**Title**
Hierarchically nested river landform sequences. Part 1: Theory



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Title: Hierarchically nested river landform sequences. Part 1: Theory

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**Abstract**

Past river classifications use incommensurate typologies at each spatial scale and do not capture the pivotal role of topographic variability at each scale in driving the morphodynamics responsible for evolving hierarchically nested fluvial landforms. This study developed a new way to create geomorphic classifications using metrics diagnostic of individual processes the same way at every spatial scale and spanning a wide range of scales.  We tested the approach on flow convergence routing, a geomorphically and ecologically important process with different morphodynamic states of erosion, routing, and deposition depending on the structure of nondimensional topographic variability. Five nondimensional landform types with unique functionality represent this process at any flow; they are nozzle, wide bar, normal channel, constricted pool, and oversized. These landforms are then nested within themselves by considering their longitudinal sequencing at key flows representing geomorphically important stages. A data analysis framework was developed to answer questions about the stage-dependent spatial structure of topographic variability. Nesting permutations constrain and reveal how flow convergence routing morphodynamics functions in any river the framework is applied to. The methodology may also be used with other physical and biological datasets to evaluate the extent to which the patterning in that data is influenced by flow convergence routing.

**Introduction**

River classification background

Geomorphic river classification serves a variety of purposes (Frissell, 1986; Brierley and Fryirs, 2000; Faustini, 2012) and has a rich history reflecting different perspectives on what aspects all rivers have in common and what differentiates them (Shen *et al.*, 1981; Rosgen 1994; Kasprak *et al.*, 2016). Many classifications are predicated on the theory that geomorphic processes (i.e., dynamic mechanisms of topographic/lithologic change and stability) create a characteristic assemblage of landforms (Davis, 1909; Thornbury, 1954). The literature on fluvial processes cites many different geophysical and chemical mechanisms governing morphodynamics (Johnsson and Meade, 1990; Hancock *et al.*, 1998; Alonso *et al.*, 2002; Yumoto *et al.*, 2006; Kleinhans, 2010). Wyrick and Pasternack (2015) mapped 19 different geomorphic processes occurring on a single 37-km segment of a gravel/cobble bed river.

Unfortunately, the process-morphology linkage may be confounded by equifinality (Thornbury, 1954). For example, a pool may be formed by a heterogeneous flow regime (De Almeida and Rodríguez, 2012) via a diversity of mechanisms, such as turbulence-induced local scour associated with a forcing element (Thompson, 2006), phase shifts in the location of peak shear stress associated with one-dimensional sediment transport (Wilkinson *et al.*, 2004), flow-convergence routing driven by locally varying cross-sectional areas (MacWilliams *et al.*, 2006), helical hydraulics driving lateral migration (Thompson, 1986), differential scour and deposition driven by differences in sediment size distributions along a channel (De Almeida and Rodríguez, 2011), particle queuing and selective sediment sorting (Naden and Brayshaw, 1987), and changes in the relative balance of sediment supply to sediment transport capacity at the reach scale (Montgomery and Buffington, 1997). As a result, inference of a river's process sets by description of river morphology (and heuristic correspondence to associated processes at any scale) is a challenging, open inverse problem yet commonly done (e.g., Frissell et a., 1986; Rosgen, 1994; Brierley and Fryirs, 2000). Meanwhile, several reach-scale river classification methods segregate by the magnitude of simple erosion potential metrics (e.g., reach-scale shear stress or stream power functions), usually computed from contributing catchment area, local slope, and fitted parameters (e.g., Flores *et al.*, 2006; Schmitt *et al.*, 2007). However, these are based on physics assumptions readily violated in many rivers, even at the reach scale. In addition, erosion potential metrics are incapable of accounting for and differentiating multiple processes occurring at the same time and in close proximity. These considerations motivated a new approach for process-linked geomorphic classification that is independent of spatial scale and thus may be hierarchically nested within itself.

## Classifying with a process indicator

Scientific and practical applications using river classification need more detailed and more accurate representation of physical processes and how they shape landform patterns. Earth's surface physical processes are driven by climatic and tectonic force regimes, such as those associated with air, water, and sediment flux. Different magnitudes of the driving force regime can affect a process differently. Processes are also highly sensitive to the boundary conditions of the local setting.

In this study, we propose a conceptually new framework for process-based geomorphic classification (not only for rivers) that involves four steps: (i) conceptualize the suite of Earth surface physical processes governing a study domain at multiple scales, (ii) identify a metric capable of representing the status of each process at any location that is scale-independent for use across all magnitudes of the driving force regime, (iii) create a spatially continuous analysis and classification of process metrics for each mechanism at each important magnitude of the driving force regime (e.g., calm, normal, and aggressive conditions), and (iv) nest results from different levels of forcing to reveal the hierarchical structure of the mechanistic assemblage. Applying this generic conceptual framework to rivers involves considering a hydrological force regime.

Study purpose

The overall study goal involved developing and demonstrating the new classification approach theorized above by performing a continuous, multi-stage analysis of one corroborated, explicit morphodynamic mechanism- flow convergence routing. The classification can be applied to any river, whether alluvial or bedrock, to help interpret the role of this morphodynamic mechanism. Given the breadth of this study to explain new theoretical developments, test the key, underlying hypothesis against observational data, and present new scientific findings using real river data, the work is divided across two articles. This article presents the new landform classification theory and the landform analysis concepts to be applied to classification results. Across the two articles this study reveals new basic insights into process-morphology linkages in rivers and demonstrates how linkages can be used in river classification in the 21st century given the emergence of meter-scale digital elevation models of river networks. Now that this has been done for one physical process, it can be replicated for multiple processes, eventually leading to a merged classification accounting for all the processes in a river, followed by a comparison among diverse rivers.

## Flow Convergence Routing Landform Classification

Detrended bed elevation (a surrogate for depth) has been used to classify rivers using the zero-crossing method (Church, 1972; Milne, 1982; Carling and Orr, 2000), which yields two landforms– crest and trough. The problem with this for understanding geomorphic mechanisms like flow convergence routing is that they are driven by channel nonuniformity occuring as much or more in width than depth. The new classification has four archetypes representing the endmember combinations of linked oscillations in width and detrended bed elevation (Figure 1), with a fifth type (not shown) involving a channel of average dimensions. Because the classes depend on derived variables in a morphodynamic theoretical framework, it is helpful to understand the scientific literature underpinning this system as well as the data and workflow for obtaining the variables used to make the classification.

## Flow convergence routing review

Typical erosion and deposition analysis of rivers focuses on the central tendency of a river (i.e., bankfull width, bankfull depth, and reach-average slope) on the assumption that the river is uniform and subjected to nearly steady flow, resulting in gradual spatial and temporal trends in elevation (e.g., Gasparini *et al.*, 2004; Ferguson, 2005). However, studies reporting natural channel and floodplain morphodynamics rarely describe such incision and/or deposition periods consistent with the simple math of central tendency of fluvial form (Kleinhans, 2010). In contrast, fluvial physical processes typically exhibit abrupt and complex spatial and/or temporal variabilities (Ashworth and Ferguson, 1986; Jerolmack, 2011; Wyrick and Pasternack, 2015). Meander migration, knickpoint migration, braiding, pool-riffle formation and maintenance, gullying, channel cut-offs, etc. involve deviations from central tendency, not specific values of central tendency. In other words, having uniformly more or less erosive potential in a reach is not the defining aspect of fluvial morphodynamics. Therefore, an essential step in producing a mechanistic river classification must address spatial variability.

One important morphodynamic mechanism entirely founded on topographic deviation from central tendency is called flow convergence routing (MacWilliams *et al.*, 2006), where flow convergence relates to the hydraulic aspect of the mechanism and routing relates to its sediment dynamics. In its most general conceptualization, this mechanism involves longitudinally varying spatial funneling of flow (i.e., “flow convergence”) by the nonuniform topography that is inundated by the river, with the locations of most concentrated flow (i.e., geometric constrictions or nozzles) at any discharge having the greatest potential to scour and route sediment through them (Carling and Wood, 1994; Booker *et al.*, 2001; MacWilliams *et al.*, 2006; Caamaño *et al.*, 2009). In contrast, the locations of least concentrated flow at any discharge have flow divergence and the highest likelihood of sediment deposition at that flow. Secondarily, rivers can have abrupt expansion zones downstream of a nozzle that can sustain sediment routing and enhanced erosion caused by high turbulence intensity (Clifford, 1993; Thompson *et al.*, 1996; Thompson, 2006). When a longitudinal pattern of strongly convergent and divergent flow is present at any discharge, then there will be spatially differentiated erosion, routing, and deposition governed by the topographic structure, and this pattern will vary with discharge as controlled by the topographic regime. Finally, a naturally varying hydrograph will serve as the driving force regime to produce a morphodynamic time sequence of patterns of erosion, routing, and deposition. As a result, flow convergence routing is a complete hydraulic and morphodynamic mechanism that functions in space and time. Because it is extremely difficult to observe and record spatial patterns of fluvial morphodynamics as they occur in a river, flow convergence routing is most commonly detected by looking for its hydraulic and topographic indicators, but the mechanism itself is a morphodynamic one, not just a hydraulic pattern.

Because the structure of nonuniform local topography changes with discharge in many settings (Brown and Pasternack, 2014, 2017), the pattern of flow funneling is stage-dependent; therefore, the locations of scour and deposition shift with discharge. Studies that only investigated base flow to bankfull discharge focused on the notion of a two-stage “reversal” in the epicenter of scour, from riffles at low flow to pools at bankfull flow (e.g., Cao *et al.*, 2003; Jackson *et al.*, 2015). Some have now considered moderate to large floods that showed a diversity of flow funneling behaviors as a function of discharge (Sawyer *et al.*, 2010; Strom *et al.*, 2016). Further, Brown and Pasternack (2014, 2017) looked at the role of flow-dependent variability over a wide range of base to flood flows in modulating channel change locally and detecting coherent patterns of bed and width oscillations, respectively. Thus, to understand how morphodynamics driven by flow convergence routing is governed by the combination of input flow regime and topography, it is necessary to ascertain the nested structure of topographical deviations from central tendency. This new research asks if patterns of topographic variability can be classified based on a geomorphic process interpretation, and if so, what that reveals about nested topographic patterning.

Flow convergence routing is but one of many fluvial processes. It has known ecological importance (Wheaton *et al.*, 2010) that should be assessed in a mechanistic framework. Other processes involving secondary flow hydraulics, pool bypassing over point bars, bed material heterogeneity, fluctuations in turbulent intensity, sediment supply regimes, etc. could also be important to characterize. They may also interact with flow convergence routing.

This study focused on how morphodynamics (as interpreted using velocity as an indicator of flow convergence routing) are driven by nonuniform topographic structure, but morphodynamics in turn change topographic structure as well. Therefore, there is some duality in analysis.  On one hand, the present structure provides insights into what must have happened to get to the current state, and on the other hand, it indicates what comes next. For example, a geological nozzle (Kieffer, 1989) could either exist because it is composed of a highly resistant lithology that cannot erode or from a pause in transient morphodynamics of equally erodible material that left that spot constricted. Either way, flow convergence routing dictates that it will be the epicenter of erosive potential during the next nozzle activation event. Whether one wants to understand the past, the future, or just transient morphodynamics in and of itself, an analysis of topographic structure deviating from central tendency as related to flow convergence routing ought to be meaningful, and that is what this study aims to evaluate.

Data processing workflow

A standardized, universal workflow yields the variables for the new classification (Figure 2). The entire workflow is achievable with a single data input– a high-resolution (~ 1-m) digital elevation model (DEM) of a river valley (Gore and Pasternack, 2016), making this methodology readily accessible. However, improved results are achieved given geomorphic reach breaks obtained from expert evaluation and water surface area polygons for selected discharges obtained from two-dimensional (2D) hydrodynamic modeling. Velocity results from 2D modeling can confirm the velocity hypotheses built into flow convergence routing classification for confidence in the mechanistic interpretation.

Workflow steps are conceptually straightforward, but require many minor decisions depending on data nuances for any given river. The overall strategy involves extracting longitudinal series of bed elevation and top width, and then analyzing their joint geometric structure (Brown and Pasternack, 2014, 2017). This section presents the recommended approach for each step, but also discusses uncertain complexities involved in geometric analysis of river corridors.

Traditionally, geomorphic longitudinal analysis follows the thalweg and analyzes thalweg bed elevation, but in this workflow the bisecting centerline of the water surface area is superior for two reasons. First, because some channels can be highly sinuous and/or thalweg sinuosity may not align with bank sinuosity, cross sections stationed along the thalweg can overlap or even double back into the channel upstream or downstream. Second, thalweg depth is the maximum possible water depth for a cross section (Figure 3), and thus it significantly overestimates cross-sectional area. Given a complete river corridor DEM, one can directly calculate cross-sectionally averaged depth, and this is the correct variable to compute a cross-sectional area. The convention of using top width is retained in this workflow.

Although many geomorphologists seek DEM-only analysis methods (Drăguţ and Eisank, 2011; Wheaton *et al.*, 2015), a lack of hydraulic information complicates mapping inundated area to extract top width longitudinal series. It is possible to slope detrend a DEM and take horizontal water surface slices through and above the detrended terrain (e.g., Jones, 2006; Greco *et al.*, 2008), thereby transforming ground elevation into a measure of water depth for each slice, which then enables a determination of stage-dependent width. However, the corresponding discharge of each slice is uncertain.

Many methods of slope detrending exist, but there are significant problems with all detrending methods– a topic that is beyond the scope of this study. It is accessible to use the slicing approach with any preferred slope-detrending method. Performing coarse-resolution hydraulic simulations is easy, fast, and more accurate than slope detrending. From one perspective, modeling is a methodology for slope detrending, just one based on the laws of physics rather than unconstrained geometric modeling. High-resolution 2D hydrodynamic modeling provides the most detailed water surface area polygons.

The framework developed in this study assesses the relative cross-sectional area along the flow path. Given the bisecting centerline of the water surface area at each flow, the stationing interval is user-selectable, informed by DEM resolution and channel size. We recommend a spacing of ~ 3-5% of bankfull width. Mean bed elevation is computed in a rectangle centered on each centerline station and clipped by the water surface area boundary for each flow (See Figure 4 of Wyrick and Pasternack (2014) for a map illustration of such rectangles). This value was assigned to the centerline station point in the rectangle. The longitudinal profile of mean bed elevation is detrended on a piecewise linear basis, with each geomorphic reach detrended independently. The slope trend equation for each reach is determined using linear regression. Next, the mean and standard deviation of detrended bed elevation is computed for the entire river segment. These values are used to standardize the variable by subtracting the mean and dividing by the standard deviation. The resulting series of detrended, standardized, cross-sectionally averaged bed elevation (Zs) is a nondimensional surrogate for average water depth useful for comparing relative magnitude along the profile; however, bed elevation has the opposite interpretation as depth (i.e., high Zs equals low depth, Figure 1).

Width at each centerline station is computed as the water surface area of the clipped rectangle for that station divided by the user-selected length of the rectangle. This method is superior to cross-section line width for flow convergence routing assessment, because it averages along a length to give a more representative value. Mean and standard deviation of width are computed for the entire river segment. These values are used to standardize the variable by subtracting the mean and dividing by the standard deviation. The resulting series of standardized width (Ws) is a nondimensional hydraulic variable useful for comparing relative magnitude along the profile.

Width is explicitly a hydraulic variable, so it does not necessarily require detrending the way bed elevation does to understand its influence on flow convergence routing. If discharge is constant along a study reach, then any systematic change in width along the reach influences the morphodynamic mechanism and should be used in the classification. If major tributaries bring additional water into a reach, then it may be necessary to evaluate whether detrending to remove that hydrological effect would be warranted prior to classification.

Classification decision tree

A consideration of the signs and magnitudes of Ws and Zs reveal a simple 5-unit classification of geometry (Figures 1-2). Four geometric possibilities depend primarily on the combination of signs of Ws and Zs (Brown and Pasternack, 2017). The fifth landform type recognizes that there must be a baseline, normal configuration indicated by Ws and Zs value close to zero. A decision tree was developed to classify each centerline station at each flow using two-character identification codes (Figure 2).

The question is how strongly must geometry deviate from the average to be considered significant enough to denote a new landform type as a starting point before many data sets can be analyzed for possible threshold criteria? We have piloted this methodology using three river datasets, one from a gravel/cobble river (see Pasternack et al., 2018) and two from mountain bedrock-boulder rivers (Gore and Pasternack, 2016). Using those datasets, sensitivity analysis was done to answer this, but these details are too lengthy to cover herein. Conceptually, the more that Ws·Zs threshold values deviate from zero, the more uniform a river will seem. Depending on the application, a geomorphologist may wish to choose lower or higher threshold values at their discretion. The Ws·Zs threshold values we recommend and used in Pasternack et al. (2018) were -0.5 and 0.5, yielding a wide range in Ws·Zs for the baseline, "normal channel" landform type. These numbers are conservative, equidistance thresholds in the sense of assuming much more of the river is normal, not only because of the wide range of Ws·Zs values, but also because it does not constrain the individual Ws and Zs values. For example, using the base flow gravel/cobble bed lower Yuba River data from Pasternack et al. (2018) as an example, ~ 60% of stations with $-0.5 < Ws \cdot Zs < 0.5$ had individual Ws and Zs values also meeting that same criterion.

Note that it is possible to conceive of many alternate ways to set flow convergence routing landform classification criteria. A similar but more exacting and specific system requires both variables to individually exceed a threshold (Figure 4a). A more comprehensive system adds in four more classes to account for when one variable strongly deviates but the other does not (Figure 4b). The mechanistic validity of the approach selected for this study was tested in Pasternack et al. (2018). Using the product Ws·Zs and the thresholds of -0.5 and 0.5, flow convergence routing was confirmed, so this worked. Whether the proposed alternative classifications would work better has not yet been tested.

**Landform Analysis Concepts**

The classification described in the previous section is not an end unto itself, but a means for evaluating the patterning of a river’s topography with respect to flow convergence routing. Many methods analyze the longitudinal sequencing of landforms (e.g., Richards, 1976; Grant et al. 1990). Wyrick and Pasternack (2014) introduced an object-oriented framework for two-dimensional spatial analysis of landforms addressing abundance, diversity, adjacency, lateral variability, and longitudinal distribution and spacing. Legleiter (2014) introduced a geostatistical framework for analyzing river DEMs and began the effort of linking resultant new metrics to morphological features. Brown and Pasternack (2017) applied spectral and statistical methods to analyze high-resolution width and detrended bed elevation series. Past methods can be used directly or adapted for analysis of the spatial structure of flow convergence routing landforms. The key nuance is that these landforms are explicitly indicative of a morphodynamic mechanism, so there is a unique potential for analysis to explain how flow and topography interact to produce these landforms and drive future morphodynamics.

There are three broad categories of data analysis envisioned to understand the results of the classification with no other data inputs. A fourth category of analysis involves testing for the underlying hydraulic mechanism involved in flow convergence routing using velocity data. Once the topographic structure of the river is understood with these analyses, then the classification objects may be used with other datasets the evaluate the nexus between flow convergence routing and patterns in the other data.

Analysis of Ws, Zs, and Ws·Zs series

The first step of landform analysis involves steps similar to those of Brown and Pasternack (2017), which is to first understand the stage-dependent structure of fluvial topographic deviation from central tendency using the Ws and Zs series. As a community, we do not know the scope and organization of global Ws and Zs variability. The degree to which Ws and Zs deviate from their central tendencies can be quantified by simple tabulation of the percent of Zs and Ws values more than one-half, one, or more standard deviations away from the mean, depending on the application. Besides knowing the frequency of variability, it is also important to ascertain its randomness. The non-parametric test for the number of runs of Zs or Ws values above and below the median determines whether a series is random or not (Wald and Wolfowitz, 1940). To see if Ws and Zs are linked as implied by the flow convergence routing mechanism, Pearson’s product-moment correlation analysis can be used to compare the two series, and this should be done by reach and for each flow. Finally, for flow convergence routing to be important at a given spatial scale for a reach as a whole, the mean and median of the product Ws·Zs should be above zero (Brown and Pasternack, 2017). Analysis of the Ws·Zs series reveals where this is occurring or not, and this varies by discharge. For example, in a boulder-dominated mountain river one would expect the median of Ws·Zs to be negative from base flow to possibly quite a high flood flow. Eventually, when the flow is reached that is powerful enough to re-organize the boulder framework, then the median of Ws·Zs would be positive, and this switch would be diagnostic of the onset of the flood flow range that is morphodynamically significance.

## Analysis of landform abundance and sequencing

Analysis of landforms abundance and sequencing evaluates the presence of organizational tendencies and their implications for morphodynamics. For flow convergence routing to be a dominant morphodynamic process controlling the landform patterning in a river, there must be a range of discharges for which wide bar and constricted pool are more abundant than oversized and nozzle. Further, the sequencing of landforms should alternate between wide bar and constricted pool, which would necessitate some length of normal channel in between to make the transition.

Abundance of each landform class is determined by counting the number of stations of each landform type and computing relative percent. Some landforms are thought to co-occur, but this is rarely tested (e.g., Grant *et al.*, 1990; Wyrick and Pasternack, 2014). In the analysis framework for this study, the number of times that each unit type follows each other can be computed. This test should be performed first using all landform types, but then a second time without normal channel. This second step is necessary because it is mathematically impossible to transition directly from a landform type with -Ws·Zs to one with +Ws·Zs without going through Ws·Zs=0. It may be that the length of the normal channel units is small in these transitions, so excluding them provides a way to quantify the tendencies for how the other units are sequenced. These abundance and sequencing analyses should be performed for a whole river corridor and individual reaches, and that is repeated for each flow investigated.

Analyses of hierarchical landform nesting

The most novel and important analyses developed in this study reveal and assess nested landforms structure. Bankfull flow is widely thought responsible for shaping channel landforms. However, this implies specific landform nesting permutations. For example, under conventional theory, a bankfull nozzle should promote scour of the things inside of it. If a depositional wide bar was nested in a bankfull nozzle, then that would contradict the classic expectation. If the inset bed material was substantially finer, then it would indicate a role for lower flows depositing potentially ephemeral inset landforms (e.g., benches) likely on a rapidly falling limb of a flood. On the other hand, if bed material is the same for bankfull and nested smaller landforms, then it would strongly suggest that bankfull and baseflow nested landforms were emplaced at the same time as a result of a significantly larger flow.

A decision has to be made how many discharges to use for nesting analysis. Although landforms sequences could be analyzed in each of many flows across the discharge continuum, it is likely that there would be a lot of insignificant correlation in such an incremental approach. Therefore, the valley-scale patterning of the river corridor can inform the meaningful flows to analyze. For a simple channel-floodplain pairing in a wide valley floor with low slope and fine sediment, two discharges may be sufficient- baseflow and bankfull flow. If there exists a macrochannel tiered structure (e.g., Croke *et al.,* 2014), then one discharge per terrace level would be sensible. Given five nested terraces combining to steer morphodynamics, there would be 3125 permutations of nested landforms- a scope of river classification never before considered, and this is for just one fluvial mechanism. Of course, many theoretical permutations may prove nonexistent in nature– in Pasternack et al. (2018) 1/3 were nonexistent. Still, a very simple mechanistic conceptualization can produce an extraordinarily complex and complete understanding of how a single process is functioning across scales.

Most commonly, three discharges are likely to be most useful, consisting of baseflow, bankfull flow, and a representative flood flow constrained by proximal valley hillsides. One sensible choice would be the flow filling the floodprone area (Rosgen (1994). Given five landform types and three nested scales, there are 125 possible landform permutations- again, several of these may be nonexistent.

The recommended workflow for analysis of landform nesting once the number of flows is decided involves joining the landform ID series for all flows to a common centerline and analyzing the structure hierarchical permutations. Because the length of a sinuous river centerline often decreases with discharge, the centerline stationing of the lowest flow is the best choice for this analysis (Brown and Pasternack, 2017). The primary analysis of nested data involves counting the frequency of each permutation to ascertain the top 3-5 most frequently occurring nesting permutations. Beyond just overall permutations across all three scales and five landform types, it is informative to consider the top permutations by landform, because this extra analysis is independent of the relative abundance of landforms. This extra analysis can be done by starting with a given flood discharge landform type and seeing what is nested within that. The same can be done for looking at bankfull landforms and seeing both what these are nested within at a higher flow and what is nested within them at a lower flow. Results can be compared to those expected in an ideal scenario with flow convergence routing.

Validating the hydraulic mechanism

The classification presented herein is predicated on the past literature showing that wide, shallow riffles and deep, narrow pools exhibit specific stage-dependent differences in velocity (V) associated with flow convergence routing (Sawyer *et al.*, 2010; Strom *et al.*, 2016). Even if highly conservative criteria delineate normal channel geometry, it is always wise to test whether the fundamental hydraulic hypothesis underlying the mechanism of flow convergence routing holds with this classification that assumes it does. There are three reasons why the classification might not yield the anticipated hydrogeomorphic mechanism. First, the magnitude of width and depth constriction or expansion might not be extreme enough to trigger a significant enough deviation in velocity to cause flow convergence routing. If that was the case, then the decision tree classification could be revised and the outcome re-tested. Second, there might be strong enough geometric deviations, but the resulting 2D velocity field could exhibit a much different effective flow width (i.e., the fraction of width carrying the majority of flow as in Harrison and Keller, 2007), yielding a different mechanism than if the entire cross section was active. For example, an oversized landform would be expected to have low velocity, but if the effective flow width was 1/10 of the full width, then it would have a much higher peak velocity than average velocity. Third, it is possible that the differentiation in velocity between landforms is not due to differences in cross-sectional area, but differences in bed roughness and/or slope. Therefore, testing with 2D velocity rasters can reveal if the classification is actually capturing flow convergence routing or not.

To do a velocity validation analysis of the classification, 2D numerical modeling (Pasternack, 2011) is needed, because the mechanistic deviations from expectation cannot be adequately revealed by analytical, empirical, or one-dimensional numerical velocity estimation methods. Given a 2D model, velocity rasters for discharges ranging from baseflow to as high of a flood flow as possible should be obtained. These rasters are then stratified by landform type. Finally, the landform-averaged velocity and 95$^{th}$ percentile of velocity of raster cells in that landform are computed (e.g, Strom *et al.*, 2016).

For this classification to adhere to theory, oversized should have a low velocity, nozzle should have a high velocity, and normal channel should have an intermediate velocity between those two. These relative magnitudes should hold across all discharges. Meanwhile, constricted pool and wide bar should have flow-dependent relative velocities, with the former having a higher velocity than both normal channel and wide bar during floods. How wide bar versus oversized velocity might compare as well as how constricted pool versus nozzle velocity, is an open question investigated in Pasternack et al. (2018), given the possibility of a narrower effective flow width in one or more landform types.

## Discussion

Geomorphologists have long believed that rivers have a diversity of organized landforms, yet still many quantitative analyses of process-morphology linkages assume uniform flow. While rivers in general exhibit a central tendency of increasing erosive potential with discharge, evidence from several individual sites firmly establishes that rivers do not have to work that way, because hierarchical scales of longitudinally organized topographic complexity yield a different mechanism than widely assumed based on the uniform flow assumption used throughout geomorphology. The overwhelming evidence of nonuniform flow creates an imperative to the progression of the discipline that geomorphologists abandon the math of uniform flow for everything from river classification and assessment to landscape evolution modeling in favor of methods that account for topographic variability as well as the resulting spatial hydraulic variability. In addition to multidimensional numerical modeling tools, this study offers a topographical analysis workflow that allows practitioners to classify and analyze fluvial topographic complexity to interpret a river corridor's potential for one important mechanism, flow convergence routing.

This study is not about trying to find simple approaches that end the rise of 2D modeling as a powerful tool for river science and engineering, but instead to provide practitioners with the right tool at the right stage of activity. Studies using meter-scale 2D modeling over tens of kilometers of rivers are well established and showing tremendous capability to reveal spatially explicit hydraulics and associated processes (Pasternack, 2011). Soon scalable, parallel-processing algorithms (e.g., TUFLOW GPU and JFLOW) will run meter-scale 2D simulations of entire dendritic river networks, with results handed off to algorithms that will reveal hydrogeomorphic processes and ecological functions. That future is very bright. Yet what is also apparent is that humans still need simplified representations and abstractions to make sense of ever growing, vast informatics datasets. Whether it is in lieu of cutting edge numerical modeling or to synthesize modeling results, the procedures in this study quickly yield useful results that practitioners can employ to assess how functional rivers are and to aid the design of more functional river corridors.

Applications with other datasets

Beyond using the concepts and methods presented here to better understand hierarchically nested river landforms, there is significant utility in using maps of these landform polygons to assess whether a variety of hydraulic, sedimentary, geomorphic, and ecological processes have a nexus with flow convergence routing. An obvious application to further understand morphodynamics would be the analysis of DEM difference rasters by hierarchically nested river landforms. There are specific hypotheses as to what DEM differences should be necessary to create individuals of each landform type as well as what DEM differences should be driven next given a particular nesting and sequencing of these landforms. Another issue that has been neglected in the development of this method is the important role of variations in grain size for morphodynamics (Bayat *et al.*, 2017). Given bed material facies data, one could evaluate the relative roles of topographic versus substrate variability. Beyond geomorphology, one could look at emerging ecogemorphic topics, such as large wood storage patterns in a river network relative to patterns of topographic variability. One can also look at the abundance and distribution of organisms by landform type.

For any geospatial dataset, one may run simple tests to determine if the data is present in any of the landforms more than would be expected by random chance given the abundance of each landform found in a particular river. For example, if the relative area of wide bar to nozzle was ten to one, but the abundance of an organism in those was two to one, respectively, then that would show a significant preference for nozzle, even though more are found in wide bar, because the relative abundance of nozzle is so much less. It shows that the organism is packing much more densely into nozzle.

This concept of analyzing abundance data on an area-free basis is widespread in science. In geomorphology, Grant *et al.* (1990) and Wyrick and Pasternack (2014) used this concept to compare landform abundances relative to random uniform distributions. Strom *et al.*, (2016) used the idea to analyze the abundance of patches of peak velocity among landforms on an area-free basis.

In ecology, the concept is widely used, and one of the dominant area-free metrics is called the forage ratio that indicates an organism's preference or avoidance for a certain type of prey (Savage, 1931; Ivlev, 1961). Today, the forage ratio and other similar indices are used to compare all kinds of data against other kinds of data. For example, one can look at the abundance of an organism or an indicator of an ecological process relative to the abundance of microhabitats of different quality or wholesale fluvial landforms (Pasternack *et al.*, 2014). Kammel *et al.* (2016) developed and applied a statistical bootstrapping method that quantifies the statistical significance of ratios of data abundances relative to the areas of each classifying object.

**Conclusions**

This study developed new theory and methods that show how the same scale-independent landform types may be mapped at many scales and nested to obtain a hierarchical framework. Past morphological unit classification methods either have diverse morphologies yet are fundamentally descriptive or have supposedly process-based metric thresholds yet only account for the central tendency of river form that actually has little to do with the direct mechanisms that cause fluvial landform patterning in rivers. This study is the first fluvial classification whose landforms are explicitly governed by a morphodynamic mechanism.  At the highest level, this study shows that it is feasible to take an individual geomorphic process, conceptualize how it operates relative to hierarchical topographic complexity, produce a metric for it, and then map the spatial pattern of where it does the different functions it performs over a wide range of flows. Although there are many minor nuances in the methods to be debated and refined as the approach is tested in different settings, the underlying concept stands up to validation against more sophisticated 2D hydrodynamic modeling. It is highly feasible for geomorphologists to move beyond the simple erosion potential metric that assumes steady uniform flow and repeat this effort for a diversity of actual hydrogeomorphic mechanism in rivers, which largely require spatio-temporal complexity, not simplicity.

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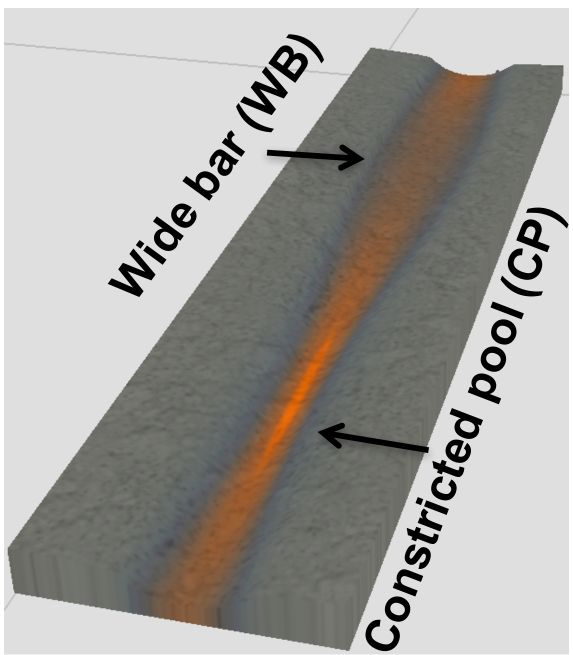
Figure Captions

Figure 1. Flow convergence routing landform classification used in this study.

Figure 2. Data processing workflow to obtain all topographic variables used in this study.

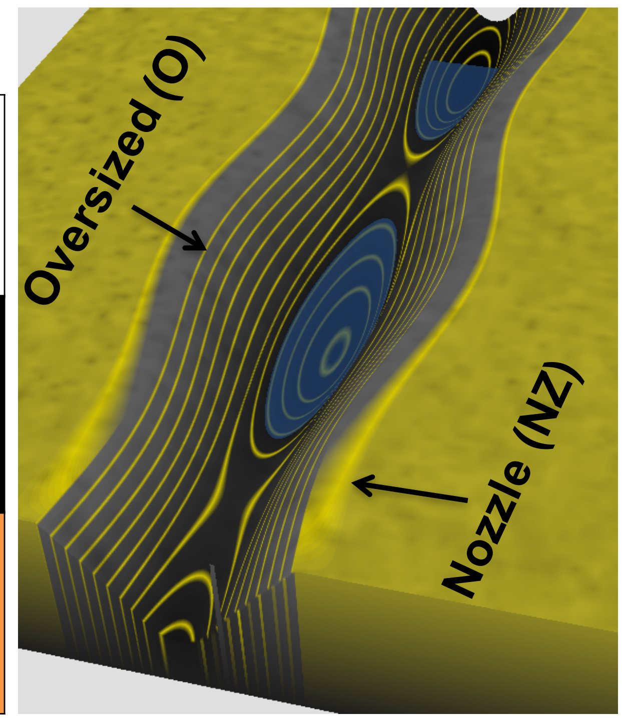
Figure 3. Cross-sectional area schematic. Grey denoted the actual wetted cross-section. The black box is the equivalent area as a rectangle given an observed top width. Using thalweg bed elevation (Zt) would overestimate cross-sectional area, while using the cross-section's average detrended bed elevation (Zs) would better estimate cross-sectional area.

Figure 4. Alternate, interesting flow convergence classifications not used in this study.

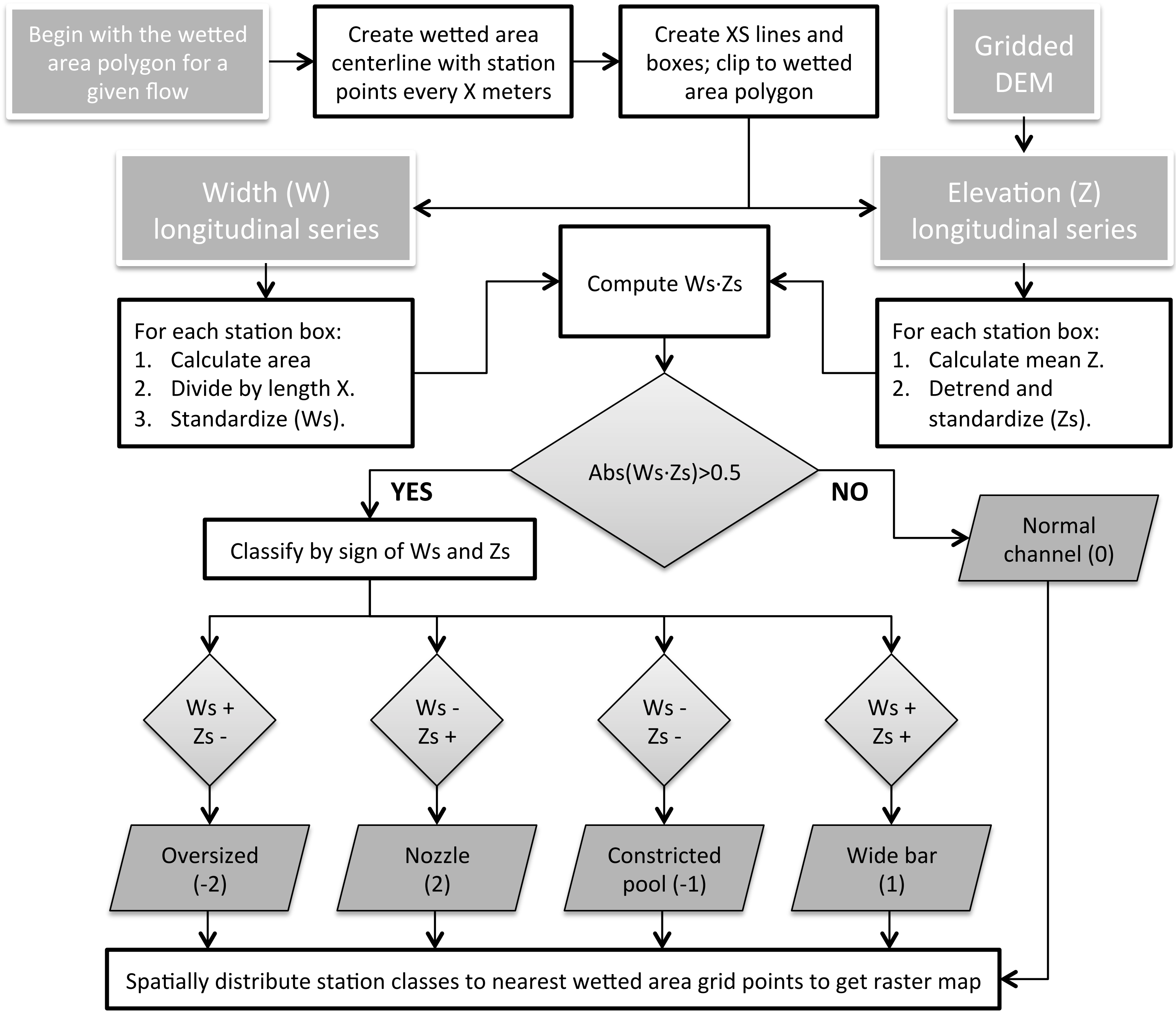


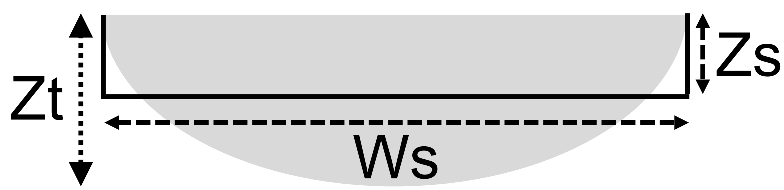

Flow Convergence Routing Landform Classification*

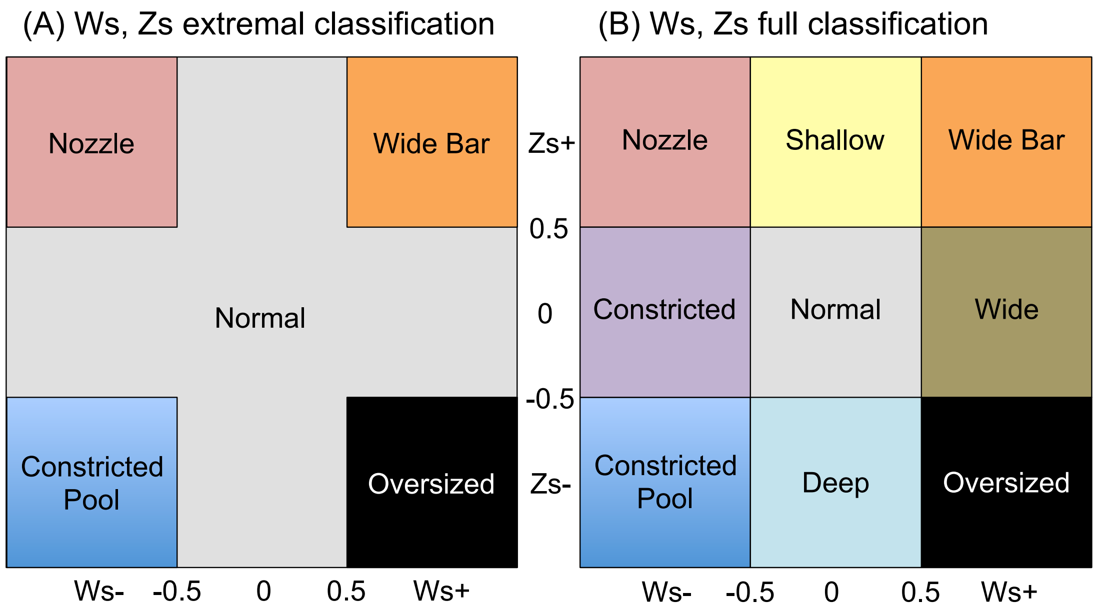
| | Low Ws<br>- | High Ws<br>+ |
|---|---|---|
| Low Zs<br>- | Constricted pool (CP)<br>-- → + | Oversized (O)<br>-+ → - |
| High Zs<br>+ | Nozzle (NZ)<br>+- → - | Wide bar (WB)<br>++ → + |




*Ws = standardized width; Zs = detrended, standardized bed elevation


Begin with the wetted area polygon for a given flow
Create wetted area centerline with station points every X meters
Create XS lines and boxes; clip to wetted area polygon
Gridded DEM
Width (W) longitudinal series
Elevation (Z) longitudinal series
Compute Ws·Zs
For each station box:
1. Calculate area
2. Divide by length X.
3. Standardize (Ws).
For each station box:
1. Calculate mean Z.
2. Detrend and standardize (Zs).
Abs(Ws·Zs)>0.5
YES
NO
Classify by sign of Ws and Zs
Normal channel (0)
Ws + Zs -
Ws - Zs +
Ws - Zs -
Ws + Zs +
Oversized (-2)
Nozzle (2)
Constricted pool (-1)
Wide bar (1)
Spatially distribute station classes to nearest wetted area grid points to get raster map


Zt
Zs
Ws


(A) Ws, Zs extremal classification
Nozzle
Wide Bar
Normal
Constricted Pool
Oversized
Ws-
-0.5
0
0.5
Ws+
Zs+
0.5
0
-0.5
Zs-
(B) Ws, Zs full classification
Nozzle
Shallow
Wide Bar
Constricted
Normal
Wide
Constricted Pool
Deep
Oversized
Ws-
-0.5
0
0.5
Ws+