Such detail is generally difficult to replicate with hand drawings (e.g., Milne and Sear, 1997; Borsanyi et al., 2004; Moir and Pasternack, 2008). Third, the channels exhibit high lateral variability at any given cross section that may be lost in field delineations. This point is particularly important for identifying slender units along the margin that may not dominate any given cross section but are valuable for habitat studies. Lastly, these example sites are only small sections of complete longitudinal coverage maps that extend for ~ 37 km (Fig. 3) and ~ 12 km (Fig. 4), lengths that would be onerous to hand-map at this resolution. These examples are provided not to highlight specific hydraulic thresholds and MU combinations, but rather as templates as to how the mapping process, tailored for any river system, would look.

3. Applications

Morphological unit maps provide insight into the geomorphic structure of the river corridor. The generation of basic map statistics may also provide feedback and refinement for the mapping process described in the previous sections. More importantly, analyses of MUs can be used to address fundamental questions about the structure and function of river landforms. Previous literature on landform delineation (e.g., Grant et al., 1990; Hauer et al., 2009) provided four broad groups of MU analysis metrics: abundance and diversity, longitudinal distribution and spacing, lateral variability, and nondirectional adjacency. Because this article emphasizes theoretical developments for MU mapping, these MU statistics were not developed herein for a case study but have been applied with success to two diverse rivers thus far (Pasternack and Senter, 2011; Wyrick and Pasternack, 2012). However, some example scientific questions that could be addressed with a detailed MU map may include whether (i) MUs are organized in a nonrandom, coherent spatial structure, (ii) a river exhibits significant lateral variability, or (iii) MUs are organized across multiple spatial scales.

A detailed MU map also provides a basis for stratification of ecohydraulic data sets (e.g., Abu-Aly et al., in press). An example scientific question might be to determine whether the rates of change for hydraulic variables as discharge increases can be isolated for a particular MU type to determine locations of possible velocity reversals. Or, in other words, at what discharge will pool units exhibit higher average velocities than riffle units, if at all? With an MU map, the locations of various lifestage habitats can be linked to the geomorphic variables. One could determine whether a relationship exists between MU type (and/or size, number, location, etc.) and areas of salmonid spawning or rearing. The applications of an accurate, detailed MU map are only bounded by data set availability and users' imaginations.

4. Conclusions

Mesoscale fluvial landforms have been described as *fundamental building blocks of rivers* (Brierly and Fryers, 2000) and have been inserted as important links within channel classification hierarchies (e.g., Frissell et al., 1986; Newson and Newson, 2000). Thus, improved identification and delineation of these morphological units are vital to the progress of river science. The methodology presented in this study increases the level of objectivity in the mapping procedure and provides a basis for streamlined, repeatable, and rigorous classification within any river system.

This study presented several key advances to the science of river morphology delineation. First, an MU is a flow-independent, structural landform; and identification of the landform's morphology is important for defining the MU. Second, 2D hydrodynamic results were used as a basis for identifying and delineating MUs, which provide the means to create a continuous map in the context of any spatial scale. Third, the ability to manipulate the delineation procedure digitally allows for a repeatable and more objective methodology of MU mapping. Fourth, the robustness of the methodology is such that imprecision on which low flow discharge to use in the procedure does not add uncertainty to the final MU maps. Lastly, digital delineation can return results that are scaled to pixel sizes smaller than what field methods produce, therefore creating maps that are more detailed and ultimately more accurate than large scale averaging.

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Table 1
Descriptions of MUs common to gravel-bed rivers; descriptions of depth and velocity refer to those typically created by the landforms during low flows

MU	Description at low flow
pool	Topographic low in the channel that exhibits high depth and low velocity, and low water surface slope. This unit covers both ‘forced pool’ and ‘pool’. 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 often associated with static structures such as wood, boulders, and bedrock outcrops. A pool is not formed by a forcing obstruction. The distinction between forced pool and pool cannot be made automatically within GIS.
riffle	Topographic high that exhibits shallow depths, moderate to high velocities, rough water surface texture, and steep water surface slope. Riffles are generally associated with the crest and backslope of a transverse bar (e.g., Knighton, 1998).
run	An area that exhibits moderate to high velocities, 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.
glide	An area that exhibits low to moderate velocities and depths and low water surface slope. Glides commonly occur along the periphery of channels and flanking pools and can also exist in straight sections of low bed slope.

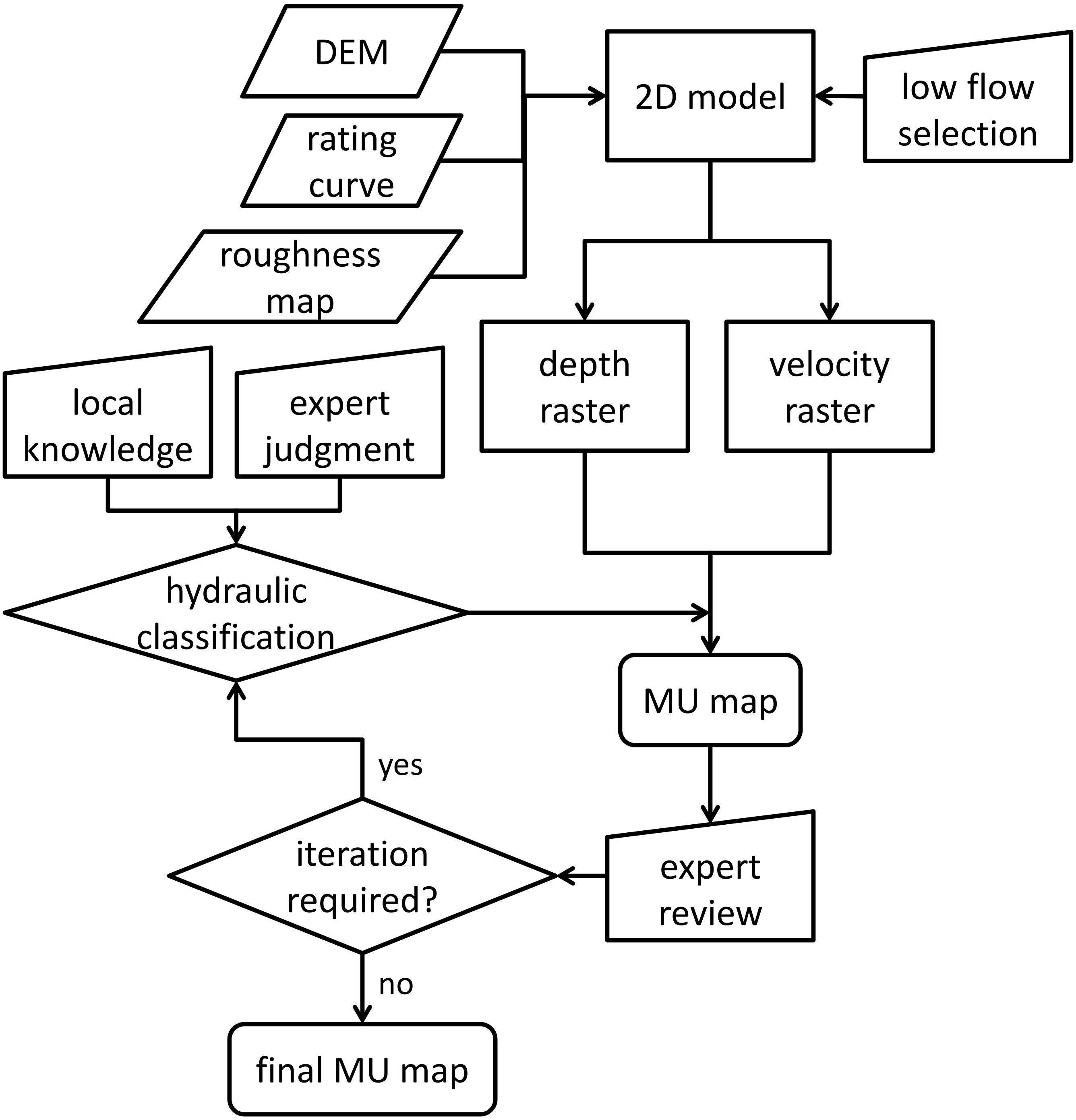
Figure Caption

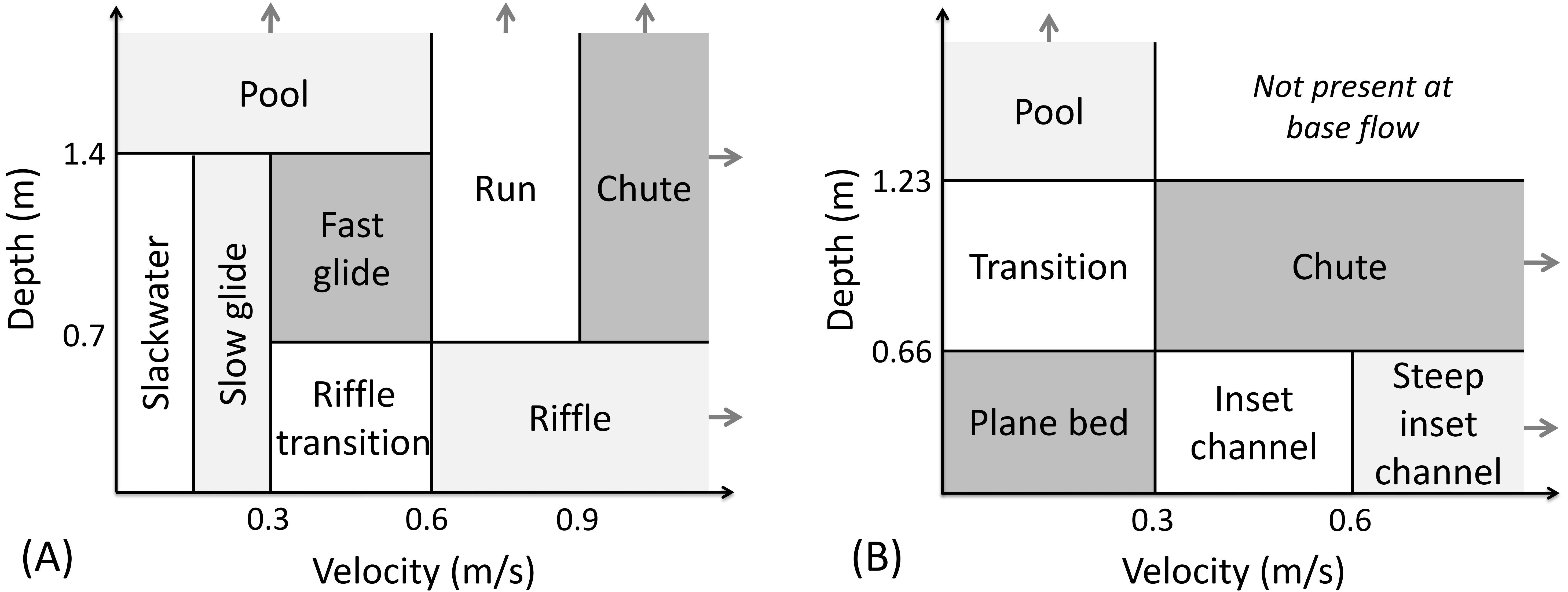
Fig. 1. Flowchart of MU delineation procedure. Parallelograms represent prepared data input; trapezoids represent manual input; diamonds represent decisions.

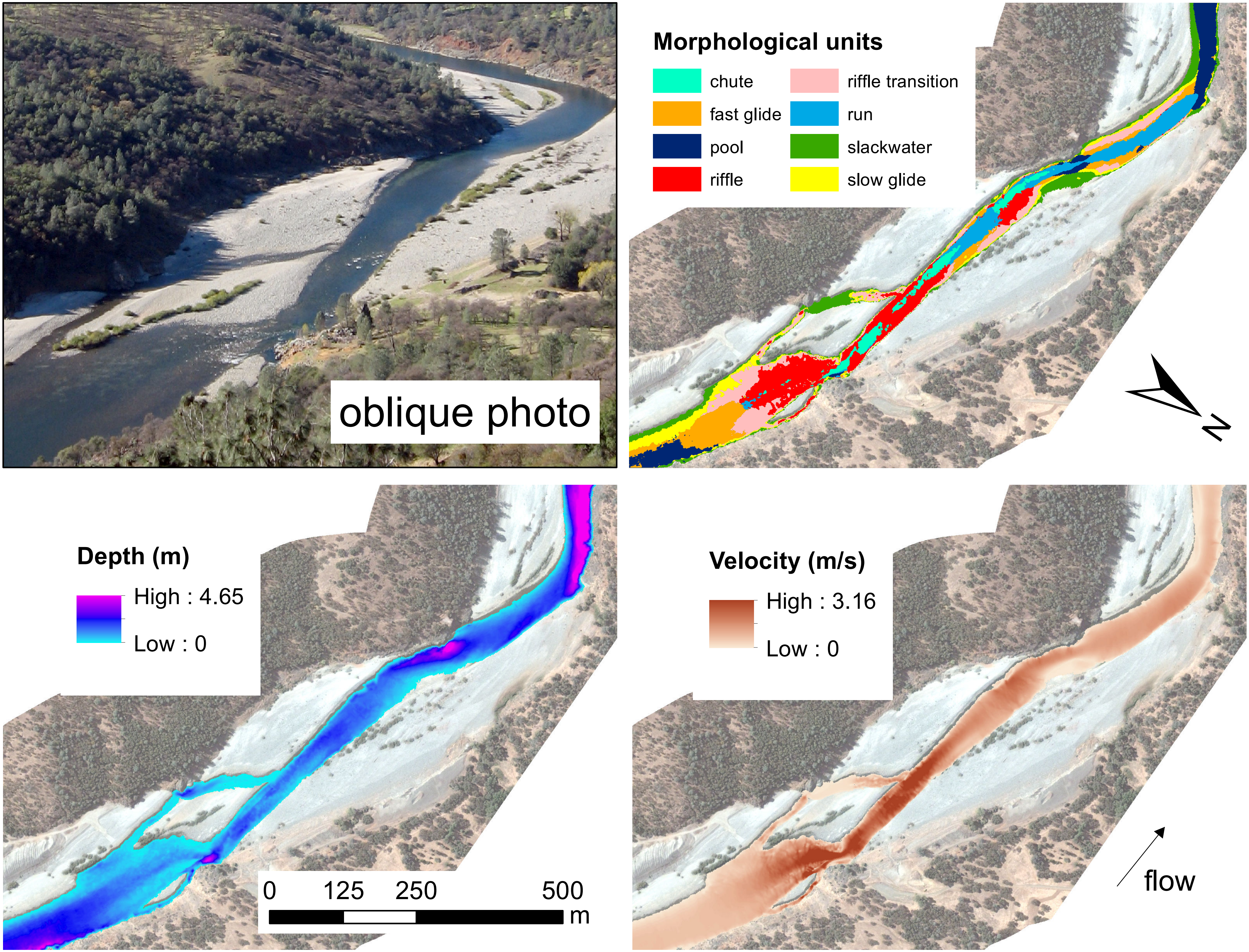
Fig. 2. Example MU types and hydraulic thresholds for two river morphologies. (A) Lowland, gravel–cobble river at a low flow of 24.92 m^3/s (Wyrick and Pasternack, 2012); (B) upland, cobble–boulder river at low flow of 2.577 m^3/s (Pasternack and Senter, 2011).

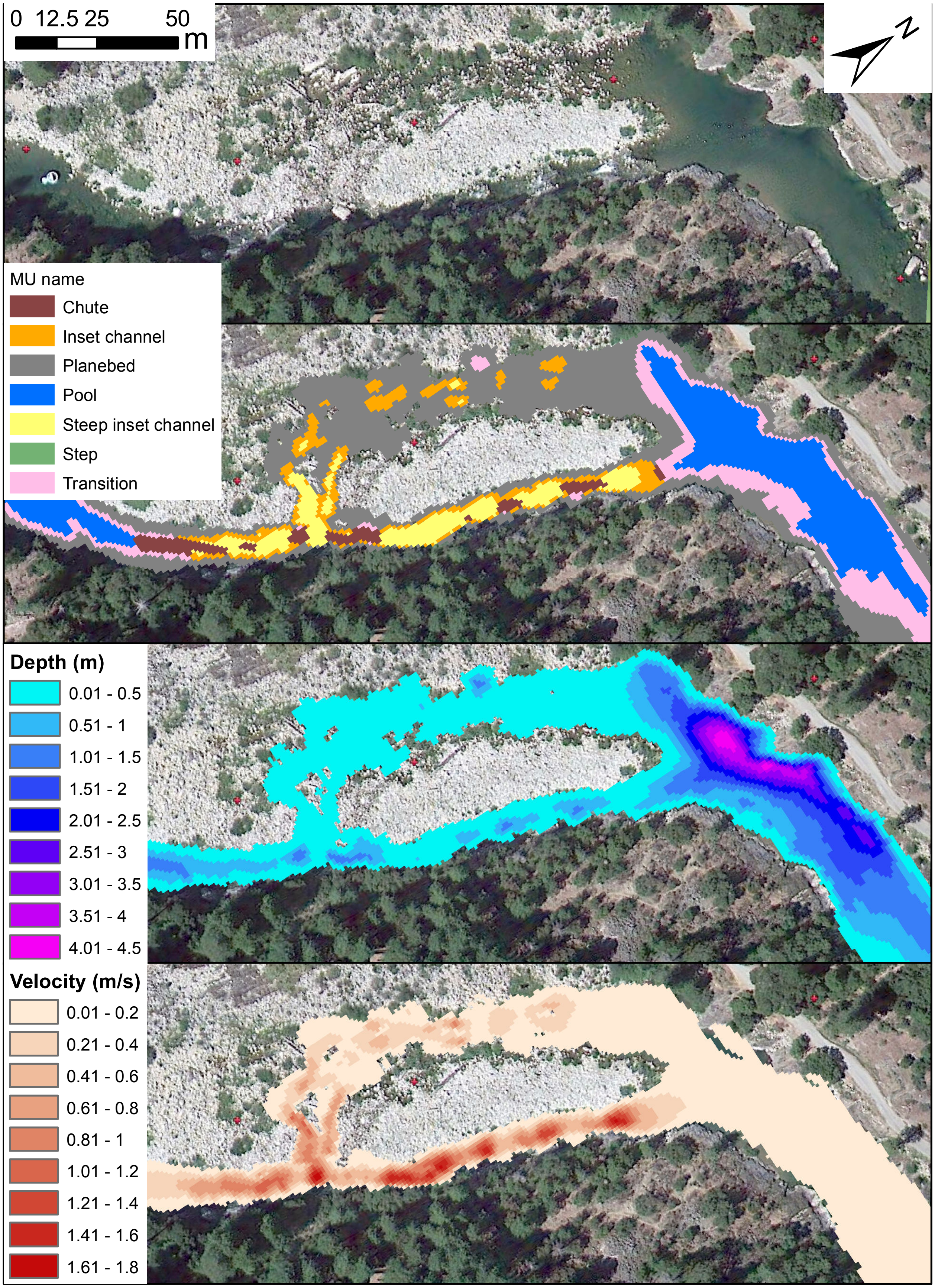
Fig. 3. Example MU delineation procedure for a lowland gravel–cobble river (Wyrick and Pasternack, 2012).

Fig. 4. Example MU delineation procedure for an upland cobble–boulder river (Pasternack and Senter, 2011).


DEM
rating curve
roughness map
2D model
low flow selection
depth raster
velocity raster
local knowledge
expert judgment
hydraulic classification
MU map
expert review
iteration required?
yes
no
final MU map


Pool
Slackwater
Slow glide
Fast glide
Riffle transition
Run
Chute
Riffle
1.4
0.7
Depth (m)
0.3
0.6
0.9
Velocity (m/s)
(A)
Pool
Not present at base flow
Transition
Chute
Plane bed
Inset channel
Steep inset channel
1.23
0.66
Depth (m)
0.3
0.6
Velocity (m/s)
(B)


oblique photo
Morphological units
chute
fast glide
pool
riffle
riffle transition
run
slackwater
slow glide
N
Depth (m)
High : 4.65
Low : 0
0
125
250
500
m
Velocity (m/s)
High : 3.16
Low : 0
flow


0 12.5 25 50
m
N
MU name
Chute
Inset channel
Planebed
Pool
Steep inset channel
Step
Transition
Depth (m)
0.01 - 0.5
0.51 - 1
1.01 - 1.5
1.51 - 2
2.01 - 2.5
2.51 - 3
3.01 - 3.5
3.51 - 4
4.01 - 4.5
Velocity (m/s)
0.01 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1
1.01 - 1.2
1.21 - 1.4
1.41 - 1.6
1.61 - 1.8