The Blurred Line between Form and Process: a Comparison of Stream Classification Frameworks

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Supporting information S1 attached as .docx

ABSTRACT

Stream classification provides a means to understand the diversity and distribution of channels and floodplains that occur across a landscape while drawing linkages between geomorphic form and process. Accordingly, stream classification is frequently employed as a watershed planning, management, and restoration tool. At the same time, there has been intense debate and criticism of particular frameworks, on the grounds that these frameworks classify stream reaches based largely on their physical form, rather than direct measurements of the hydrogeomorphic processes operating therein. Despite this critical debate surrounding stream classifications, and their ongoing use in applied watershed management, direct comparisons of channel classification frameworks are rare. Here we apply four classification frameworks that contain a range of form- and process-based methods within a watershed of high conservation interest in the Columbia River Basin, U.S.A. We compare the results of the River Styles Framework, Natural Channel Classification, Rosgen Classification System, and a channel form-based statistical classification at 33 field-monitored sites. For stream network-based frameworks (Natural Channel Classification and River Styles) we compare classification outputs across the entire Middle Fork John Day Watershed. We found that the four frameworks consistently classified reach types into similar groups based on each reach or segment's dominant hydrogeomorphic elements. Where divergence in classified channel types occurred, differences can be attributed to the (a) spatial scale of input data used, (b) the requisite metrics and their order in completing a framework's decision tree and/or (c) whether the framework attempts to classify current or historic channel form. The relative agreement between frameworks indicates that criticism of classification based simply on whether a classification contains form-based measurements, devalues each

framework's relative merits. These form-based criticisms may also ignore the geomorphic tenet that channel form reflects formative hydrogeomorphic processes across a given landscape.

1. INTRODUCTION

The physical form of a stream channel is the result of the coupled climatic, biotic, and hydrogeomorphic processes acting upon it [1,2,3]. Accordingly, the classification of rivers into reach types based on their physical characteristics lends insight into the formative processes that shape rivers, and the range of river characteristics that occur across a landscape [3,4]. These insights can be leveraged when assessing river condition relative to pre-disturbance characteristics and/or prioritizing the management and restoration of degraded streams [5,6,7]. There are numerous frameworks for classifying streams, many of which have diverse spatial and temporal output scales (see [8,9,10]).Over the past two decades, there has been intense debate and criticism of the utility of particular frameworks [11,12,13,14,15] in the context of river management and restoration. These criticisms range from the spatiotemporal limitations of a given framework, to criticisms of the decisions that can arise when a framework is misapplied, to the fact that measurements of process rates (e.g. sediment flux, bank migration) are absent from most frameworks and process is often inferred from channel form. An unfortunate effect of these criticisms is that river classification frameworks, regardless of their utility have been overlooked, not for what they provide, but for perceptions of classification's past (mis)applications.

The discussion of individual stream classification frameworks has been subsumed in a broader conversation, often focused on stream restoration [14,16,17], that differentiates frameworks in terms of whether they are 'form-based' or 'process-based', criticizing the former as overly simplistic. Yet to condemn frameworks on the notion that they are 'only form-based' is to ignore a basic tenet of geomorphology, that *form implies process* [3]. That is, measurements of river form are direct reflections of the processes acting to shape that form [1,2,18,19]. Indeed, nearly all classification frameworks use metrics that describe the capacity of a channel to perform geomorphic work and adjust laterally within a valley bottom. For example, many classifications include channel gradient, measures of valley setting or entrenchment, and sediment characteristics; [9,20,21,22]. We argue that the separation of classification frameworks into 'form-based' and 'process-based' approaches strips the debate of each framework's relative merits [23]. This common simplification implies that the two approaches are at best, distinct, and at worst, mutually exclusive. In reality, the line between form and process is blurred as river form and hydrogeomorphic processes are directly related.

In a long history of disagreement between proponents and detractors of particular classification frameworks, and over the relative utility of form- versus process-based classification in general, it is of note that direct comparisons of frameworks are exceedingly rare [13,24,25,26]. This may be due to the inherent difficulty in comparing methodologies that produce results over vastly different spatial scales and which seek to describe past or present river condition. These methodologies also often require disparate types and amounts of input data, analysis time, and geomorphic expertise to complete. Nevertheless, the geomorphic community would benefit from a more clear understanding of the degree to which various river classifications, which differ in their inclusion of process or form, reach similar or disparate conclusions with regard to their output [3].

This paper applies four classification frameworks across a watershed of high conservation interest in the Pacific Northwest, USA. Each of these frameworks contains, to varying degrees, metrics that reflect the form of channels and floodplains, and/or the processes operating upon those channels and floodplains. Our goal is to perform one of the first direct comparisons of classification frameworks at the watershed scale, and in so doing, to elucidate the similarities and differences between classification outputs. Where frameworks differ, we attempt to ascertain the methodological differences that lead to divergence in classification. We further explore the complexity of each analysis, along with the requisite amount of time and degree of geomorphic expertise necessary for successful river classification using each framework. Herein we focus on the *River Styles Framework* (RSF; [9]), *Natural Channel Classification* (NCC) [27], and the popular *Rosgen Classification System* (RCS; [28,29]). We contrast these with an example of a flexible *statistical classification* approach that clusters field-measured, reach-scale data into channel form-based groups. Of the many classification frameworks that are available [3], this research aims to familiarize watershed scientists with four distinct approaches. These frameworks have been selected given their popularity in management and restoration, the fact that their outputs span a wide spatiotemporal range, and the varying degree to which they directly or indirectly account for processes operating in river systems (Table 1).

Table 1. Summaries of the four classification frameworks applied to wadeable streams of the Middle Fork John Day River: River Styles, Columbia Basin Natural Channel Classification, Rosgen Classification System, and statistical classification.

Classification Framework (abbreviation)	Description	Examples	Data requirements	Classified output	References
River Styles Framework (RS)	A hierarchical, multi-scale classification scheme for describing river character and behavior. River Styles can be used to understand river condition, recovery potential and prioritize management.	Use in river management practice across NSW, Australia [9,30,31] Correlates to downstream sediment storage and landscape connectivity [32,33,34,35,36] Ecological community composition varies as a function of River Styles [37,38]	Field, remote-sensing and other GIS data on geology, hydrology, and stream geomorphic setting to identify broad-scale to local controls on river character and behavior.	Continuous stream network (NHD+)	[9,30,31,39]
Columbia Basin Natural Channel Classification (NCC)	NCC is a model-based stream classification using a machine-learning (support vector machine) algorithm to group reaches based on their historic, undisturbed planform. Divides reaches into groups based on channel width before sub-dividing on reach-level remote sensing data.	A historic planform map and dataset for the Columbia River Basin [27]	Remotely-sensed channel slope, discharge, valley confinement, sediment supply, and sediment size are used as predictors of channel planform in a modeling framework.	Continuous, pre-disturbance stream network (NHD)	[27]
Rosgen Classification System (RCS)	RCS is a stream-reach taxonomy based on field-collected empirical data that classifies geomorphic stream features to identify stream types by numerically bounded physical metrics. This is arguably the most commonly used stream classification system in North	RCS can be employed to successfully restore a reach to a reference condition, provided that the reference reach is stable [40] RCS stream type	Valley morphology for broad context, and reach-scale monitoring data to calculate basic dimensionless metrics linking form to physical processes.	Individual reaches within a stream network (field-monitored reaches)	[28,29]

	America and the world.	classifications provide inferences into the sensitivity of stream reaches to natural channel changes [41]			
Statistical Classification (SC)	Statistical classification refers to any classification methods used to differentiate or group stream reaches, watersheds, etc. based on multiple physical, chemical, and/or biological attributes. Attributes are often selected for their role in driving or responding to dominant processes within a catchment.	Comparing restored, forested, and urban channels [42]; Identifying vegetation communities and environmental filters [43]; classification of desert washes [44]	Requires reach-scale monitoring data for "bottom-up" classifications. Requires remote sensing and GIS data to classify reaches from the "top-down" or correlate classified reaches to larger-scale environmental or physical processes.	Individual reaches within a stream network (field-monitored reaches). Can be applied to networks if inputs are available for stream segments/networks.	[3,43,44]

2. METHODS

The Middle Fork of the John Day River (MFJD; Oregon, USA) is 117 km long and drains 2051 km^2 within the Columbia River Basin (Figure 1). The MFJD watershed was chosen for this research given the wealth of stream data available there, largely as a result of ongoing watershed monitoring aimed at understanding physical factors limiting salmonid population resilience (Section 2.2). These data enabled completion of the four classification frameworks herein (Sections 2.3 – 2.6).

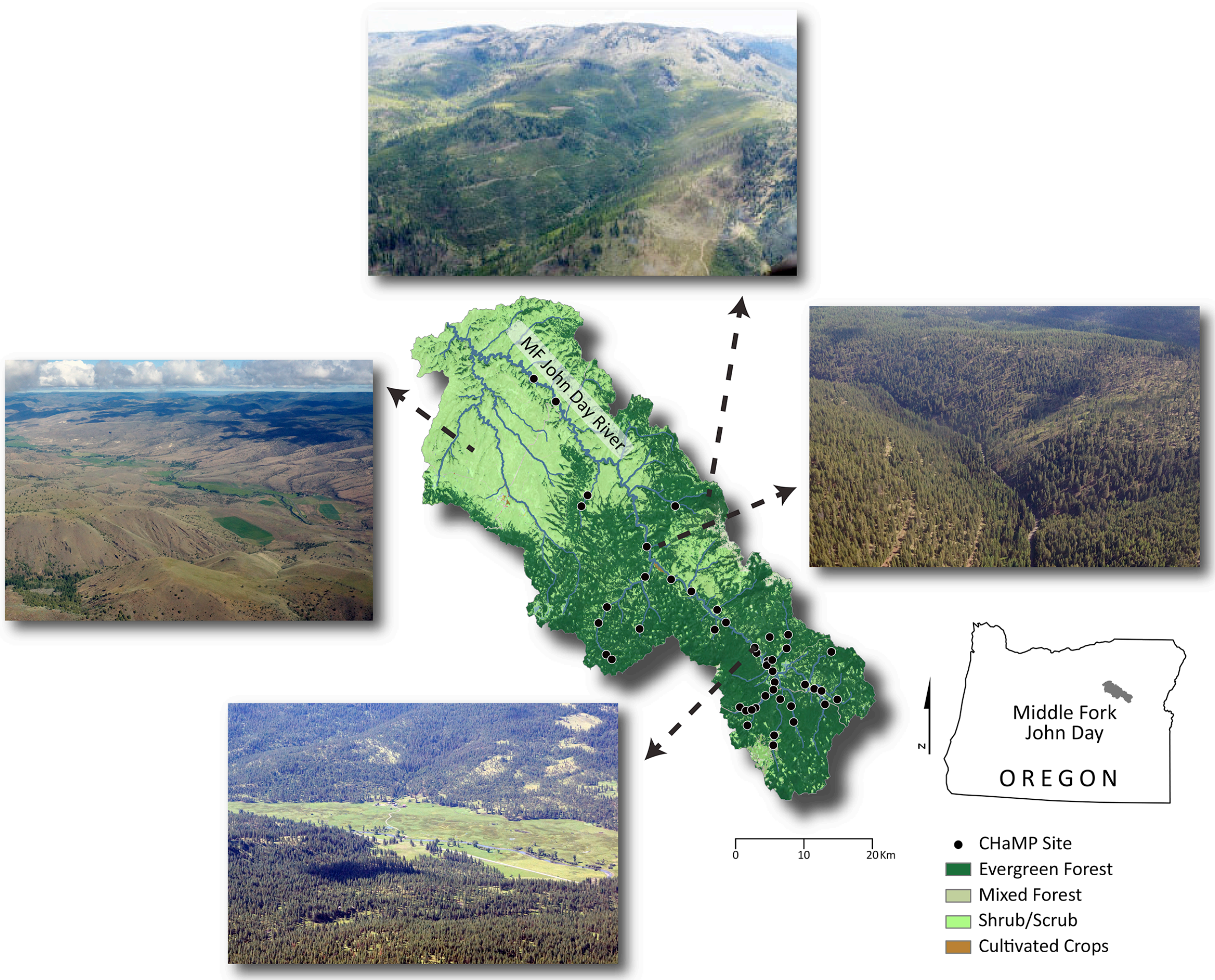

Figure 1.Map of the Middle Fork John Day Watershed, Oregon, USA. The 33 Columbia Habitat Monitoring Program (CHaMP) reaches monitored between 2012-2013are shown in

circles. The National Landcover Dataset (USGS) is presented as the base map to illustrate biophysical gradients across the watershed.

2.1. LANDSCAPE, HYDROLOGIC, AND ECOLOGICAL SETTING

The landscape of the MFJD basin is largely composed of metamorphic and igneous rocks underlain by basalt and older extrusive rock, which have been uplifted and reworked to create a watershed marked by steep-sloped canyons, deeply dissected highlands, dissected tablelands, and rounded uplands containing broad meadows. The watershed is generally semi-arid, receiving 560 mm of annual precipitation throughout the basin on average [45]. However, the John Day Basin is also marked by a distinct elevation-dependent precipitation gradient: the upper 10% of elevations receive an average of 880 mm of precipitation, while the lowest 10% receive 370 mm. Average annual streamflow measured at the Ritter, Oregon gauging station (USGS #14044000, A_d = 1334 km^2; 83 years of record) is 7.4 m^{3}s^{-1}.This varies considerably from the spring months when snowmelt in the uplands causes peak flows that average21.0 m^3 s^{-1}to summer baseflows that average 1.1 m^{3}s^{-1}. Lowland vegetation is dominated by sagebrush (*Artemisia sp.*) and grasslands interspersed with juniper (*Juniperus sp.*), while uplands are comprised of forests dominated by subalpine fir (*Abieslasiocarpa*), Engelmann spruce (*Piceaengelmannii*), lodgepole pine (*Pinuscontorta* spp. *latifolia*) and Douglas fir (*Pseudotsuga menziesii*) [46]. Riparian vegetation ranges from gallery cottonwood (*Populusbalsamifera*) forests, to alder (*Alnus spp.*) and willow (*Salix spp.*) shrublands, to wetland meadows dominated by sedges (*Carex spp.*), graminoids, and forbs [46].

2.2. SALMONID CONSERVATION AND WATERSHED MONITORING

Reductions in native fish populations throughout the Columbia River Basin, including the MFJD, have led to large-scale aquatic habitat monitoring across the Columbia Basin. In particular, steelhead trout (*Oncorhynchusmykiss*), listed as threatened under the U.S. Endangered Species Act, have seen drastic reductions in the size of their runs [47], presumably due to a combination of anthropogenic habitat degradation and hydropower development throughout the basin [48]. As a result, watersheds throughout the Columbia River Basin have received intensive monitoring efforts to document the status and trend of salmonid populations and habitat.

The MFJD is also monitored as part of the larger Columbia Habitat Monitoring Program (CHaMP; http://www.champmonitoring.org). CHaMPdata, which are used herein to complete the four classification frameworks, are collected at wadeable, perennial streams throughout the Columbia River Basin[49].Here we use survey data from the MFJD watershedcollected during 2012 and 2013 (n = 33 sites) describing channel bankfull width and depth, gradient, substrate, and sinuosity. Discrete sampling reaches in the 2012-2013 dataset are twenty times as long as the bankfull channel width at each site and range from 120 to 360 meters in length.

2.3. THE RIVER STYLES FRAMEWORK

The River Styles framework seeks to provide a "coherent set of procedural guidelines with which to document the geomorphic structure and function of rivers, and appraise patterns of river types and their biophysical linkages in a catchment context"[9]. In practice, the RSF offers the potential for a process-based, watershed-scale classification system for rivers, with implications for prioritizing their management and restoration. It consists of four distinct stages that progress from (1) classifying landscapes and current river form and function, to (2) assessing geomorphic river condition in context of reach evolution, to (3) understanding and forecasting trajectories of river change, and (4) prioritizing catchment management. A full description of the methods entailed in the RSF can be found in [9]. Here we describe the application of stage one of the RSF, which has been completed for the MFJD as part of an ongoing effort to contextualize site-specific CHaMP monitoring data in a watershed-wide framework [50]. Stage one provides a baseline assessment of current reach types (referred to as 'river styles') in a system with emphasis on longitudinal variability of river form (i.e. longitudinal profile analyses) along the mainstem channel and tributary network.

The RSF begins with the classification of landscape units (Figure S.1). Each landscape unit has a propensity to contain a unique distribution of river styles. Within a given landscape unit, stream reaches are classified based on their valley confinement, presence or absence of floodplains, channel planform, distribution of in-channel and floodplain geomorphic units, and dominant channel substrate (Table 2). In contrast to the other classification systems presented herein and those used among practitioners (e.g. [22,28]), there is no intrinsic limit on the number of river styles that may occur in a watershed of interest. In practice, once the diversity of river styles for a particular watershed is known, a river styles tree (FiguresS.2 – S.4) can be constructed that allows for the classification of any stream segment from those found in the watershed. The top-level discriminator in the RSF is valley confinement (Figures S.2 – S.4), which Brierley and Fryirs[9] define as "the proportion of the channel length that abuts a confining margin on either side." Therein, *confined* channel reaches abut a confining margin along more than 90% of their length, *laterally unconfined* channel reaches abut a confining margin along less than 10% of their length, and *partly confined* channel reaches abut a confining margin along 11-89% of their length [9].

We used O'Brien and Wheaton's [2015] delineation of river styles for the MFJD where the boundaries between landscape units were defined using geospatial datasets for elevation (10 m and 1 m digital elevation models;[51]), slope, underlying geology [52], dominant vegetation[53], and Level IV EcoRegion boundaries [49]. Following the delineation of landscape units, individual river styles were initially digitized on the National Hydrography Dataset (NHD; as polylines in ArcGIS; ESRI, Redlands, CA) using aerial photos ([54]; 1 m resolution) and elevation datasets as a guide. Field visits were conducted in the summer of 2012 and 2013 to confirm the accuracy of these delineations, refine the distinguishing characteristics of each river style and its location in the river style tree (FiguresS.2 – S.4) and pinpoint boundaries between river styles.

Because the RSF is a hierarchical framework, components of it can be considered both form- and process-based (Table 2). For example, individual River Styles are classified in part by their behavior (i.e. interpreting how instream and floodplain geomorphic features (landforms) are formed and reworked under various flow regimes). This interpretation is ratified via geomorphic mapping during field visits to sites [50]. The initial differentiation of reaches is conducted at the valley setting scale, based on valley confinement. This serves as an analog to Montgomery's [55] process domains, which reflect the channel's access to sediment sources and the mechanisms through which sediment reaches the channel (Table 2). Stream power is estimated continuously along the channel can be used to infer reach boundaries [9]. Within each valley setting, river styles are classified based on metrics of channel form that are directly tied to geomorphic processes like stream discharge and power that govern sediment transport. These metrics include channel planform (and the presence or absence of a channel), the array of instream and floodplain geomorphic units along the reach and bed material texture (Table 2).

Table 2. Form-based channel metrics included in classification analyses. Note that inclusion of metrics in each classification framework reflects only the stages that were completed in this research, and that 'processes' only include geomorphic dynamics, and exclude ecological processes.

Metric of channel form	Relationship to channel processes	RSF	NCC	RCS	Clustering
Bankfull width	Transport competence via stream power[56,57,58,59]			X	X
Gradient or channel slope	Transport competence via stream power [56,57,58,59]	X	X	X	X
Presence or absence of channels	Magnitude/frequency of flow[9] Presence of hyporheic flow[9] Valley sedimentation/filling [30]	X			
Distribution of floodplains	Accommodation space for flow[39] Influence of vegetation on flow[60]	X			
Sinuosity	Competence via slope/stream power[61,62] Ability for lateral adjustment[63] Input of vegetation/sediment from banks[64]	X		X	X
Number of channels	Accommodation space for flow[9]	X			
Lateral channel stability	Ability for lateral adjustment[65] Input of vegetation/sediment [64,65,66]	X			
D_{16}, D_{50}, D_{84}	Transport competence [61,62]	X			X
Unit stream power	Transport competence [56,57,58,59]	X			
Site discharge	Transport competence via stream power [56,57,58,59]		X		
Integrated wetted width	Transport competence via stream power [56,57,58,59]				X
Valley width	Ability for lateral adjustment [9,60]	X		X	

	Supply of sediment and vegetation [27,55,64]				
Bankfull depth	Transport competence [61,62]			X	
Width: depth ratio	Transport Competence [67] Influence of Vegetation on Flow [68]			X	X
Valley confinement	Ability for lateral adjustment [9,60] Supply of sediment and vegetation [27,55,64]	X	X		
Entrenchment ratio	Accommodation space for flow [60] Transport competence via stream power [56,57,58,59] Ability for lateral adjustment [69] Input of sediment and vegetation[27,55,64]			X	
Bed material (categorical)	Transport competence [61,62]			X	
Geomorphic units (channel and floodplain)	Transport competence [70] Transport regime[71] Magnitude/duration/frequency of flooding[9,39,56,71] Influence of vegetation on flow[72,73]	X			
Relative reach slope	Relative sediment supply (surplus/deficit) [27]		X		
Upstream basin land cover	Sediment supply/caliber [27]		X		

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2.4 NATURAL CHANNEL CLASSIFICATION

Natural channel classification [27] seeks to predict the background, or pre-disturbance, planform of alluvial channels found in an area of interest. To this end, Beechie and Imaki [27] constructed a probabilistic map of pre-disturbance channel planforms across the Columbia River Basin, USA (drainage area 674,500 km^2). NCC classes include *confined* channels and four channel patterns for unconfined reaches: *straight, meandering, island-braided,* and *braided*. These four unconfined channel patterns are commonly identified planforms for alluvial, floodplain rivers [18,20,74], which have distinctly different morphologies, dynamics, and ecological attributes [74,75]. In NCC, confinement is considered as the ratio of bankfull width to valley width, and unconfined channels are those where the valley floor width is more than four times the bankfull width. Predictor variables in the model were based on known physical controls on channel pattern, including channel gradient, discharge, valley confinement, sediment supply, and sediment size [76]. Channel slope, discharge, and confinement were estimated directly from digital elevation models. Relative reach slope, percent of watershed in unvegetated alpine terrain, and percent of watershed in fine-grained erosive sediments were hypothesized to be surrogates for sediment supply and size, respectively. Relative slope is the slope of a reach minus the slope of its upstream neighbor. Positive relative slope values indicate that a reach is steeper than its upstream neighbor (likely sediment supply-limited or undersupplied), and for a given slope and discharge is likely be narrower, deeper, and more armored [20,77], whereas negative values indicate that a reach is more likely to have low transport capacity relative to bed load supply (i.e., transport-limited or oversupplied), and will likely be wider, shallower, and finer grained or less armored.

For all channel segments with bankfull width > 8 m, attributes were assigned to each 200-m long reach in the study area (> 2,000,000 reaches) based on available geospatial data, and adjacent reaches with similar characteristics were then aggregated into sets of geomorphically meaningful reaches. A sample of more than 30 relatively natural reaches of each channel pattern was selected as the training data set (i.e., the natural channel pattern was not obscured by contemporary land use or dams); hence, the model should predict channel patterns *expected in the absence of human impacts, rather than current channel form*. A support vector machine (SVM) classifier was used to relate all 63 possible combinations of reach attributes to channel pattern using a total training data set of 147 reaches. The multiple models were evaluated using cross-validation (classification accuracy), and the most accurate SVM model was then used to predict channel pattern for all reaches in the study area. Bootstrapping of the final model created 1000 separate predictions of channel pattern for each reach, and the consistency of predictions was used as an indicator of model uncertainty for each reach. For example, if 85% of the predictions for a reach were 'braided,' we considered that reach to have a high likelihood of having a braided channel pattern. This statistical approach produces maps of (1) the most likely channel pattern for each reach in the Columbia River Basin, and (2) uncertainty in the channel pattern prediction. For channels with bankfull width <8 m, reaches were classified as pool-riffle, plane-bed, step-pool or cascade based on channel gradient [22].

Like the RSF, NCC contains elements based in process and form. NCC uses channel confinement to first predict whether natural patterns can be expressed (unconfined channels), or whether the valley bottom is too narrow to allow significant meandering and side-channel formation. Basin-scale measurements of land cover and surficial geology are used to characterize the likely sediment supply and sediment size delivered to each reach [55]. In addition, remotely sensed measurements of channel characteristics (i.e. channel width, gradient, and relative slope) reflect the ability of a reach to transport supplied sediment [59,78,79]. Together, these are used to estimate the equilibrium form of each reach in the basin.

2.5. *ROSGEN CLASSIFICATION SYSTEM*

The Rosgen Classification System (RCS; [28,80]) is widely used to assess channel condition in the context of reach-scale stream restoration projects, providing a standardized workflow for river classification based on a field survey of the geomorphic characteristics of a particular stream reach. RCS consists of four hierarchical stages of classification moving from coarse to fine spatial scales [29]. In Level I, the system uses spatial data describing valley confinement, channel planform, local soil types, hydrologic regime, and watershed physiography to establish a broad geomorphic characterization of river reaches. In Level II, the geomorphic characteristics of a site (e.g. entrenchment ratio, width/depth ratio, sinuosity, median grain size, and gradient) are assessed and a particular stream type is assigned to the reach using the decision tree first presented by Rosgen [28]. Like the RSF and NCC, in Level II the RCS emphasizes valley setting and confinement early in the process. RCS uses a field-measured entrenchment ratio (channel wetted width at two times bankfull depth divided by the bankfull width), which is analogous to the valley width to bankfull width ratio that NCC uses to calculate channel confinement. In Level III, the stream's condition is assessed based on channel planform, bed and bank stability, occurrence and type of riparian vegetation, and any alterations in flow regime. Finally, stream types delineated in Levels II and III are field-checked by direct measurements of sediment transport and size, flow, bed/bank stability, and rates of bank erosion to ensure a valid stream type classification has been made (Level IV).

We classified the 33 CHaMP reaches in the Middle Fork John Day watershed (Figure 1) using Levels I and II of the RCS. We used DEMs (10 m and 0.1 m grid resolution), aerial imagery (1 m resolution), and ground-based assessments to infer the Level I valley types surrounding each CHaMP reach. Delineation of bankfull elevation was completed by trained technicians in the field and surveyed as part of the CHaMP topographic survey. Calculations of width-to-depth ratio, channel sinuosity, entrenchment ratio, and channel gradient were derived from CHaMP topographic survey DEMs (0.1 m grid resolution) using the River Bathymetry Toolkit (RBT; [81]). A bankfull water surface was derived by detrending a DEM and best-fitting a water stage through the measured bankfull points and examining inflections in the hydraulic geometry using the CHaMP Topo Toolbar (https://sites.google.com/a/northarrowresearch.com/champtools/). Measurements that typically are derived from cross sections using RCS were derived from averages of 100+ of cross sections spaced at 1-meter intervals at every CHaMP site and processed using the RBT. These metrics allowed us to categorize each CHaMP reach into broad level RCS stream types (A-G). By combining broad RCS stream types with median grain size data (D_{50}) collected during CHaMP surveys, we classified each site into a final channel type according to the RCS classification. Although we did not explicitly validate our reach type delineations in the field (e.g. Level IV as described above), the wealth of on-the-ground photographs and high-resolution topographic data (0.1 m-resolution DEMs) collected as part of CHaMP surveys were used to ensure the validity of classified reaches.

Perhaps more so than the RSF or NCC, Level II of the RCS is a form-based approach, relying on measurements of channel geometry and bed material size to classify stream reaches (Table 2; [29]). It has received criticism in the geomorphic literature for being a strictly form-based approach [14,16,17]. At the same time, the RCS, like the other classification frameworks used here, relies on measurements of channel form as surrogates for geomorphic process, and perhaps more so than the other three approaches, requires direct field-based measurements to do so. For example, a channel's entrenchment ratio reflects its ability to adjust laterally across the valley bottom and access floodplain sediments, while measurements of gradient and bed material size reflect the capability of the channel to transport supplied sediment [61,62].

2.6 STATISTICAL CLASSIFICATION

Multivariate statistical classification provides a flexible framework to identify patterns between reaches based on channel form and/or landscape setting. Multivariate statistical approaches, including hierarchical clustering, use distance measures to group stream reaches based on their similarity (or dissimilarity) across multiple stream attributes [82]. Statistical classification is a family of techniques, rather than a single technique, allowing flexibility in the input data used, the distance measure used to compare similarity across observations, and in the case of clustering, the algorithm used to identify meaningful groups of observations [83]. Here we show an example of how these techniques can be employed in the spirit of the other stream classifications compared here.

We classified the 33 CHaMP reaches in the Middle Fork John Day Watershed by clustering reaches on multiple instream geomorphic attributes: bankfull width, wetted width, site sinuosity, stream gradient, bankfull width to depth ratio, and D_{16}, D_{50}, and D_{84} particle size. CHaMP metrics that reflect sediment size and channel form were selected in order to maintain consistency with data used in the classifications presented in Sections 2.3, 2.4, and 2.5. We selected a partitioning around medoids clustering algorithm in R (cluster package; [84]), a divisive clustering technique, to identify clusters of distinct reach types based on the Euclidean distance between reaches' instream geomorphic attributes. We validated differences in stream attributes between reach clusters using PERMANOVA [85]. We plotted the cluster solution within a principal components analysis (PCA) of the same stream channel attributes, visually comparing CHaMP reaches classified under each method (RSF, NCC, RCS, clustering). Full statistical methods and results are presented in the supporting information (Text S1).

The statistical classification applied here is purely form-based, incorporating geomorphic process only by grouping channels on their physical attributes' similarity (Table 2). Field-derived measurements of channel gradient, bankfull channel dimensions, and bed material size were used to describe channel form, which, in aggregate, reflect the ability of a given stream reach to transport supplied sediment, similar to how RCS estimates process using form-based attributes (Section 2.5). An important distinction between the statistical classification and the other three classifications used here is how they incorporate valley setting. While RSF, NCC, and RCS estimate sediment supply and delivery processes by classifying valley setting (albeit at a later stage in RCS), the statistical clustering employed here does not use valley confinement or surrogates (stream order, valley slope) to estimate a channel's propensity to adjust laterally and receive sediment inputs from the valley.

2.7 ASSESSING CLASSIFICATION FRAMEWORK AGREEMENT

To compare the level of agreement between each classification framework at the 33 CHaMP sites discussed in Section 2.2, we compared classifications by approximating analogous reach types between each classification framework. We began by using the eight reach types identified by Natural Channel Classification, as these descriptors provided intuitive descriptors of channel planforms and associated physical characteristics. For each NCC reach type, we identified the most closely related reach types from the RSF, the RCS (using top-level channel types A-G), and statistical clustering. Where available (RSF, RCS), decision trees were used to select those reach types that best approximated each NCC type based on common geomorphic metrics (gradient, geomorphic units present, planform). In the case of statistical clustering, the geomorphic attributes inherent to each of the four clusters (Figure 4) were used to approximate the corresponding NCC reach type.

Those RSF, RCS, and statistical clustering reach types that were most closely related to each NCC type were classified as being in “good” agreement (e.g. all geomorphic attributes of the reach type could conceivably be present in the associated NCC channel class), while those which were only marginally related to each NCC class (that is, some aspects of the reach types fit with an NCC class while others did not) were classified as having “moderate” agreement (Table 3). RSF, RCS, and clustering reach types with no characteristics in common with NCC classes were classified as having “poor” agreement. While this method is inherently qualitative, we attempted to take an inclusive approach when determining agreement among reach types between frameworks, as considerable geomorphic variability can exist across each reach type within a given framework [9,29].

Table 3. Cross-walking of analogous reach types between NCC, RS, RCS, and statistical clustering based on common geomorphic attributes. Those reach types with good (G) or moderate (M) agreement are included, while those with poor agreement are not shown here, but are noted in Table 4.

NCC reach type	River Styles reach type	RCS reach type	Statistical cluster
Island Braided	Low Sinuosity Planform Controlled Anabranching (G)	D (G)	2: Wide, Sinuous (M)
	Intact Valley Fill (M)		
	Alluvial Fan (M)		
Meandering	Meandering Gravel Bed (G)	C (G)	4: Wide, Sinuous (G)
	Meandering Planform-Controlled Discontinuous Floodplain (G)	E (G)	1: Narrow, Sinuous (M)
	Low-Moderate Sinuosity Gravel Bed (M)	G (M)	2: Wide, Low-Gradient (M)
	Low-Moderate Sinuosity Planform-Controlled Disc. Floodplain (M)	F (M)	
	Bedrock-Controlled Elongate Discontinuous Floodplain (M)		
	Low-Moderate Sinuosity Gravel Bed (M)		
Straight	Boulder Bed (G)	A (G)	2: Wide, Low-Gradient (G)
	Meandering Planform-Controlled Disc. Floodplain (G)	B (G)	3: Steep, Narrow (G)
	Confined Valley – Floodplain Pockets (G)	G (M)	
	Low-Moderate Sinuosity Partly Confined Disc. Floodplain (G)		
	Low-Moderate Sinuosity Gravel Bed (G)		
	Alluvial Fan (M)		
	Bedrock-Controlled Elongate Discontinuous Floodplain (M)		
Confined	Entrenched Bedrock Canyon (G)	A (G)	1: Narrow, Sinuous (G)
	Confined Valley – Floodplain Pockets (G)	F (G)	3: Steep, Narrow (G)
	Step Cascade (G)	G (G)	2: Wide, Low Gradient (M)
	Steep Perennial Headwater (M)	B (M)	
	Steep Ephemeral Hillslope (M)		

Table 3. (Continued)

NCC reach type	*River Styles reach type*	*RCS reach type*	*Statistical cluster*
Cascade	Step Cascade (G)	B (G)	3: Steep, Narrow (G)
	Boulder Bed (G)	F (G)	1: Narrow, Sinuous
	Floodplain Pockets (M)	G (G)	
	Steep Perennial Headwater (M)	A (M)	
	Steep Ephemeral Hillslope (M)		
Pool Riffle	Meandering Gravel Bed (G)	C (G)	1: Narrow, Sinuous (G)
	Meandering Planform Controlled Discontinuous Floodplain (G)	F (G)	2: Wide, Low Gradient (G)
	Confined Valley – Floodplain Pockets (G)	G (G)	4: Wide, Sinuous
	Bedrock-Controlled Elongate Discontinuous Floodplain (G)	E (G)	
	Low-Moderate Sinuosity Planform Controlled Disc. Floodplain (M)	B (M)	
	Meandering Partly-Confined Floodplain (M)		
Step Pool	Boulder Bed (G)	B (G)	3: Steep, Narrow (G)
	Step Cascade (G)	F (G)	1: Narrow, Sinuous (M)
	Steep Perennial Headwater (G)	G (G)	
	Steep Ephemeral Hillslope (G)	A (M)	
	Confined Valley - Floodplain Pockets (M)		
Plane Bed	Entrenched Bedrock Canyon (G)	A (G)	3: Steep, Narrow (G)
	Confined Valley – Floodplain Pockets (G)	B (G)	1: Narrow, Sinuous (F)
	Bedrock Controlled Elongate Discontinuous Floodplain (G)	C (G)	4: Wide, Sinuous (F)
	Low-Moderate Sinuosity Planform Controlled Disc. Floodplain (G)	F (G)	
	Meandering Planform Controlled Floodplain (M)	G (G)	
	Boulder Bed (M)		
	Steep Perennial Headwater (M)		
	Steep Ephemeral Hillslope (M)		

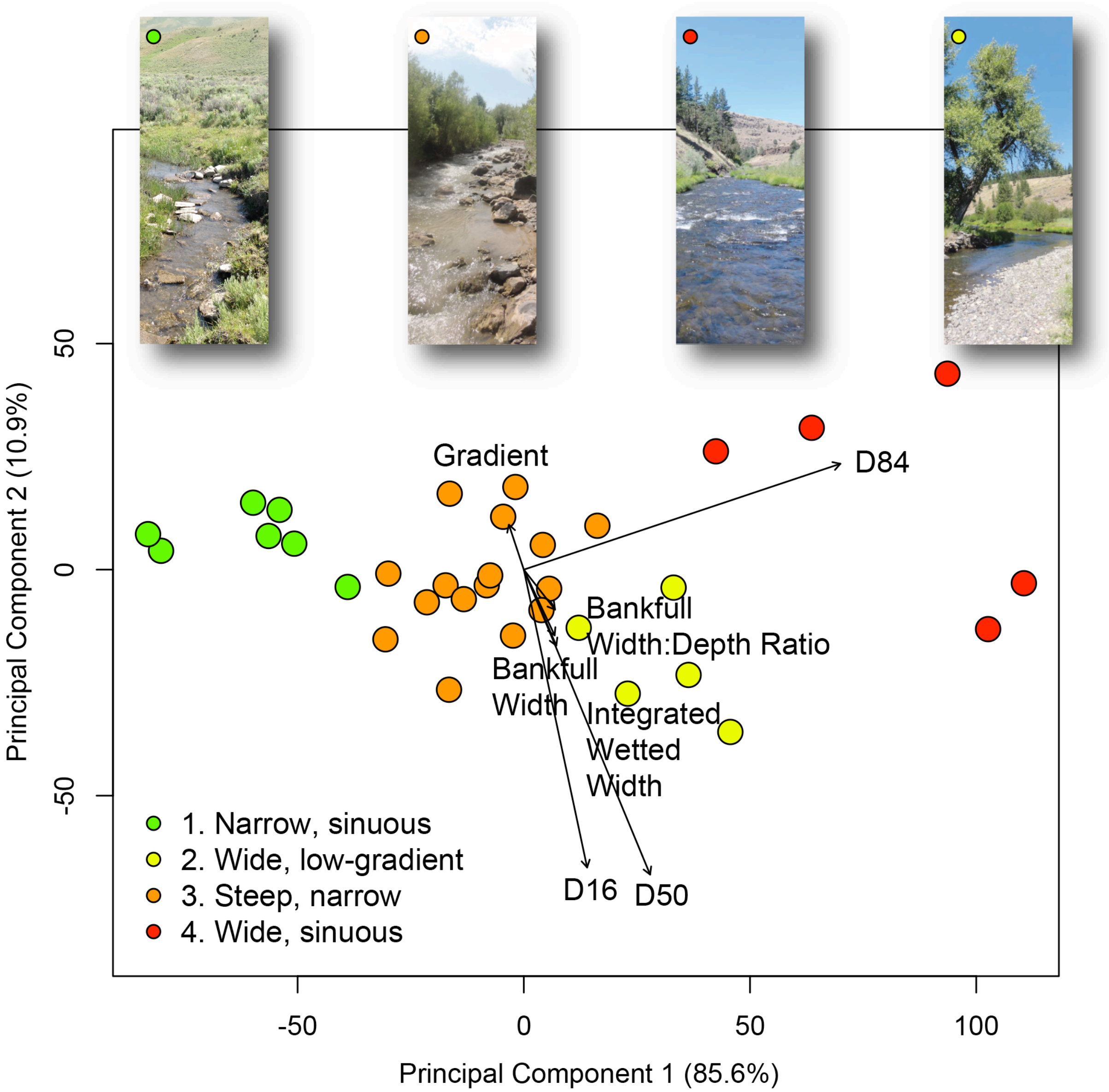

Figure 4. Principal Components Analysis (PCA) of reaches based on gradient, D_{16}, D_{50}, D_{84}, bankfull width, bankfull width:depth ratio, and integrated wetted width, illustrating differences between CHaMP reaches classified into four discrete groups using partitioning around medoids. Vectors of stream channel variables are plotted based on the strength of their correlation to the PCA (e.g. longer vectors are more strongly correlated to the channel form variable PCA). The first and second principal components explained 85.6% and 10.9% of the variability in the reach attribute data within the PCA.

3. RESULTS

3.1. THE RIVER STYLES FRAMEWORK

In total, 14 distinct river styles were classified across the MFJD Watershed. To begin, landscape units were classified across the watershed (Figure S.1). The river styles trees showing the characteristics of each river style are shown in Figures S.2 - S.4, and the distribution of river styles within the MFJD Watershed is shown in Figure 2A, with distinctions made based on valley confinement (confined, partly confined, laterally unconfined; [33]). Overall, confined valley channels were the most common river styles across the MFJD Watershed (86% of total stream length), whereas channels in partly confined valley (8%) and laterally unconfined valleys (6%) were far less common although they comprise the majority of the mainstem (Figure 3A). Small, low-order, confined channels (boulder bed and steep ephemeral hillslope river styles) comprised the majority of total stream length within the watershed (68%, Table 2). Regarding the most common classifications of CHaMP sites, 33% of sites were classified as partly confined valley with low-moderate sinuosity planform-controlled discontinuous floodplain reach types, 15% were classified as confined valley with occasional floodplain pockets, and 12% each were classified as partly confined valley with meandering planform-controlled discontinuous floodplain and bedrock-controlled elongate discontinuous floodplain reach types (Figure 3A). Classification of all channels (approximately 4100 km total length) across the MFJD Watershed required roughly three to four months to complete using desktop based reach delineation and field work.

Table 4. Classification results for the four methods compared here. River Styles and Columbia Basin Natural Channel Classification are summarized across the entire network and at CHaMP sites, while the Rosgen Classification System and clustering classifications are summarized only for reaches with CHaMP channel data.

Classification framework	Reach types		Total stream length (km)	% Total length	% CHaMP reaches	# CHaMP reaches
River Styles	Confined valley	Boulder bed	1230.7	30.2	3.0	1
		Entrenched bedrock canyon	121.1	3.0	6.1	2
		Occasional floodplain pockets	242.5	6.0	15.2	5
		Step cascade	37.9	0.9	0	0
		Steep ephemeral hillslope	1542.3	37.9	0	0
		Steep perennial headwater	319.4	7.8	0	0
	Partly confined (discontinuous flood-plains)	Meandering planform controlled discontinuous floodplain	34.5	0.8	12.1	4
		Low sinuosity planform controlled anabranching	18.2	0.5	6.1	2
		Low-moderate sinuosity planform-controlled discontinuous floodplain	170.2	4.2	33.3	11
		Bedrock controlled elongate discontinuous floodplain	113.8	2.8	12.1	4
	Laterally unconfined	Low-moderate sinuosity gravel bed	31.9	0.8	3.0	1
		Alluvial fan	49.3	1.2	3.0	1
		Meandering gravel bed	62.9	1.5	6.1	2
		Intact valley fill	99.4	2.4	0	0
Columbia Basin Natural Channel	Bankfull width > 8m	Straight	132.9	7.8	24.2	8
		Meandering	34.7	2.0	9.1	3
		Island-braided	42.8	2.5	6.1	2

Classification		Confined		76.5	4.5	9.1	3
	Bankfull width < 8m	Plane bed		431.5	25.4	24.2	8
		Pool riffle		129.9	7.7	15.2	5
		Step pool		595.3	35.1	12.1	4
		Cascade		253.7	14.9	0	0
Rosgen Classification System	Entrenched	A	A4			12.1	4
		F	F3			3.0	1
		G	G4c			3.0	1
	Moderately Entrenched	B	B3c			6.1	2
			B4			24.2	8
			B4a			3.0	1
			B4c			15.2	5
	Slightly Entrenched	C	C3b			3.0	1
			C4b			24.2	8
		E	E3			3.0	1
			E4			3.0	1
Statistical classification	Narrow, sinuous (1)					21.2	7
	Wide, low-gradient (2)					15.2	5
	High-gradient, narrow (3)					48.5	16
	Wide, sinuous (4)					15.2	5

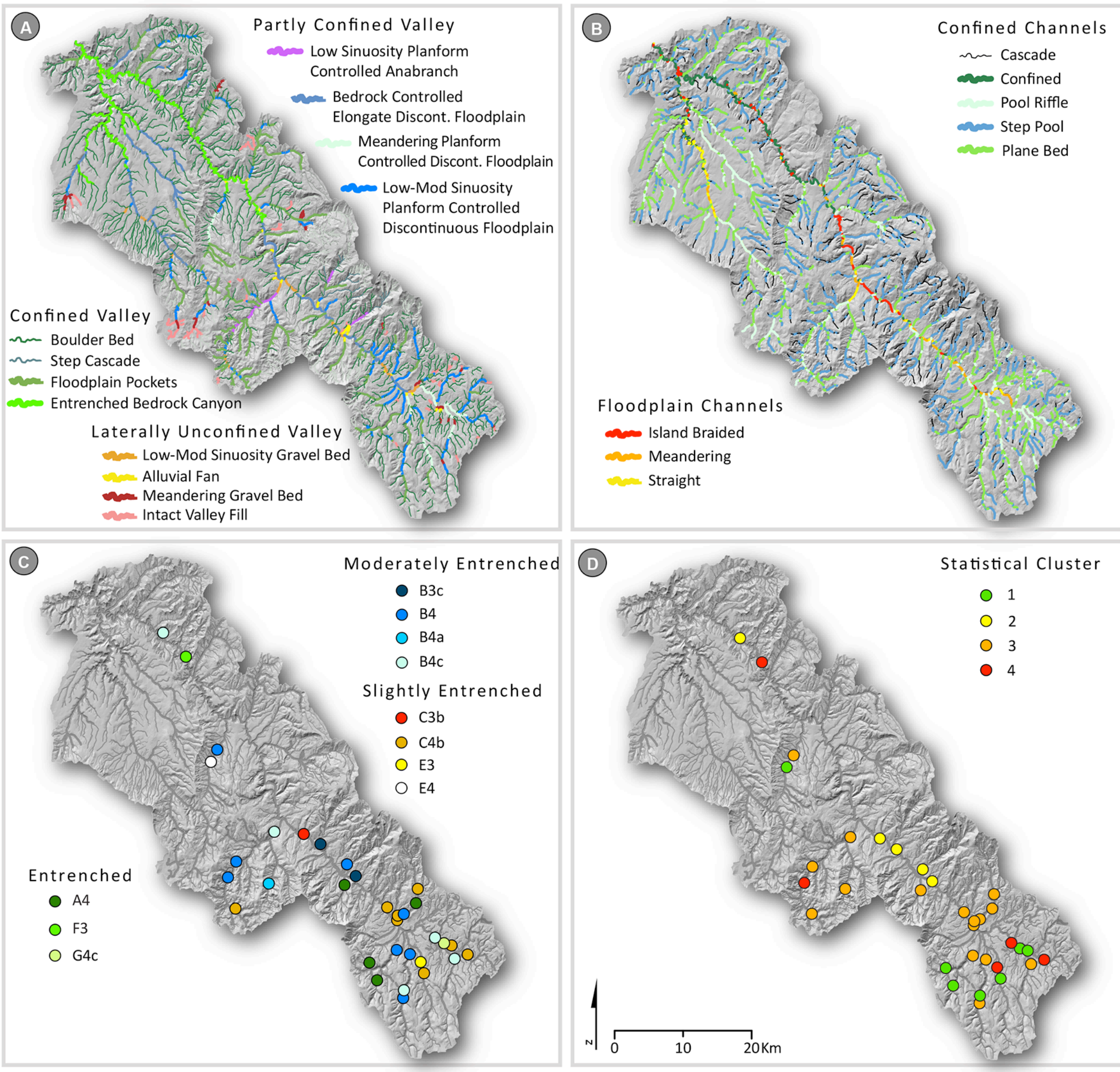

Figure 2. Results of the four classifications. (A) River Styles, (B) Natural Channel Classes, (C) Rosgen Classification System, and (D) statistical classification with clustering (partitioning around medoids), mapped across the Middle Fork John Day Watershed. River Styles and Natural Channel Classes are mapped across the entire stream network, while Rosgen Classification System and statistical classification results are presented only for CHaMP reaches. Full River Style and Natural Channel Class results for CHaMP reaches are presented in Table 4.

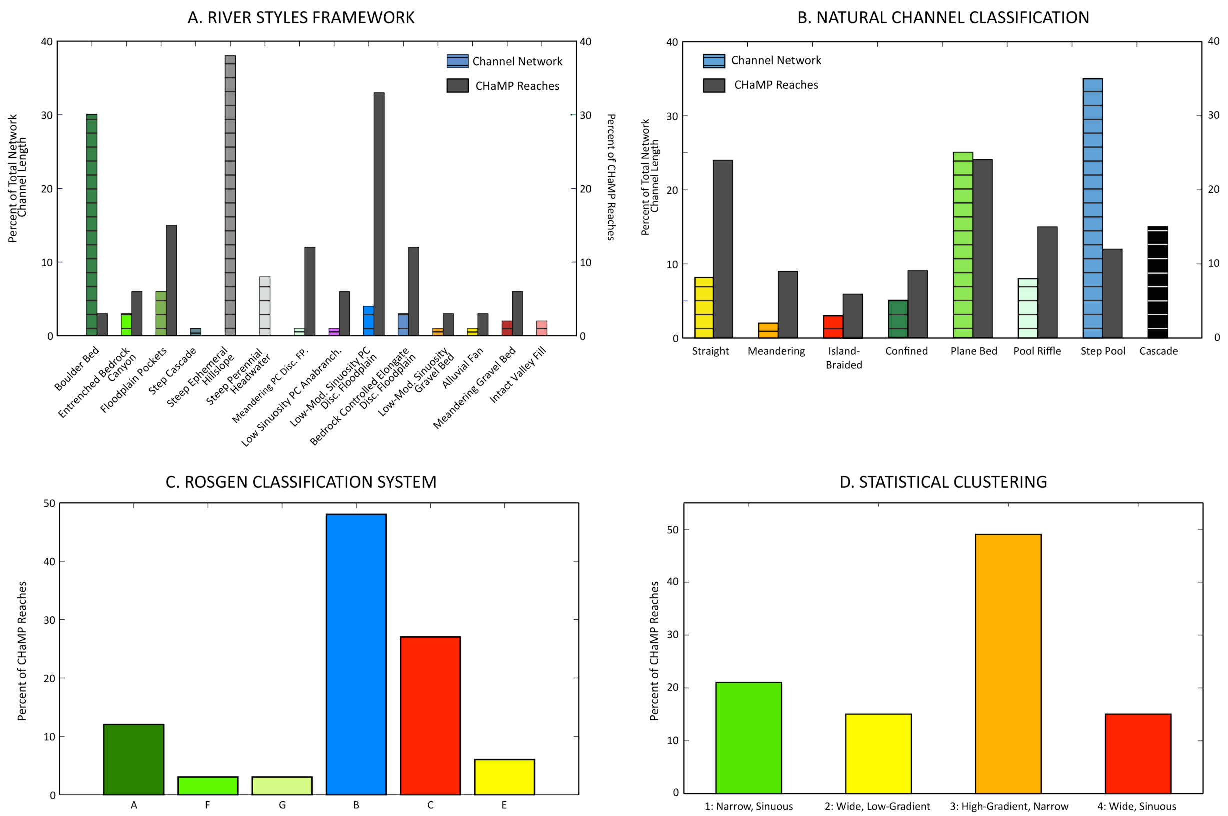

Figure 3. Classification results across network and sites. Percent of total network channel length and percent of CHaMP sites classified into reach types using each classification framework (A-D).

3.2 NATURAL CHANNEL CLASSIFICATION

Natural Channel Classification derived nine channel patterns across the Columbia River Basin [27], eight of which were predicted within the MFJD Watershed (Figure 2B). By total stream length, the majority of reaches (83%) were small channels with bankfull width <8 m. Across the MFJD, 35% of the total reach length was classified as step-pool channels, and 25% classified as plane-bed channels[22]. For channels > 8 m bankfull width, 8% of the total reach length was classified as having a straight planform, 3% of channels classified as island-braided, and 2% classified as meandering (Figure 3B; Table 2). The remaining reaches >8 m were classified as confined channels because valley width was less than four times bankfull channel width [27].

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With regard to the most common classifications of CHaMP sites, 25% of sites each were classified as straight or plane bed reaches, with an additional 15% of sites classified as pool riffle (Figure 3B). Classification was completed for all channels > 3 m bankfull width over the entirety of the Columbia River Basin. Model development, including data collection and pre-processing - projecting to a common coordinate system, mosaicking of individual raster tiles and subsequent analysis required roughly two months to complete. Once data were collected and pre-processed, actual model run time was approximately 48 hours.

3.3 ROSGEN CLASSIFICATION SYSTEM

We classified 11 RCS stream types within 33 CHaMP surveyed reaches in the MFJD Watershed (Figure 2C). The most common stream types, each containing 24% of the CHaMP reaches, were B4 (stable plane bed with occasional pools) and C4b (low gradient, meandering, riffle/pool sequences; Figure 3C). In total, 50% of the reaches were B stream types, all of which were within valley type II (colluvial, moderately steep and confined), with a single exception. C stream types (sinuous, wide and low-gradient) were the next most common (27%) and E (highly sinuous, coarse-fine bed), F (entrenched, wide, moderately sinuous, low gradient), and G (entrenched, low-gradient, low width:depth ratio) types were the least common (3% each). Only one CHaMP site had a substantial length of side channels (24%), however the other metrics did not fit a D stream type. Therefore, we did not delineate any multi-threaded channels (RCS stream type D). Surveying of individual CHaMP sites required approximately eight hours of crew time (typically 2-4 individuals), although some of this time was spent collecting data not used in the classifications here. Subsequent manual RCS classification of all 33 CHaMP sites required about 80 hours.

3.4 STATISTICAL CLASSIFICATION

Because statistical clustering does not confirm an *a priori* set of outcomes, we compared multiple clustering results (two to ten clusters of channels) from the partitioning around medoids algorithm. We selected a four cluster final solution based on cluster fidelity, that is the statistical and geomorphic differences in the multiple attributes used to distinguish between groups, minimizing overlap between cluster groups (Figure 4; Tables S.2. – S.4.). We did this objectively rather than trying to create an *a priori* number of reach types to match the other frameworks number of outputs. After plotting the final cluster solution within a principal component analysis (PCA), the clustered stream channel attributes showed that each group differed based on multiple channel form attributes. The PCA indicated that the four identified clusters were meaningful representations of the sampled reaches and not just statistical artifacts. Each cluster was named based on the dominant attributes that differentiated clusters from one another. The four final groups consisted of (1) narrow, sinuous, high-gradient reaches (n=7), (2) wide, low-gradient, coarse substrate reaches with high width to depth ratios (n=5), (3) high-gradient, narrow reaches with moderate-sized substrates (n=16), and (4) moderate gradient, wide and sinuous, coarse-substrate reaches (n=5; Figure 4). The number of CHaMP sites assigned into each cluster are shown in Figure 3D. Channel clusters were significantly different from one another (PERMANOVA; $p< 0.05$), and particle D_{16}, D_{50}, and D_{84} were the attributes that were most strongly correlated to the principal component analysis (Tables S.2. – S.4.). Clusters in the final four-cluster solution were distinct (silhouette widths 0.24-0.60; mean width 0.41; Figure 4). The cluster group assigned to each CHaMP site is shown in Figure 2D and Figure S.7. Because the same CHaMP sites were classified using statistical clustering and RCS, the data collection time was identical to RCS classification detailed above. Actual run time of clustering algorithms was less than one minute.

4. SYNTHESIS

4.1.COMPARING OUTPUTS BETWEEN CLASSIFICATION FRAMEWORKS

The analysis of agreement between reach types of each framework (Section 2.8; Table 3) generally indicates that far more often than not, frameworks produced reach type classifications that were congruent with one another. When comparing the level of agreement between NCC and each of the other three frameworks at 33 CHaMP sites (for a total of 99 comparisons), we found "good" agreement at 60 sites (61%), "moderate" agreement at 19 sites (19%), and "poor" agreement at 20 sites (Table 4). Thus, reasonable agreement was found at 80% of sites. The reasons that each framework's reach classification does (or does not) agree with those of the other frameworks may be the result of the spatial scale of the input data, the timeframe (e.g. current or historic) that each framework attempts to classify, or as a result of differences in the each framework's workflow. We also note that the number of output classes for a given classification framework may influence the degree of agreement between frameworks. This is particularly true in the case of statistical clustering, which contained four output classes compared to an average of 9 classes for RSF, RCS, and NCC. However, as clusters were specifically chosen to distinguish groups (i.e. minimize cluster overlap; Section 2.6), we do not directly explore the effect of the number of stream type classes on agreement. In the case of RSF and RCS, there are also nested sub-classes that allow for coarse groupings based on confinement. We do not compare these coarse groupings. Instead we focus on the final classes that exhibit a range of agreement between frameworks, and the likely reasons for this agreement (Figure 5).

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Table 5. Classification results and agreement for each CHaMP site across the four classification frameworks. The table is sorted by River Styles confinement classes, River Styles channel classes, and then by statistical clusters.

CHaMP Site ID	Stream name	UTM Easting	UTM Northing	Rosgen Class. System	Statistical Clustering	Natural Channel Classes	River Styles	River Style valley confinement	Agreement
CBW05583-250506	Lunch Creek	377638	4930916	A4	Narrow, sinuous	Step Pool	Boulder Bed	CV	RS: Good RCS: Mod Cluster: Good
CBW05583-004682	Middle Fork John Day River	333505	4971313	B4c	Wide, low-gradient	Island Braided	Entrenched Bedrock Canyon	CV	RS: Poor RCS: Poor Cluster: Poor
CBW05583-021066	Middle Fork John Day River	337657	4968709	F3	Wide, sinuous	Confined	Entrenched Bedrock Canyon	CV	RS: Good RCS: Good Cluster: Mod.
CBW05583-144114	Vinegar Creek	380932	4942422	A4	Steep, narrow	Step Pool	Floodplain Pockets	CV	RS: Mod. RCS: Mod. Cluster: Good
CBW05583-223986	Bridge Creek	379613	4935524	B4	Steep, narrow	Plane Bed	Floodplain Pockets	CV	RS: Good RCS: Good Cluster: Good
CBW05583-456690	Butte Creek	369488	4942756	A4	Steep, narrow	Plane Bed	Floodplain Pockets	CV	RS: Good RCS: Good Cluster: Good
OJD03458-000017	West Fork Lick Creek	357991	4940711	B4a	Steep, narrow	Step Pool	Floodplain Pockets	CV	RS: Mod. RCS: Good Cluster: Good
CBW05583-051954	Dry Fork Clear Creek	383698	4934662	E3	Wide, sinuous	Straight	Floodplain Pockets	CV	RS: Good RCS: Poor Cluster: Poor
CBW05583-189938	Granite Boulder	369068	4945617	B4	Wide, low-gradient	Straight	Alluvial Fan	LUV	RS: Mod. RCS: Good

	Creek								Cluster: Good
CBW0558 3-449266	Middle Fork John Day River	376782	4941104	C4b	Steep, narrow	Meandering	Low-Moderate Sinuosity Gravel Bed	LUV	RS: Mod. RCS: Good Cluster: Poor
CBW0558 3-003826	Summit Creek	386503	4937885	G4c	Narrow, sinuous	Pool Riffle	Meandering Gravel Bed	LUV	RS: Good RCS: Good Cluster: Good
CBW0558 3-358130	Squaw Creek	388721	4936107	B4c	Steep, narrow	Pool Riffle	Meandering Gravel Bed	LUV	RS: Good RCS: Mod. Cluster: Poor
CBW0558 3-289522	Middle Fork John Day River	378688	4939623	C4b	Steep, narrow	Island-Braided	Bedrock-controlled Elongate Discont. Floodplain	PC	RS: Poor RCS: Poor Cluster: Poor
CBW0558 3-275954	Middle Fork John Day River	364436	4947549	B3c	Wide, low-gradient	Straight	Bedrock-controlled Elongate Discont. Floodplain	PC	RS: Mod. RCS: Good Cluster: Good
CBW0558 3-290034	Middle Fork John Day River	370912	4944299	B3c	Wide, low-gradient	Straight	Bedrock-controlled Elongate Discont. Floodplain	PC	RS: Mod. RCS: Good Cluster: Good
CBW0558 3-415218	Middle Fork John Day River	361529	4948510	C3b	Wide, low-gradient	Confined	Bedrock-controlled Elongate Discont. Floodplain	PC	RS: Poor RCS: Mod. Cluster: Mod.
CBW0558 3-030730	Camp Creek	352247	4942752	B4	Steep, narrow	Straight	Low-Moderate Sinuosity Planform-	PC	RS: Good RCS: Good Cluster: Good

							Controlled Discontinuous Floodplain		
CBW05583-330226	Camp Creek	357015	4947826	B4c	Steep, narrow	Straight	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Good
CBW05583-118770	North Fork Bridge Creek	375925	4933066	A4	Narrow, sinuous	Step Pool	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Poor RCS: Mod. Cluster: Mod.
CBW05583-299658	Clear Creek	382042	4930368	B4c	Narrow, sinuous	Plane Bed	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Mod.
CBW05583-438922	Dry Fork Clear Creek	384597	4933274	C4b	Narrow, sinuous	Straight	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Poor RCS: Poor Cluster: Poor
CBW05583-234122	Clear Creek	382238	4929332	B4	Steep, narrow	Plane Bed	Low-Moderate Sinuosity	PC	RS: Good RCS: Good

							Planform-Controlled Discontinuous Floodplain		Cluster: Good
CBW05583-381682	Vinegar Creek	380718	4944390	C4b	Steep, narrow	Plane Bed	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Good
CBW05583-383986	Camp Creek	353774	4936398	C4b	Steep, narrow	Plane Bed	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Good
CBW05583-404210	Vinegar Creek	379442	4940614	B4	Steep, narrow	Plane Bed	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Good
CBW05583-477938	Clear Creek	381713	4935379	B4	Steep, narrow	Straight	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Poor RCS: Good Cluster: Good
OJD03458-000536	Vinegar Creek	378654	4940187	C4b	Steep, narrow	Plane Bed	Low-Moderate Sinuosity Planform-Controlled Discontinuous	PC	RS: Good RCS: Good Cluster: Good

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							Floodplain		
CBW0558 3-325362	Summit Creek	390544	4937077	C4b	Wide, sinuous	Pool Riffle	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Mod. RCS: Good Cluster: Good
OJD0345 8-000031	Camp Creek	351579	4940332	B4	Wide, sinuous	Confined	Low-Moderate Sinuosity Planform-Controlled Discontinuous Floodplain	PC	RS: Poor RCS: Mod. Cluster: Poor
CBW0558 3-144394	Slide Creek	344959	4955342	E4	Narrow, sinuous	Pool Riffle	Meandering Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Good
CBW0558 3-429810	Summit Creek	387760	4937802	C4b	Narrow, sinuous	Meandering	Meandering Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Good Cluster: Mod.
CBW0558 3-013322	Slide Creek	345607	4957140	B4	Steep, narrow	Pool Riffle	Meandering Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Mod. Cluster: Poor
CBW0558 3-298738	Middle Fork John Day River	385006	4938373	B4c	Wide, sinuous	Meandering	Meandering Planform-Controlled Discontinuous Floodplain	PC	RS: Good RCS: Poor Cluster: Good

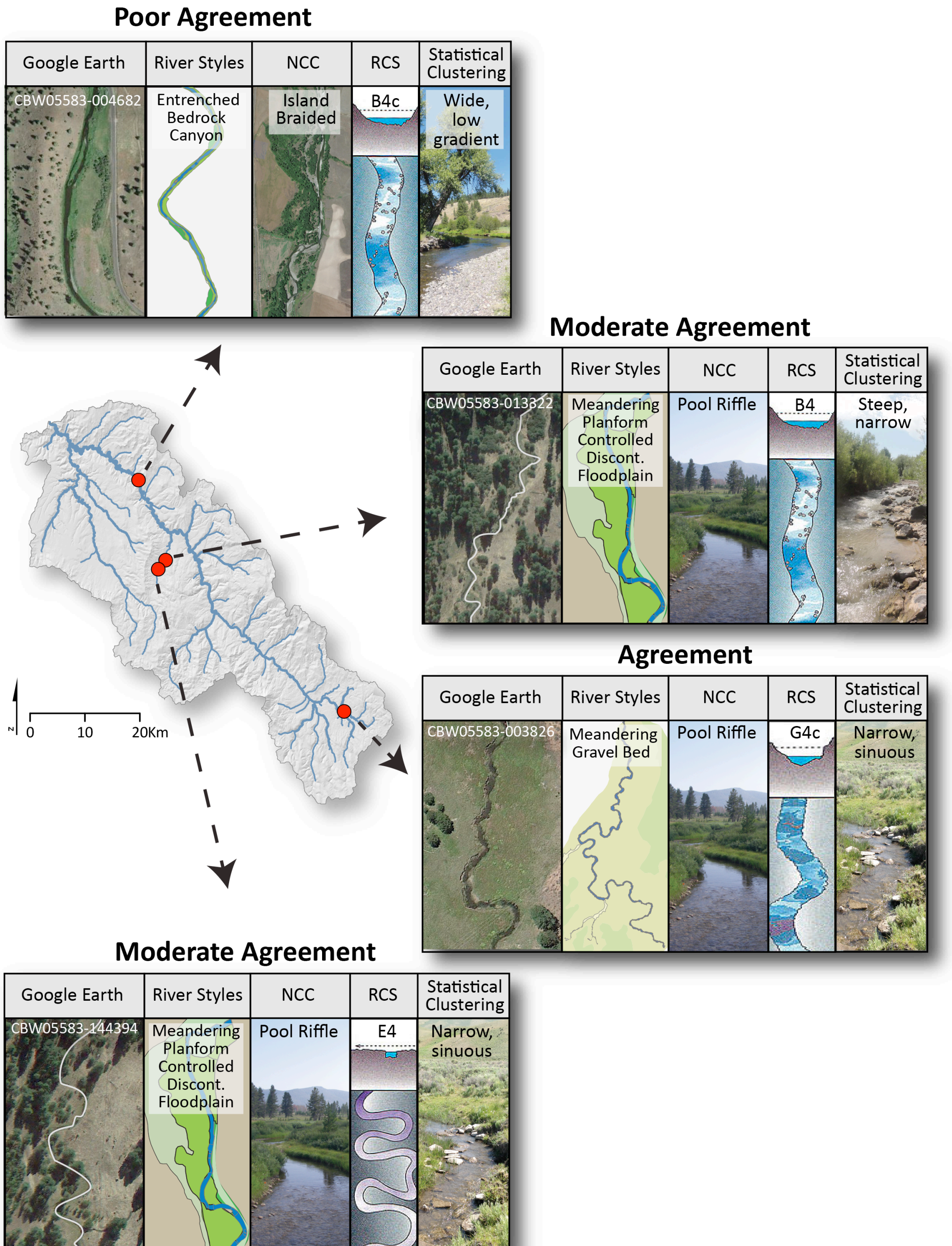

Figure 5. Example reaches describing agreement between classification outputs. Four reaches at which the four classifications had poor agreement, moderate agreement and good agreement in the observed channel planform.

At a confined valley reach on the Middle Fork John Day River (CHaMP site: CBW05583-004682), we found a B4c RCS type, wide, low-gradient statistical cluster, island-braided NCC, and entrenched bedrock canyon river style (Figure 5). The statistical classification matched the definition of a wide, low-gradient, B4c RCS channel type. While it is plausible that a B4c RCS channel type and an entrenched bedrock canyon river style could be applied to the same reach, the island-braided NCC classification is deserving of further exploration as it may hint at a departure from historic channel condition, which NCC attempts to predict. Subsequent field visits by *O'Brien* [Personal Communication] note that numerous deposits of legacy sediment (e.g.[86])above the active channel at this site, along with the wide valley bottom allowing a high capacity for channel adjustment, may imply that the system was overwhelmed by sediment during the early Holocene. Accordingly, the pre-disturbance classification of an island-braided channel using NCC may be appropriate in this case, and could hint at the background morphology of the channel. Thus, the divergence in classified reach types at this site may arise as a result of NCC's attempting to discern the background, pre-disturbance channel planform, while the other frameworks classify present channel condition.

In contrast, we found good agreement between all classification frameworks at two example reaches. The first is a laterally unconfined reach on the Middle Fork John Day River (Figure 5; CHaMP site: CBW05583-003826) classified as a G4c RCS type, narrow sinuous statistical cluster, pool-riffle NCC, and meandering gravel bed river style. The second site is a partly confined reach on Slide Creek (Figure 5; CHaMP site: CWB05583-144394), classified as a meandering planform-controlled discontinuous floodplain river style. This site was further classified as an E4 RCS reach, pool riffle RCC type, and narrow, sinuous statistical cluster. At these locations, the combination of geomorphic characteristics produced a reach classification that was highly similar in terms of valley setting, planform, and assemblage of geomorphic units between all four frameworks. In the case of the former site, the reach occurs within a broader ~10 km reach of the Middle Fork John Day that exhibits a sinuous planform in an unconfined valley. The latter site also occurs in a ~5 km segment of Slide Creek that exhibits a consistent meandering planform. These more longitudinally-continuous reaches are undoubtedly helpful for agreement in classification among continuous frameworks (e.g. RSF and NCC) that may use disparate spatial scales of data (e.g. NHD+ and field-based validation versus NHD and basin-scale 10 m DEMs, respectively) and derive classifications remotely prior to field-based verification.

An example moderate agreement site was found in a partly confined valley setting on Slide Creek (Figure 5; CHaMP Site CBW05583-013322). This reach showed different, but plausible combinations of channel types. The reach was classified as a partly-confined valley with meandering planform-controlled discontinuous floodplain river style - whose in-channel geomorphic unit assemblage is essentially repeating pool-riffle sequences - and pool-riffle in NCC, but was classified as a B4 RCS and steep, narrow statistical cluster. Reaches such as this one that exhibit mixed agreement between classification frameworks highlight that subtle differences in channel characteristics, such as gradient and sinuosity, can lead to significant differences in the classification of an individual reach. These differences arise as a result of the hierarchical and statistical clustering classifications used here, as the order of appearance of geomorphic metrics in a decision tree can vary between frameworks and subsequently affect classification output.

Individual reaches classified into groups of similar morphologies within one framework sometimes failed to align with a comparable group under another classification framework (Table 4). This pattern was most apparent in confined reach types that did not aggregate into consistent groups across statistical clusters, Rosgen Classification System types, and natural channel classes. For example, River Styles' confined valley with occasional floodplain pockets were classified as all four statistical clusters, five different RCS reaches, and three NCC classes (Table 4). In contrast, partly confined channel types were more likely to be grouped into only one or two channel types from other classifications. For example, River Styles' partly confined low-moderate sinuosity, planform-controlled discontinuous floodplain grouped into RCS types of C4b and B4, and NCC classes of plane bed or straight planform, and steep/narrow and narrow/sinuous statistical clustering classes. Additionally, the partly confined low-sinuosity planform-controlled anabranching river style occurred exclusively as B4 RCS classes, straight, narrow statistical cluster, and straight NCC. The partly confined bedrock-controlled elongate discontinuous floodplain river style classified as slightly to moderately entrenched, moderate sinuosity RCS types (C, B channels), and wide, low-gradient clusters, but was less consistently grouped by NCC (straight, confined, and island braided). While strict fidelity between groups within each classification did not occur, partly confined River Styles grouped well with the other classifications based on their component inputs.

5. DISCUSSION AND CONCLUSIONS

Our comparison of four distinct classification frameworks demonstrates that there is significant overlap and agreement between outputs of the classifications used here. The most common result in all four frameworks was some variant of moderate-high gradient channel with coarse substrate, reflecting the high relief nature of the Middle Fork John Day Basin resulting from resistant igneous and metamorphic lithologies (Figure 2, Table 2). Similarly, the least common channel types in all four frameworks were those variants corresponding to wide, freely meandering, low-gradient streams. These laterally unconfined streams are the ones most emphasized in classic channel planform classification and the fluvial geomorphology literature[87], although they are rare in many montane regions[33].

The four classification frameworks showed widespread agreement between their outputs despite being variably based in either form or process (Table 2). While all four frameworks contained a combination of metrics that either directly described the processes at work in channel reaches or employed measurements of channel form as surrogates for geomorphic processes, the relative role of form- and process-based components varied between frameworks. For example, while the RSF depends on observation of processes (e.g. channel behavior at overbank flow, interaction with vegetation), NCC and RCS rely on measurements of channel form that are directly related to sediment supply and transport competence at individual channel reaches. Taken to the extreme, the statistical clustering approach used here exclusively relies on field-based measures of channel form in an attempt to differentiate individual reaches. Despite the range of form- and process-based metrics in each framework, the four approaches exhibited overall agreement, suggesting that a simple differentiation in terms of form or process does not characterize the utility of a particular approach.

Furthermore, when considering how the geomorphic and stream management or restoration communities group classification approaches (see [3]), the line between those based in form and those based in process is not necessarily clear. Many of the commonly used classification frameworks defy such simple binning, instead combining aspects of form and process to group river reaches. In general, the use of channel form metrics as surrogates for stream or valley-scale processes is widespread [3]. This is perhaps a reflection of the complexity involved in a purely process-based classification framework, which would require high-resolution measurement of rates of sediment transport, supply, and channel adjustment at many sites throughout a stream network of interest[4]. Such approaches are only possible under exceptional mandates, or with a great deal of human and financial capital[88]. In most basins, classification frameworks based on channel form metrics are the best surrogates for inferring process. Form-based assessments have been borne of a necessity to characterize river reaches over meaningful spatial scales within a reasonable timeframe and at moderate costs.

At the same time, rivers are dynamic and adjust in response to water and sediment supply [89,90]. If these current boundary conditions are not considered, an assumption of stability may be made, when in fact channel form may indicate a transient, or responding state given altered sediment or water availability. For this reason, some classification frameworks separate current character and behavior from evolution, condition and trajectory (e.g. the RSF), and others separate condition (e.g. RCS). In other systems, the degree of channel departure from background conditions is considered and may completely invalidate certain frameworks. For example, in watersheds heavily influenced by mill dams or beaver ponds and their associated legacy sediment deposits [86,91], the NCC classification approach may not provide an informative river classification as this method predicts pre-disturbance channel planform.

In contrast, RCS or RSF both lend importance to local-scale channel dimensions and, particularly in the case of RSF, the patterns of river types in a system, and may be quite revealing in pinpointing stream reaches that vary from expected channel forms. In cases of disagreement between frameworks that classify current channel form (e.g. RSF, RCS, clustering) and those that classify pre-disturbance channel planform (e.g. NCC), such disparate results may indicate departures from background conditions and allude that channel form is not at equilibrium with larger-scale controls such as valley setting. Such understandings of current channel form, compared to background form, are pivotal in appraising channel stability and potential capacity for adjustment [92]. Finally, our research does not examine the ability of form-based metrics used in river classification frameworks to capture ecological processes operating in streams, as we focus solely on river form as an indicator of physical process. Ecological dynamics in streams, such as presence/absence of aquatic biota or the distribution of riparian vegetation may be closely related to physical form [43,93]. Stream ecology may also exhibit dynamism at spatiotemporal scales not examined here (e.g. instream wood volume/frequency;[94]), or drive geomorphic processes themselves [73].

5.1 WHY DO CLASSIFICATION FRAMEWORKS DIFFER?

Differences in the output of classification frameworks ultimately arise because each framework emphasizes physical variables differently throughout the classification process. Although the data requirements between classification frameworks are similar, including channel planform metrics, substrate, and the ability of a channel to migrate and access sediment sources (Table S.1), the order in which these attributes appear within a particular framework's decision tree may vary markedly (see Supporting Information). For example, at the broad planform scale, the first step in the differentiation of reach types within the RCS is to distinguish between single- and multi-thread channels. In contrast, this characterization of channel planform is completed several steps later in the River Styles framework, which instead places the greatest importance on the degree of valley confinement. Both RCS and River Styles, however, make their final differentiation between stream types based on the bed material texture within a reach.

When considering statistical approaches such as NCC and clustering as employed here, all physical attributes are used in the grouping algorithm, and true hierarchical decision trees are foregone. Because most statistical classification techniques computationally determine which of the input variables are most important in differentiating stream types, ranking them accordingly, *a priori* importance is not placed upon a given variable. While variables can be weighted in clustering and machine-learning algorithms to emphasize the importance of specific processes, many classifications, like NCC's support vector machine, instead use training data to fit algorithms before computing classes for a data set. This approach is limited not by what variable is perceived to be most important, but rather, what training data are available from which to build a model. Similar constraints exist on clustering, which can only group reaches that have data available. In building representative statistical classifications, having spatially-balanced, randomized sampling is ideal[95]. Another key methodological consideration in using statistical classification approaches is that the number of classes is often determined by the strength of the fit between data and algorithm, and must be validated by expert judgment of the classified statistical groups and their geomorphic likelihood. Relatively strong clustering was observed here with a relatively small number of classes (four), whereas the other three classification schemes had between eight and eleven classes. Accordingly, parameter and algorithm selection, data transformation or standardization can all influence how well data fits a given clustering algorithm, with consequences on whether geomorphically meaningful groups are lumped or split.

More generally, the difference in the relative importance of each physical variable within a particular classification framework points to the form-process interactions that each classification method attempts to document or explain. Particularly in the hierarchical approaches (e.g. RSF, RCS), the order of appearance of variables in the classification (Figures S.2-S.4, S.6) has a large impact on the classification of an individual channel reach. Distinct differences are also evident when the original intent of the classification framework is considered. Some frameworks produce analyses of current reach type (e.g. RSF, RCS, statistical clustering), while others predict pre-disturbance or natural channel morphology (e.g. NCC). Differences in the temporal output of each framework may not be intuitive, but provide a critical context for interpreting and using the outputs derived[96].

5.2. COMPARISON OF TIME AND DATA REQUIREMENTS

The amount of data, time, effort, or expertise necessary for the completion of a particular channel classification varies widely between frameworks (Table 5; Figure 6). Because these requirements vary depending on the classification employed, care must be taken to assure the information provided by the chosen framework is consistent with the purpose for which the framework is applied, be it basic eco-geomorphic inquiry[38,97,98] or applications such as watershed management or stream restoration[5,13,99,100]. With regard to the classification frameworks examined here, both RCS and statistical clustering are relatively straightforward in application, and require minimal time and data to complete for a set of reaches (Figure 6). The simplicity of RCS's reach-scale classification is one of the major reasons for its widespread use within the watershed management community[11]. In our case, the RCS classification presented here (Section 2.4) required roughly three weeks to complete, excluding field data collection. Although the level of computational and statistical expertise required to complete and interpret the results of a statistical clustering framework is not trivial, the rapidity with which clustering or simple statistical classifications can be completed, altered, and adaptively run is attractive. Once metrics are selected for use in the clustering algorithm (Section 2.5), the classification can be run in a matter of minutes. It is essential to point out that in reach-level methods like RCS and statistical clustering, field-based data collection are imperative for successful classification (and verification of reach types in the case of RCS). Because we used an existing, high-resolution dataset to complete these classifications, the time spent classifying reaches was greatly reduced.

Table 6. Summary of the trade-offs between methodological assumptions, data requirements, and outputs between River Styles, Natural Channel Classification, Rosgen Classification System, and statistical clustering methods.

Classification framework	Potential advantages	Potential drawbacks
River Styles	Explicitly uses watershed-, reach- and geomorphic unit-scale processes to classify stream segments[38]. Bi-directional (top down/bottom up) approach captures holistic vision of watershed[36]	Requires relatively high-level understanding of fluvial and landscape geomorphology
	Uses flexible, defined criteria of both river forms and processes to identify groups of reaches and their requisite driving processes [9]	Data-intensive; requires a combination of spatially extensive desktop data along with field-based information on reach/unit-scale channel form
	Open-ended and generic approach that can be used in any watershed[9]	Open-ended and generic approach that can be used in any watershed [9]
	Includes components for appraising river condition, recovery potential and prioritizing restoration and management[9,101]	Time-intensive; examination of spatial data and development of river styles tree requires large time investment
Columbia Basin Natural Channel Classification	Spatially extensive, pre-calculated planform classification for channels > 3 m in width across the Columbia River Basin.	NCC channel classes are currently limited to the Columbia River Basin, but the methodology is transferable to other locations.
	Identifies possible restoration targets where planform has been modified by watershed disturbance, changes in hydrologic regime or sediment supply.	Pre-disturbance planform may not reflect current watershed disturbances or processes. Conversely, the NHD channel network reflects current conditions, which may lead to errors in predicted natural channel pattern where channel alignment has been modified.
	This classification method complements stream monitoring programs across the Columbia River Basin that measure channel attributes to infer habitat trend (e.g. CHaMP and PacFishInFish Biological Opinion; [102]	Cannot be used to assess current channel condition and limiting processes without additional information on stream disturbance and condition following European settlement.
	Machine learning workflow can be modified for other watersheds with known relationships between landscape setting, channel attributes, and planform	Relies on coarse-resolution landscape and channel data that may not be ideal for creating model training data in all channels and landscapes.

Rosgen Classification System	Effectively used to help develop restoration plans for stable meandering gravel and cobble bed rivers, provided a correct reference reach is identified[40]	Metrics for stream type classification are based on empirical data from selected streams [28]
	Provides a common language for specialized professionals in watershed science to communicate when referencing stream types [28,103]	Can be incorrectly applied due to seemingly ‘cookbook’ style of some reference materials [13]
	Correctly identified stream types have inherently different recovery potential, sensitivity to disturbance, and interactions with vegetation that can be used to inform management and restoration decisions[28]	As a restoration tool, success is primarily based on locating a stable and ‘correctly identified’ reference reach[12,40]
Statistical Classification	Can identify relationships between many interrelated reach-scale or watershed-scale processes[44]	Can find unrealistic or hydrogeomorphically irrelevant patterns in noisy data [*Caratti et al.*, 2004]
	Can take top-down (landscape – watershed – reach) or bottom-up (reach – watershed) approaches[43]	Requires *a priori* selection of important processes within a given watershed or set of reaches.
	Numerous statistical approaches are available for clustering, classifying, and testing for between-group differences across multiple reaches.	Relies on statistical expertise for effective implementation and interpretation.
	Classified groups of reaches make discrete units from which qualitative bioassessment for aquatic biota or habitat can take place.	Often relies on correlations to biotic processes to differentiate “high quality” reaches from “lower quality” reaches.
	A long tradition in ecology, hydrology, and geomorphology has developed well-understood methods that can be implemented in many software packages.	Rapidly developing methods in statistics machine learning allow for “black box” correlative models that can be difficult to interpret, understand or explain to managers.
	Allows for user-defined watershed attributes for defining classification groups.	Workflows can be time consuming and difficult to interpret to non-expert users.
	Can be used in the absence of “reference” reaches to identify typological gradients between many reaches.	Requires moderate to large sample sizes and relatively high quantities of remotely sensed or field-collected data to find meaningful patterns at large scales.

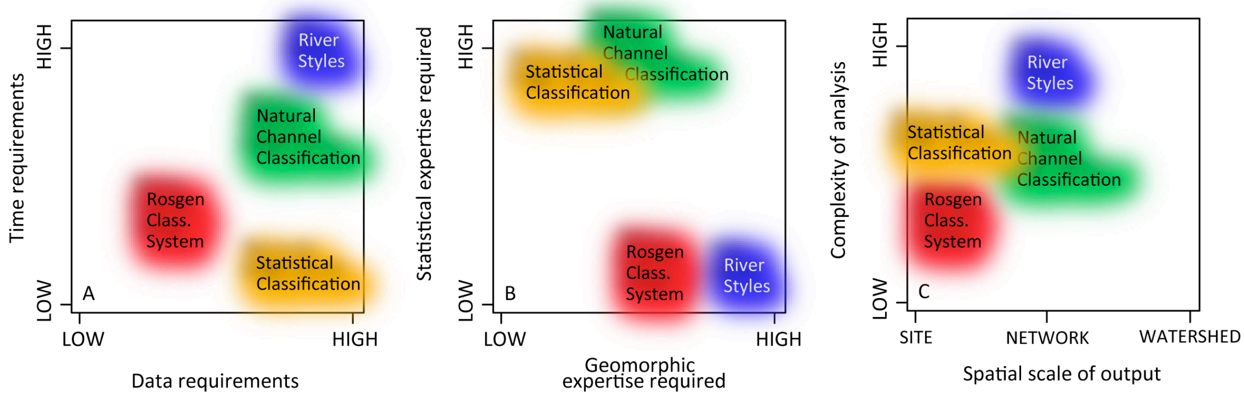

Figure 6. Trade-offs between each of the four classification frameworks shown in relative bivariate space. Trade-offs are between (A) time and data requirements required to perform a classification, (B) the amount of statistical and geomorphic expertise required by the classifying individual/organization, and (C) the complexity of analysis versus the spatial scale at which each framework operates. Note that all classifications require either significant data, expertise in statistics and/or geomorphology, and that the position of each framework in panels reflects the stage(s) to which their workflows were completed in this study only.

In the case of RCS, the classification produced output for which we confidently expect the classified channel type to accurately reflect the site-level conditions in nearly all classified reaches. At the same time, within the RCS, field-based measurement and validation of classification is of high importance, and so confidence in classification output can be increased with subsequent site visits. In fact, site visits are imperative in later stages not only to confirm reach-scale classification, but to assess channel condition and determine whether the classified channel type reflects an equilibrium or transient state [29]. We are somewhat less confident that statistical clustering will produce groups of channels that always reflect conditions in the field. This is because the distance measure, clustering algorithm, and the resulting number of groups – in effect, the number of representative channel forms found at individual reaches – is inherently a choice of the classifier. Much like RSF, the user is forced to compromise between selecting an

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informative number of classification groups and creating parsimonious groups from which to make general inference (i.e. lumping versus splitting groups). This process has major implications for subsequent statistical analyses, stratified sampling of reach types for other measurements, and condition assessment.

In contrast, the NCC framework and RSF require greater investments of time, and require greater expertise in fluvial geomorphology to achieve meaningful results (Figure 6). Not including algorithm refinement, the NCC classification can be completed for a large watershed (e.g. data gathering, preparation, computation) in roughly two months' time. However, automated classification over broad areas means that the validity of site-level predictions from NCC requires careful interpretation. For example, site visits to confirm predictions of NCC may not be straightforward, since the framework attempts to classify pre-disturbance, and not current, channel planform. Stage one of the RSF, as detailed in Section 2.2, required an investment of roughly 3-4 months. This timeframe included a desktop-based classification, field-based refinement of classes, and field-based ratification of reach boundaries that produced relatively high levels of confidence in the resulting outputs. In the case of NCC, computational expertise is paramount, in addition to a thorough understanding of the landscape-scale controls (independent or anthropogenic disturbance) on channel planform throughout a watershed of interest. In the case of RSF, a similar understanding of both landscape and local-scale controls on river form is required, as is the ability to distill the formative processes within a watershed down to the most relevant geomorphic characteristics for classification.

Perhaps obviously, the increased amount of time and expertise required for implementation of the RSF or NCC is counterbalanced by the larger spatial extent across which either framework can be applied, creating continuous, network-scale results (Figure 2; Figure 6C; Section 2.7), and in the case of RSF the level of process-based detail that is generated. While it would be difficult, if not impossible, to upscale the results of RCS or statistical clustering to approximate a continuous classification throughout a stream network, this scale of classification is a fundamental component of both RSF and NCC. As such, information regarding reach-scale anomalies in river characteristics can be easily gleaned from continuous network-scale classification frameworks.

Finally, frameworks may be differentiated on the basis of their repeatability. That is, when confronted with the same watershed (or dataset), to what degree will two individuals come to the same conclusions regarding the number of reach types and their locations throughout a watershed? The answer to this question has major implications for the transferability of a classification across watersheds and communication to stakeholders. Unfortunately, this is a largely unexplored question, and must be more fully addressed before the utility of individual classifications can be assessed. Given knowledge of the prescribed workflow for each framework, we can attempt to draw inferences regarding the repeatability of each classification used herein. The reliance of NCC and statistical clustering on pre-determined algorithms indicate that they will be highly repeatable between classification runs, *provided* that the same input data (e.g. the same set of measurements) are used during each run. The number of clusters that are settled upon in a statistical clustering workflow is reliant on a combination of fit statistics and expert judgment on the attributes being clustered. This can lead to variability in the final number of classified reach types and the processes or elements of form that distinguish them.

The finite number of possible reach types in the RCS classification, along with the discrete workflow and associated reach measurements required to work through the hierarchical tree, suggest that RCS may also be highly repeatable. While inherent observer variability may lead to differences in final stream type(e.g. [13]), Rosgen[15] argues that this issue may be corrected by increased field crew training, with particular regard for the identification of bankfull discharge level, which influences entrenchment ratio. The RSF does not set concrete quantitative breaks between distinguishing attributes leading to reach types (with the possible exception of valley confinement; Figure S.2 – S.4) and nor does it set intrinsic limits on the number of reach types that can occur within a watershed. As a result, the number of, and distinguishing factors between, basin-wide reach types using River Styles may differ markedly between investigators.

While data, time, and expertise requirements differ between stream classification frameworks, we can still conclude that *river and stream classification are powerful tools that can be used to make inference about how stream channel and floodplain landforms respond to hydrologic and geomorphic processes*. In our application of four distinct classification approaches, we found that each methodology captures the range of channel classes within the Middle Fork John Day River. Although the frameworks incorporated, to varying degrees, aspects of channel form and process, their outputs were often highly comparable and often resulted in overlapping groups of reaches with similar hydrogeomorphic setting, channel form, and bed sediment characteristics. All four classifications yielded results that, regardless of their comparison with the other classification outputs, can inform applied river management, restoration, and condition assessment.

While it is often assumed that classification merely describes the form of a stream reach, our results indicate that these classifications effectively capture how channel form may respond to hydrologic, geomorphic, and landscape processes. In the absence of exhaustive sediment transport, hydrologic, and/or hydraulic data, and the personnel to analyze them, stream classification provides a critical tool for watershed managers to better understand the range of potential reach types in their watershed and the likely driving processes. Because classifications range from thorough but time-consuming network based approaches (RSF, NCC) to more rapid reach-based approaches (statistical clustering, RCS) that categorize current (RCS, statistical clustering, RSF), historic (NCC; later stages of RSF not discussed here), and potential future trajectories (later stages of RSF not discussed here), we urge managers to use classifications appropriate for the application at hand. By pairing network based classification methods with network- or watershed-based applications (e.g. habitat audits, landscape planning) and reach-scale classification with reach-scale applications like reach-scale habitat comparisons following habitat change from hydrologic alteration or restoration activities, classification can effectively link stream forms to their governing processes in applied contexts.

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Statement of Author Contributions

This manuscript was conceptualized by AK, NH-S and RC and written by NH-S, AK, RC, GB, TB, DLR, JMW, KF, MJ, GO, and NB. Figures and tables were made by AK, NH-S, and MJ. Data was collected, managed, and analyzed by AK, NH-S, RC, HI, MJ, TB, GO, NB. Author order was determined by coin-toss between NH-S (tails) and AK (heads). Following AK and NH-S, author order is presented alphabetically and reflects equal contributions to the manuscript.

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SUPPORTING INFORMATION CAPTIONS

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