Flint Hills – NetMap
Geomorphic Stream – Aquatic Biota Classification System

For the U. S. Fish and Wildlife Service (Denver, CO)

Dr. Lee Benda, Kevin Andras and Daniel Miller
TerrainWorks (NetMap) www.terrainworks.com;Mt Shasta, California USA

1-15-2015

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Flint Hills – NetMap

Geomorphic Stream – Aquatic Biota Classification System

Executive Summary:

NetMap (www.terrainworks.com) was used to develop a coupled channel geomorphic – aquatic biota classification system in the Flint Hills ecoregion in eastern Kansas for the U.S. Fish and Wildlife Service and Kansas Department of Wildlife, Parks & Tourism. The principle objective of the classification system is to link channel physical characteristics to aquatic biota, including presence or absence of individual species, communities (or guilds) of species, and animal abundance; there are 99 species of fishes and 43 species of mussels in the Flint Hills channel system. Since the aquatic component of the Flint Hills classification system is not a part of this study scope, a customizable and iterative classification system is developed. However, the Flint Hills system was used to build three new classification systems and apply two existing systems as a first step to inform a taxonomy of channel geomorphic – aquatic biota.

A synthetic stream layer was derived using 1 m LiDAR and 10 m DEMS across the 68,000 km^2 Flint Hills landscape. The synthetic stream layer, consisting of 1.27 million individual stream segments (approximately 50 m to 250 m in length), is attributed with a suite 24 landscape, fluvial geomorphic and hydrologic parameters that can be used for classification including drainage area, gradient, mean annual flow, floodplain width, channel confinement, tributary confluence effects, width to depth ratio, and local geology among others. Field data on channel physical characteristics and aquatic biota from Kansas Department of Wildlife, Parks and Tourism were geo-referenced to individual channel reaches across the Flint Hills. A portion of those data was used to create hydraulic geometry attributes including summer and winter bankfull widths and depths, and summer and bankfull flows (and summer habitat volume).

To build flexibility and analysis capacity into a Flint Hills stream geomorphic and aquatic biota classification system, a multi-faceted approach is used that consists of four components: 1) “Parameter Nesting” that uses nested sets of remote sensing parameters to ensure classification to the upstream to downstream limits of the river networks and data, 2) “Selection Grouping” that allows for flexible combinations of parameter ranges to build classifications, 3) “Spatial Probability Mapping” that converts field data on patch-scale habitat features to measures of feature density and for its extrapolation across all Flint Hill channel segments using remote sensing data, and 4) “Biotic Sorting” that categorizes field data on fish and mussel species and their abundance by channel classes. Parameter nesting uses up to three parameters and two class breaks per parameter for a maximum of eight classes and it ensures classification to river network and data limits with no gaps. Selection Grouping is not limited to the number of parameters and gaps and partial stream classification is allowed. Both systems create non overlapping channel class types and allow use of the full suite of remote sensing channel attributes that totals approximately 24 in various combinations. Parameter Nesting and Selection Grouping utilize cumulative distribution functions of channel attributes to help guide selection of parameter class breaks. Since the primary goal of the Flint Hills channel geomorphic classification system is to inform classification of aquatic biota, the system requires the ability to explore classification fidelity and is applied iteratively.

The third component of Flint Hills classification system, Spatial Probability Mapping, utilizes field data on patch scale aquatic habitat features available from Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program. Field data were available at 307 sites that ranged in length from 150 to 300 m and measurement spatial scale was one to ten meters along the thalweg with cross

section measurements every 10 to 15 m. Physical attributes included bankfull and summer hydraulic geometry (width and depth), substrate size classes (bedrock, boulder, cobble, gravel, sand, fines), bed morphology (pools, riffles, glides, rapids) and woody debris abundance (none, sparse, moderate, heavy, very heavy). Spatial Probability Mapping calculates the proportion (or spatial probability) of different field attribute values across the study reaches. Field sites are associated with individual channel classes and spatial probabilities of bed morphology, substrate and wood storage are extrapolated to all channel segments in each channel class. This allows the remote sensing attributes used in NetMap's channel classification to be associated with field-based spatial probabilities of aquatic habitats across the entire Flint Hills landscape. Analysts can determine how different each channel class is compared to others in terms of aquatic habitats, e.g., bed morphology (pools, riffles, glides), substrates and in-stream woody debris.

The fourth component of the classification system, Biotic Sorting, is used to organize field data on species of fishes and mussels and their abundance according to individual channel classes. Biological data are converted to indices of presence or absence of individual fish and mussel species and frequency and density of juveniles and adults, by species, within channel classes created by Selection Grouping or Parameter Nesting methods. This supports the ultimate objective of linking channel and landscape physical characteristics to aquatic biota in support of efforts such as the U.S. Fish and Wildlife Service's Surrogate Species initiative and other applications.

Flint Hills field and remote sensing data indicate that reach-scale channel morphology and bed substrate are relatively homogenous across the channel network. The channel system is dominated by alternating pool-riffle and glide morphology and gravel-cobble substrate in segments less than 0.02 in slope, the portion of the network occupied by fishes and mussels. However, Nested Sorting-Spatial Probability Mapping reveals that pools increase downstream, riffles decrease downstream, sand decreases downstream and woody debris increases slightly downstream. In addition, habitat volume increases downstream and matches a pattern of increasing fish and mussel species richness downstream. Thus, the increase of channel size, habitat volume and pool abundance downstream appear to be an important classification factor (and its correlative attribute such as gradient), including for aquatic species that favor pool habitats over riffles and glides. This finding is similar to other research on distribution of fishes in Kansas streams (Martin et al. 2013, Troia and Gido 2014).

Although the Flint Hills classification system is designed to create customizable channel classes for diverse applications by other analysts, three new classification systems are built and two existing ones applied during this study. They include: 1) Parameter Nesting involving drainage area alone, 2) Two Selection Groupings encompassing combinations of drainage area, channel confinement, gradient, habitat volume and tributary confluences, 3) Buffington and Montgomery classification system (2013) based on gradient and width to depth ratios, and including a modified version to better match it to the Flint Hills landscape, and 4) Rosgen (1996) channel types that use entrenchment ratio, width to depth ratio and sinuosity. Confirming whether these classification systems can inform a taxonomy of channel geomorphic – aquatic biota in the Flint Hills is beyond the study scope because of the lack of a field based component and the extension of the classification to aquatic biota that is to be conducted by others. However, the five classification systems that extend to Spatial Probability Mapping and Biotic Sorting support the prime objective of the Flint Hills geomorphic stream – aquatic biota classification.

Channel classification that extends to aquatic assemblages can be integrated within larger landscape classification frameworks that encompass geology, soils, erosion processes and climate, called ‘geomorphic guilds’ (Watson et al. 1998). The watershed assessment platform, NetMap, contains the ability to incorporate landscape features into the development of stream classification systems and geomorphic guilds. In the present analysis in the Flint Hills, relevant landform characteristics include hillslope erosion potential (driven by slope and convergence), valley confinement, floodplain size, river network geometry via tributary confluences, geology and climate. However landforms (mostly rolling hills of low relief and slope) and channel networks (with gradients less than 0.025 occupied by fishes and mussels) in the Flint Hills do not exhibit a high degree of spatial variability, and thus limits the opportunity to link streams and aquatic assemblages to larger, spatially variable landscape features.

NetMap’s multi-faceted classification tool that includes Spatial Probability Mapping of patch scale channel features and Biotic Sorting of species and their densities by channel classes provide a robust methodology to build a taxonomy of channel geomorphic – aquatic biota relationships. The tool can support application of the U.S. Fish and Wildlife Service Surrogate Species initiative as well as various monitoring, bio-census, resource management, conservation and restoration applications. In addition, the classification tools can be used to evaluate whether current monitoring programs are spatially distributed according to channel or habitat types of interest and their relative proportions across a watershed or landscape. The coupled tools can also be used to establish new field sampling protocols based on channel types and their representative populations within a watershed or landscape.

The classification system presented in this report is designed to be applied manually using a combination of knowledge of the Flint Hills channel physical characteristics and aquatic biota, geomorphic and ecological principles, and professional judgment. However, the Flint Hills landscape is large (68,000 km^2) and potentially complex given its varying watersheds and 143 species of fishes and mussels. Nevertheless, the integrated classification components (including Spatial Probability Mapping and Biotic Sorting) lay a solid foundation for further numerical analyses. The potential exists, with additional funding, to automate and optimize via computer algorithms, building a taxonomy of channel geomorphic – aquatic biota or geomorphic guilds in the Flint Hills or in any landscape using statistical methods such as logistic regression, regression trees and multivariate cluster analysis. The automated system could also be used for other purposes such as designing monitoring and bio-census programs to reflect the range and relative abundance of different channel types across watersheds and landscapes.

Introduction

The U.S. Fish and Wildlife Service, in conjunction with Kansas Department of Wildlife, Parks & Tourism, requested development of a geomorphic stream – aquatic biota classification system for the Flint Hills ecoregion located in eastern Kansas. The geomorphic stream classification system is designed to enable a classification of aquatic biota in the Flint Hills ecoregion by the U.S. Fish and Wildlife Service to support the agencies' Surrogate Species initiative among other applications.

The geomorphic – aquatic biota classification system represents a joint effort by TerrainWorks using the NetMap system of watershed assessment (Benda et al. 2007, 2009, www.terrainworks.com), the U.S. Fish and Wildlife Service, and the Kansas Department of Wildlife, Parks & Tourism. The U.S. Fish and Wildlife Service provided guidance on channel classification for biological applications and provided funding; TerrainWorks developed a synthetic stream layer using available 1 m LiDAR and 10 m digital elevation models (DEM) and developed a multi-faceted classification system; and Mark Vanscoyoc of Kansas Department of Wildlife, Parks & Tourism provided access to a large spatial database covering physical and biological attributes in the Flint Hills ecoregion and advised on design of the classification systems.

The geomorphic stream classification component in the Flint Hills needs to inform the classification of aquatic biota using individual species, communities of aquatic organisms, and animal abundance. It can also support building relationships between aquatic assemblages and landscape characteristics, as represented by channel conditions (sensu 'Geomorphic Guilds', Watson et al. 1998). Inventoried aquatic species in the Flint Hills stream channels include 99 species of freshwater fishes (includes subspecies and hybrids) and 43 species of mussels. To link geomorphic stream classification to aquatic biota requires a customizable and iterative approach in which different combinations of stream and watershed characteristics are used to differentiate among aquatic species presence and absence, species communities (or guilds) and animal densities (number per length and unit area).

A multi-faceted classification system is built for the Flint Hills that is comprised of four main components: 1) "Parameter Nesting" that uses nested sets of parameters to ensure classification to the upstream-downstream limits of river networks and data, 2) "Selection Grouping" that allows for flexible classification using data ranges of attributes, 3) "Spatial Probability Mapping" that converts field data on patch-scale habitat features to measures of feature density across all Flint Hills channels, and 4) "Biotic Sorting" that categorizes species occurrence and their abundance by channel classes. When used in combination, the system is designed to build a taxonomy of landscape – channel – aquatic biota relationships to inform programs such as the Surrogate Species, related bio-census and other ecological monitoring programs.

Study Area

The Flint Hills ecoregion is one of the last remaining intact tall grass prairie ecosystems in North America. The EPA and the World Wildlife Fund have designated the Flint Hills as an ecoregion, distinct from other grasslands of the Great Plains. The Flint Hills project area for the stream classification project is approximately 68,000 km^2 (**Figure 1**).

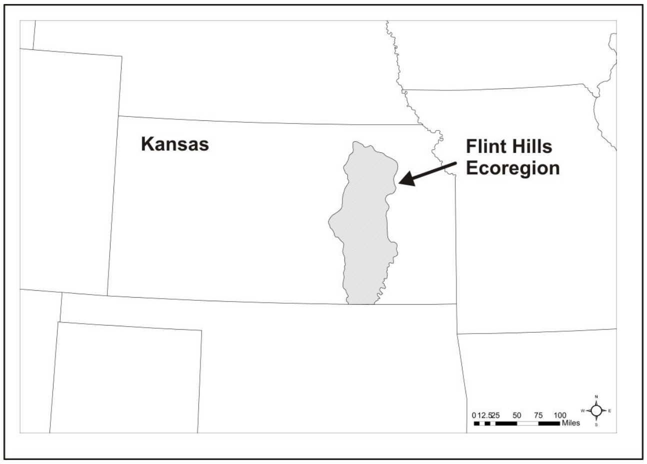


Figure 1. Study Area.

Channel drainage areas range from less than one square kilometer to over 2,000 km^2; fishes and mussels occupy channels with gradients approximately less than 0.022 in slope. Channel are mostly enclosed by dense riparian vegetation along the majority of the smaller streams; morphology of the larger channels include single to multi-threaded channels, gravel bars and alternating pools, riffles and glides (**Figure 2**).

The geology of the Flint Hills ecoregion is dominated by interbedded argillite, limestone and more modern day (Quaternary) gravel and sand deposits (**Figure 3**). The argillite and limestone lithology creates chert dominated, low productivity soils that significantly reduced farming impacts in the Flint Hills ecoregion over the last couple of centuries. The current dominant land use is cattle and bison grazing.

The 99 species of freshwater fishes (includes hybrids) include the Arkansas Darter and Shiner, June Sucker, Kendall Warm Springs Dace and the Pallid Sturgeon.

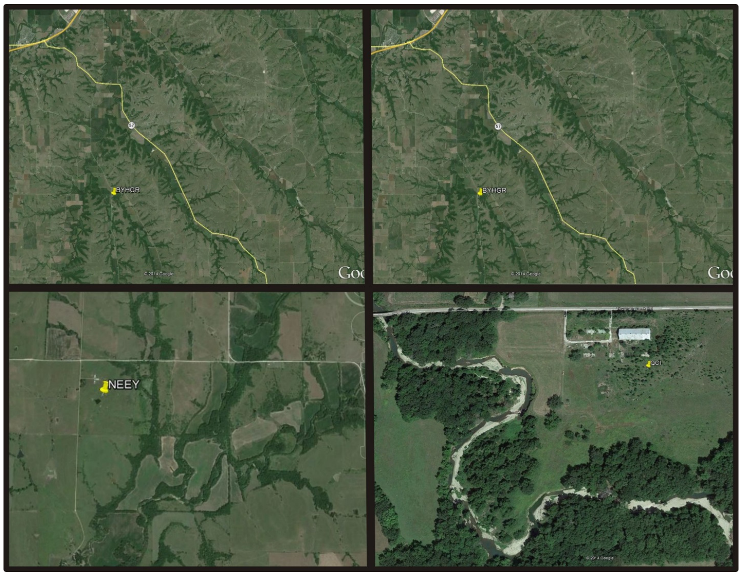


Figure 2. Study area channels on Google Earth.

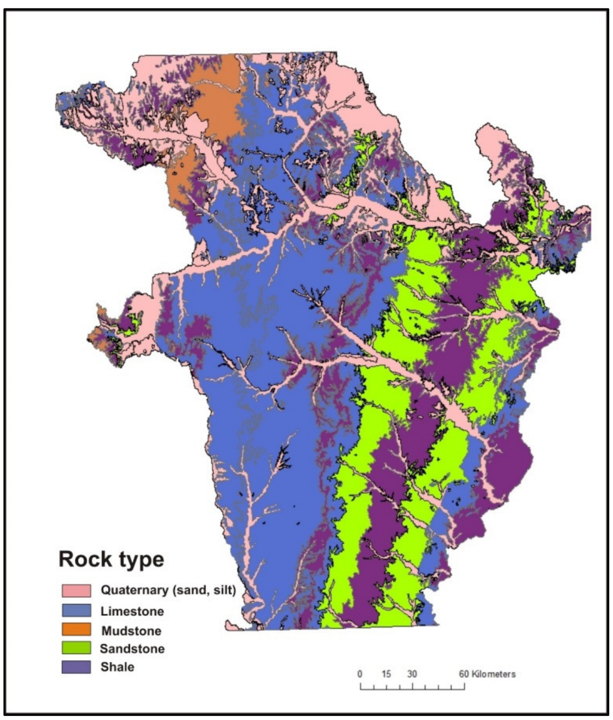


Figure 3. Rock Types in the study area.

Stream and Aquatic Habitat Classification

An important ecological principle underlying stream classification is the hierarchical spatial nature of channel morphology and aquatic habitats. Fluvial environments can be viewed as a nested set of spatial features ranging from the watershed (10^2 – 10^3 km^2), valley segment (10^2-10^3 m), reach (10^1-10^2 m), and micro habitats that include individual pools, riffles, gravel bars and log jams (10^0 – 10^1 m) (**Figure 4**, Frissel et al. 1986). This concept informs how stream classification can be applied using a range of data obtained from remote sensing to field measurements. Classification at the scale of entire watersheds or landscapes (like the Flint Hills ecoregion) that involve thousands to millions of stream reaches (the terms reaches and segments are used interchangeably in this report) require the use of remote sensing data, such as channel gradients derived directly from DEMs using a synthetic river network. However, field data collected at the scale of reaches and micro habitats (available from the Kansas Department of Wildlife, Parks & Tourism) can also be used to classify individual channel segments, or they can be coupled to remote sensing data for their extrapolation across entire watersheds and landscapes (**Figure 4** and see later).

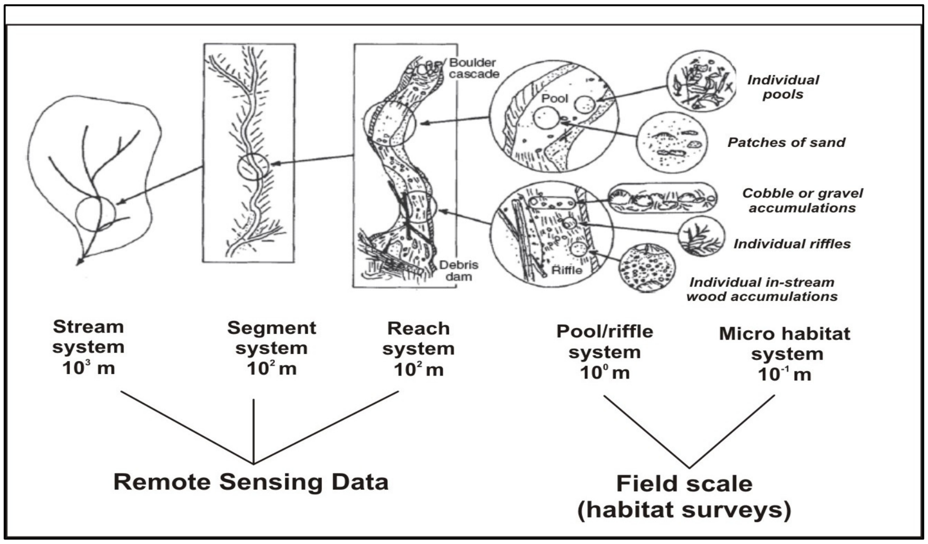


Figure 4. The hierarchical nature of aquatic habitats (after Frissel et al. 1986).

There are different types of channel classification approaches. Strahler (1952) applied a stream ordering approach on channel networks based a numerical measure of channel branching or sequence of tributary intersections. For example, the highest channel segment in a network is considered 'first order'. Where two first order channels intersect, a 'second order' channel is formed. A 'third order' occurs where two second order channels confluence, and so on. Although stream order is a handy way to organize channels by branching patterns, one limitation is that the largest order of any network or watershed is dependent on the location of the initiating stream order, which can vary significantly depending on how channel networks are mapped, either by hand using photos or derived by computers using DEMs. For example, many USGS blue line topographic maps do not include the smallest headwater, first-order channels (Heine et al. 2004). Stream order is one of the remote sensing attributes in the Flint Hills that can be used for classification.

Other stream classification techniques include classifying channel planform patterns (meandering, braided, and straight) based on bankfull discharge and gradient (Leopold and Wolman 1957). This concept was expanded to include width to depth ratios, sediment caliber and bedload to total load ratio by Schumm (1963). Other classification systems focused on the interactions between channels and their floodplains, including their response to disturbances (Church 2006). Channel sinuosity that can be used to characterize meandering versus straight reaches is included in the remote sensing attributes used in this study.

Using a large sets of field observations, measurements and general fluvial geomorphic principles in mountain terrains in the western U.S., Montgomery and Buffington (1997) created categories of stream types (alluvial, colluvial, step pool, plane bed, pool riffle and braided) based on width depth ratio, gradient, substrate size, sinuosity, sediment supply and valley morphology. The classification evolved and is currently expressed using two parameters, channel gradient and width to depth ratios (Buffington and Montgomery 2013) (**Figure 5**). The Buffington and Montgomery channel classes based on domains of gradients and width to depth ratios is applied to the Flint Hills; the classification is also modified to better match it to the Flint Hills landscape.

David Rosgen also assembled a large range of field observations and measurements of channels in the semi-arid western U.S., and combined those with fluvial geomorphic principles (Leopold et al. 1964) to create the Rosgen classification system (Rosgen 1996). The Rosgen stream classification system uses entrenchment ratio (floodplain width divided by channel width), width to depth ratio, sinuosity, channel gradient and substrate size (**Figure 6**). The classification system, that has an alphabetic nomenclature (A, B, C, D etc.), subdivides channel types primarily by slope gradient, sinuosity, single to multi thread and cross sectional geometry. The Rosgen classification system is applied to the Flint Hills ecoregion using the remote sensing data of entrenchment ratio, width to depth ratio, and sinuosity.

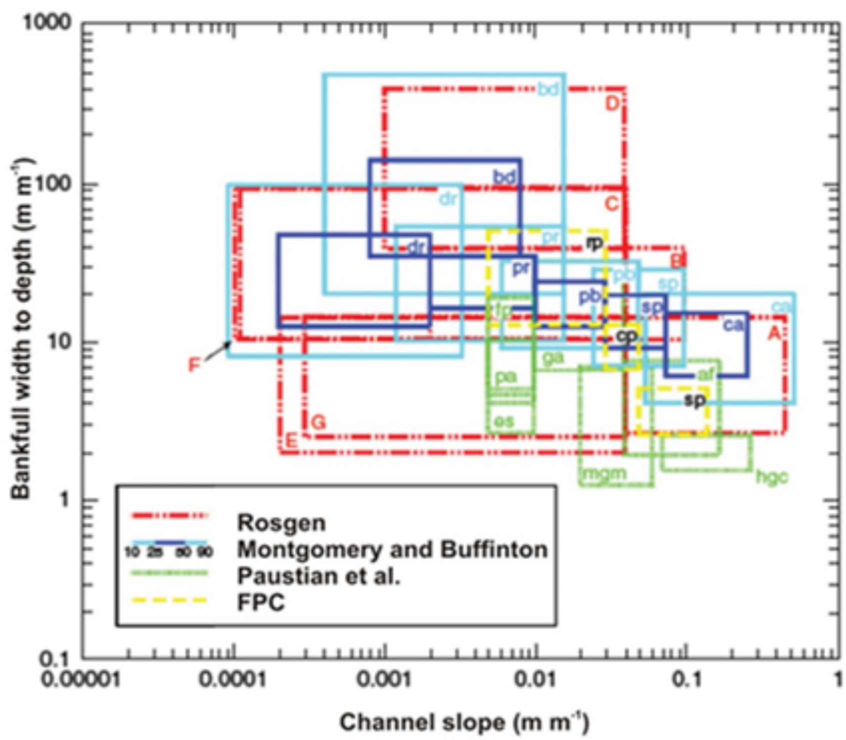


Figure 5. Buffington and Montgomery (2013) channel class domains.

"bd' = braided, "dr" = dune ripple, "pr" = pool riffle, "pb" = plane bed, "sp" = step pool and "ca" = cascades.

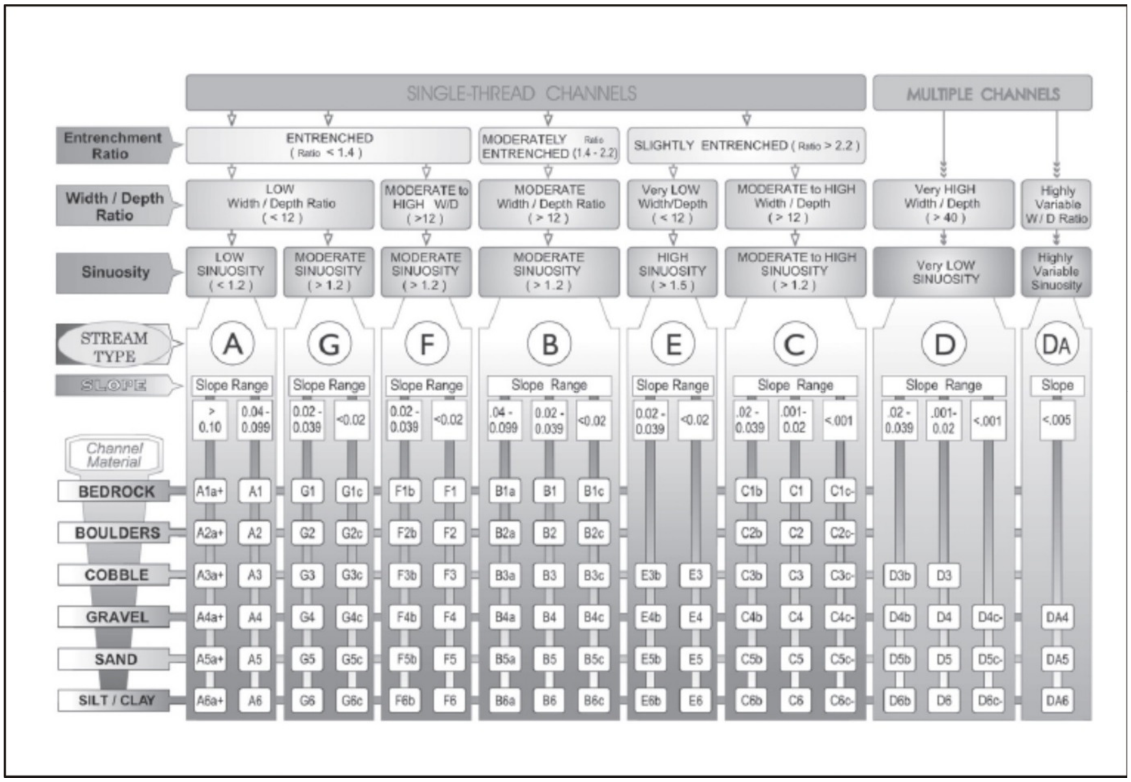


Figure 6. Rosgen (1996) channel types.

Channel classification that extends to aquatic assemblages can be integrated within larger landscape classification frameworks that encompass geology, soils, erosion processes and climate, leading to what has been called 'geomorphic guilds' (Watson et al. 1998). The watershed assessment platform, NetMap, contains the ability to incorporate landscape features into the development of geomorphic guilds. In the present analysis in the Flint Hills, landscape characteristics can include hillslope erosion potential (driven by slope and convergence), valley confinement, floodplain size, river network geometry via tributary confluences, geology and climate. Although the term channel classification is used throughout the report, it is interchangeable with the term geomorphic guilds, particularly when certain combinations of predictor variables are used or when classification systems are linked to individual watersheds or to individual types of landforms. However landforms (mostly rolling hills of low relief and slope) and channel networks (with gradients less than 0.025 occupied by fishes and mussels) in the Flint Hills do not exhibit a high degree of landform variability, and this limits the opportunity to link streams and aquatic assemblages to larger, spatially variable landscape features. This relatively low degree of heterogeneity may partially explain the recent analyses of fish communities in the Flint Hills that identified channel size alone as the most significant predictor variable of species abundance (Martin et al. 2013, Troia and Gido 2014), a finding also in accordance with this study.

Methods and Results

Building the Synthetic Stream Layer in the Flint Hills

A one meter LiDAR digital elevation model (DEM) was available for approximately two thirds of the Flint Hill project area. The LiDAR DEM was merged (and warped) with the National Elevation Dataset 10 m DEM across the remainder of the landscape using NetMap. This produced a seamless, project-wide DEM that was resampled to 2 meter resolution. The DEM was hydro-conditioned to derive flow direction and flow accumulation grids (rasters). Advanced flow routing algorithms were used to derive the synthetic stream layer (www.terrainworks.com).

Three channel initiation thresholds were used to build the synthetic stream layer: specific contributing area multiplied by hillslope gradient (an index of erosion potential), plan curvature (measure of topographic convergence) and minimum flow length over which the first two thresholds must be met (**Figure 7**). Calibration involved matching predicted locations of channel heads to actual locations of channel heads in the Flint Hills using Google Earth images and ensuring that channel density is not excessive (no channel feathering) (**Figure 8**). Candidate channel initiation sites, combined with flow accumulation, led to delineation of the synthetic network (**Figure 9**). The resulting Flint Hills synthetic network consists of 1.27 million discreet channels reach segments of approximately 50 m to 200 m in length (**Figure 10**). Thus, when displaying classification results in ArcMap using the full Flint Hills NetMap synthetic stream layer it is recommended to add a "definition query" (in ArcMap's legend editor) that limits the number that need to be drawn (and thus limiting the time to draw), such as drainage area less than 1 km^2 or 0.5 km^2 or a slope of less than 0.022 (the limit of fish and mussel occupancy as in the Kansas field data).

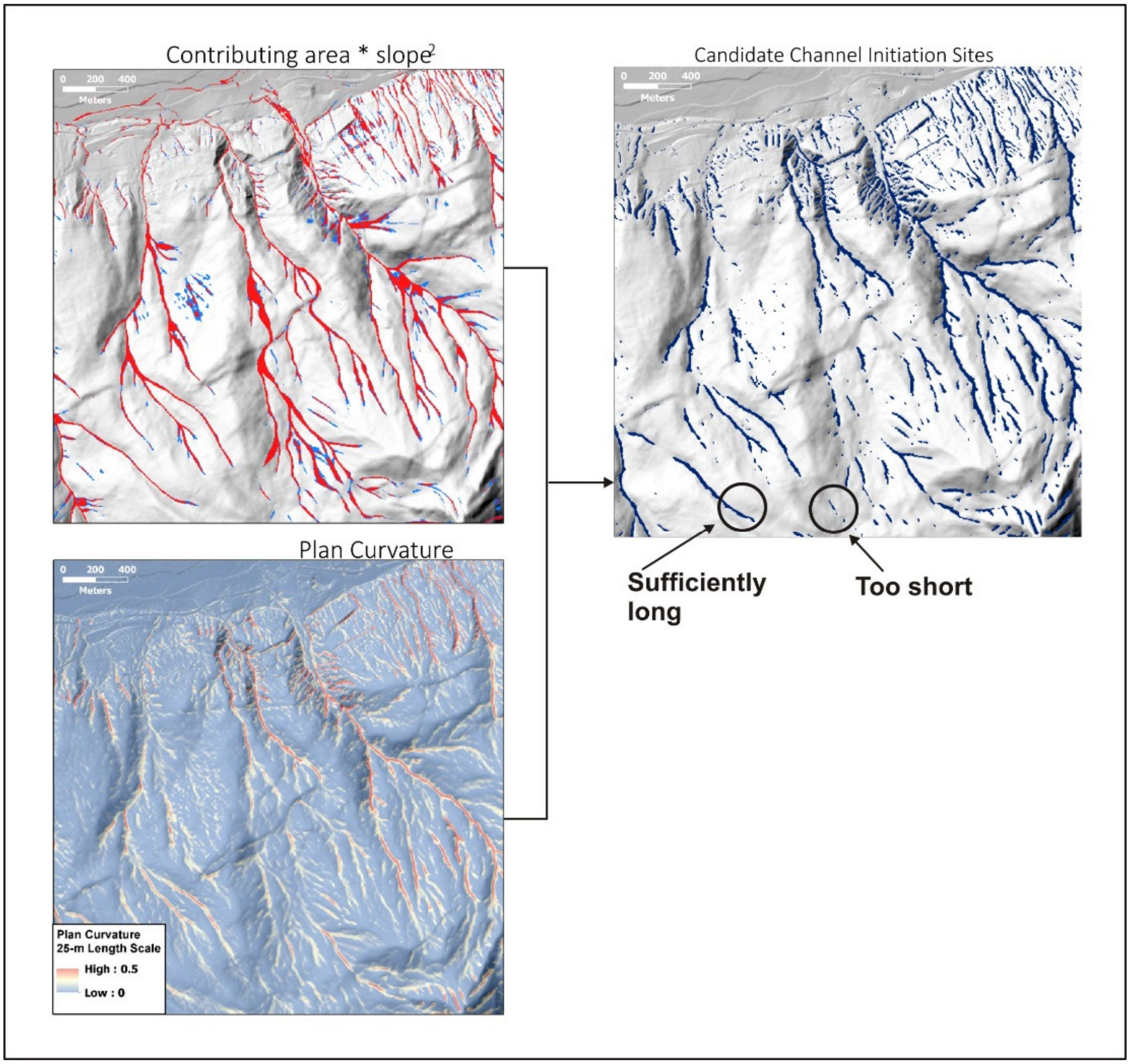


Figure 7. NetMap's parameters used to delineate the synthetic stream network in the Flint Hills.

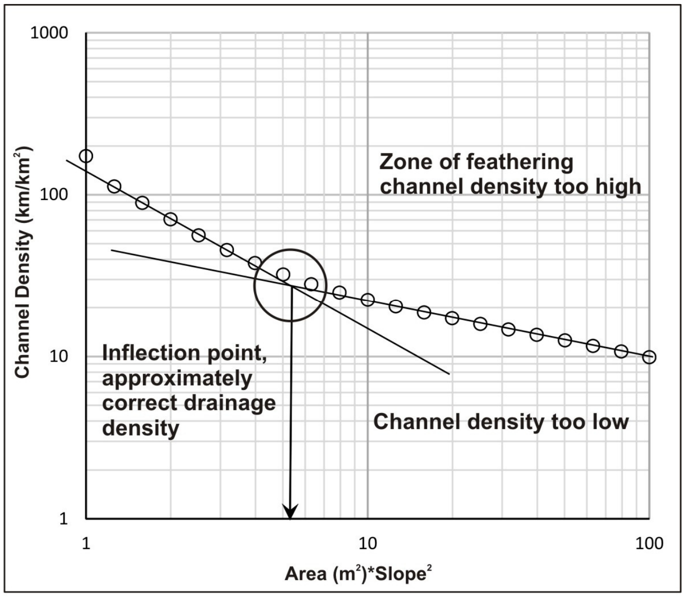


Figure 8. Calibrating the synthetic stream network in the Flint Hills.

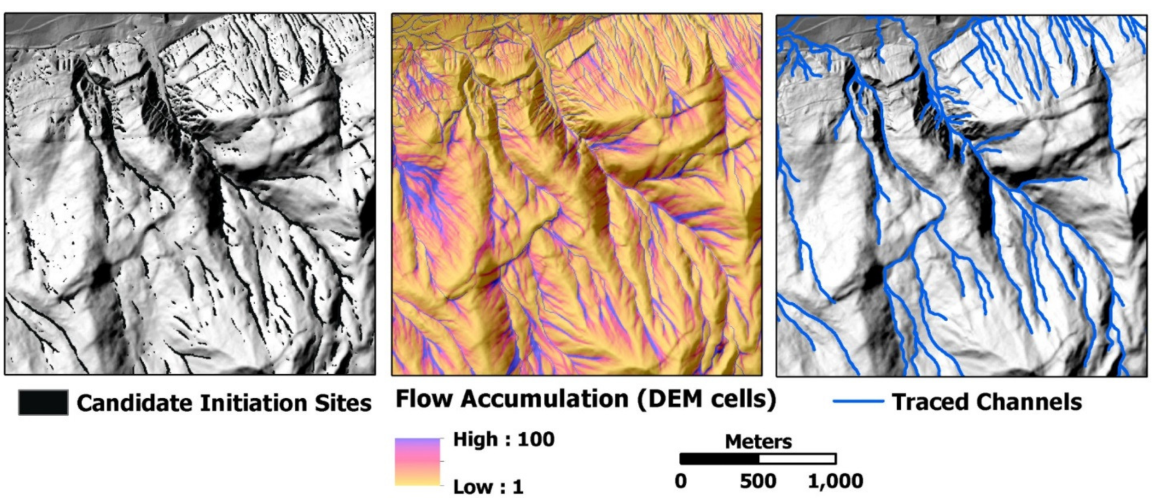


Figure 9. Steps involved with building NetMap's synthetic stream layer in the Flint Hills.

Field data from Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program collected at 307 locations in the Flint Hills ecoregion were used to derive statistical regressions for bankfull and summer channel width and depth (**Appendix 1 and 1_2**). These were used within the synthetic stream layer to create hydraulic geometry attributes across all 1.27 million stream segments (Table 1). Flow velocity was predicted in each of the synthetic network segments using the Manning Equation (1889). Required parameters include channel gradient, channel bed roughness and hydraulic radius. Predicted flow velocity, channel width and depth are used to calculate bankfull and summer lower flow discharges. Summer width and depth were also used to calculate summer habitat volume along one meter reaches of channels across the entire Flint Hills ecoregion.

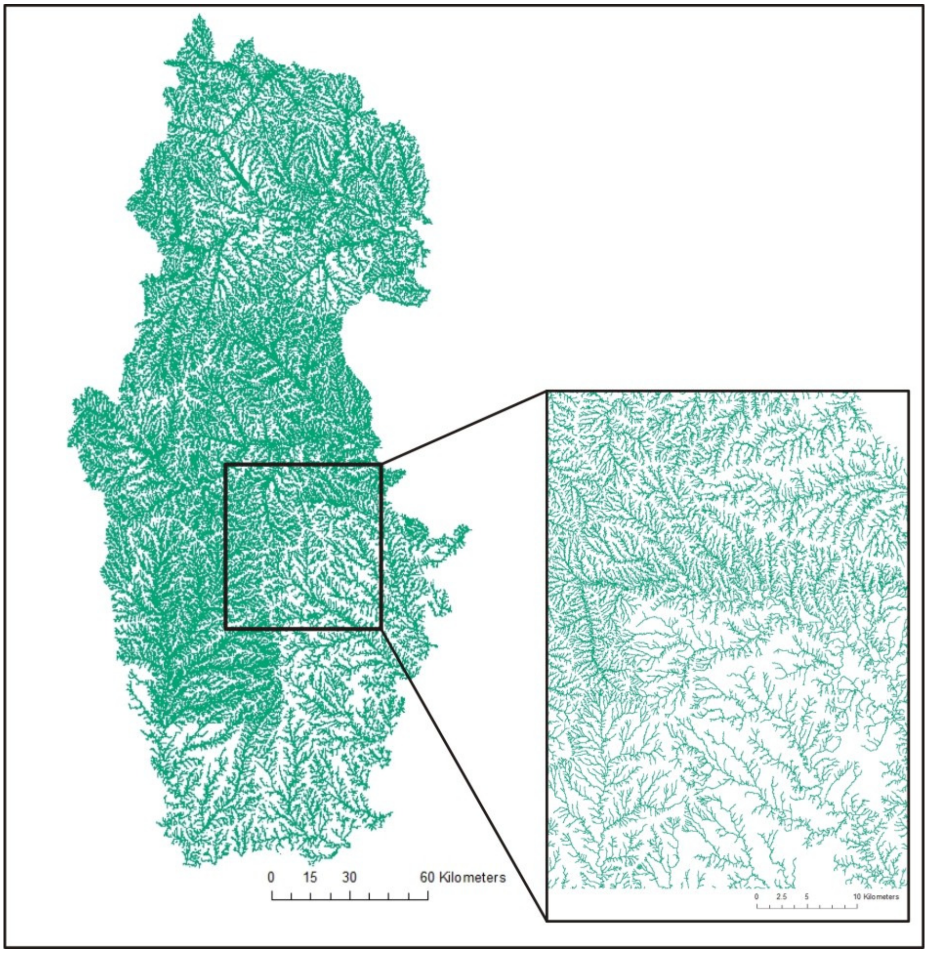


Figure 10. The Flint Hills synthetic stream network consisting of 1.27 million channel segments.

Table 1. Hydraulic geometry relationships built for the Flint Hills landscape using field data available from Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program.

Hydraulic Geometry and Flow	Expression	Coefficients
Bankfull flow (m^3s^{-1})	= a* (drainage area^b)* (Precip^c)	a=3.71, b=0.30, c=0.71
Bankfull width (m)	= a* (drainage area^b)* (Precip^c)	a=3.35, b=0.35, c=0
Bankfull depth (m)	= a* (drainage area^b)* (Precip^c)	a=0.52, b=0.07, c=0
Summer flow (m^3s^{-1})	= a* (drainage area^b)* (Precip^c)	a=0.80, b=0.45, c=0
Summer width (m)	= a* (drainage area^b)* (Precip^c)	a=0.1.6, b=0.41, c=0
Summer depth (m)	= a* (drainage area^b)* (Precip^c)	a=0.26, b=0.14, c=0.52

Mapping floodplains and calculating channel confinement are necessary for classifying channels or building a landform taxonomy. Typically the most accurate approach for delineating floodplains is to use field measurements and aerial photography. However, creating stream classification using remote sensing data requires an automated procedure for mapping floodplains in all valleys across the Flint Hills study area. To characterize floodplains in NetMap, DEM cells are classified according to elevation above the channel (**Figure 11**). Each cell within a specified search radius of a channel (a multiplier of bankfull widths) is associated to the closest channel cell, with distance to the channel weighted by intervening relief. Valley-floor DEM cells are associated with specific channel segments that are closest in Euclidean distance and have the fewest and smallest intervening high points. The elevation difference between each valley floor cell and the associated channel location is normalized by bankfull depth or by the absolute elevation above the channel. This procedure is repeated for every channel segment. For additional information on the use of NetMap's floodplain mapping tool see Technical Help and (http://www.hydrol-earth-syst-sci.net/15/2995/2011/)

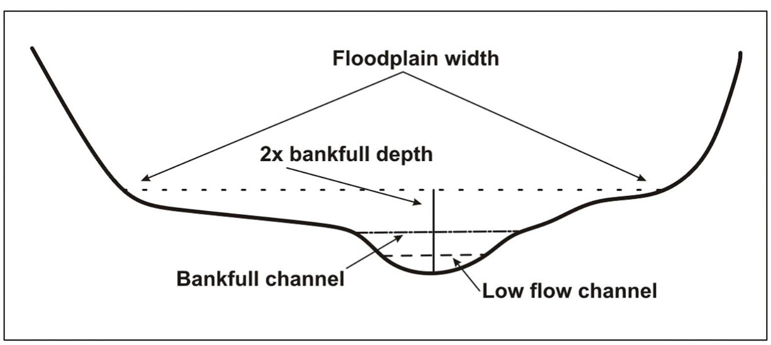


Figure 11. Mapping floodplains in the Flint Hills landscape.

In the Flint Hills landscape, floodplain width is mapped at 2, 3, 4, and 5 bankfull depths above the channel to provide a range of data that can be used to identify floodplains at different elevations, terraces and channel confinement.

Twenty-four landscape, fluvial geomorphic and hydrologic parameters were attributed to all reach segments in NetMap's synthetic network to support the Flint Hills stream geomorphic classification. Parameters range from hydraulic geometry (summer and winter channel widths and depths), bankfull and summer flows, summer habitat area and volume, channel gradient, floodplain width, channel confinement and many others (**Table 2**). NetMap's routed synthetic stream layer allows segment attributes to be summarized downstream, such as flow and precipitation. NetMap's local contributing areas located adjacent to each synthetic stream segment, called 'drainage wings', are used to summarize terrestrial information to individual stream segments (such as rock type) and then segment scale information is routed and summarized downstream.

Table 2. List of NetMap remote sensing parameters located in the Flint Hills synthetic stream layer and that can be used for classification.

Parameter (units)	**Parameter (units)**
Drainage area (km^2)	Sinuosity (LL^{-1})
Elevation (m)	Mean annual precipitation (m)
Gradient (LL^{-1})	Tributary confluence effects (P)
Azimuth	Floodplain width (n=5, m)
Bankfull width (m)	Bankfull width to depth ratio (LL^{-1})
Bankfull depth (m)	Entrenchment ratio (LL^{-1})
Summer width (m)	Channel confinement (LL^{-1})
Summer depth (m)	Summer habitat volume (m^3)
Bankfull flow (m^3s^{-1})	Stream order
Summer flow (m^3s^{-1})	Mean annual flow (m^3s^{-1})
Rock type	Hillslope erosion potential (GEP)
Valley width	Maximum downstream gradient (LL^{-1})

Channel bed substrate could be incorporated into stream classification systems. However, this requires network wide predictions of bed substrate in the Flint Hills. Although substrate data were available at the 307 field sites in the Flint Hills, the absence of distinct spatial patterns of dominant substrate size with predictor variables such as channel gradient, drainage area and lithology precluded network wide predictions of substrate (**Appendix 2** and see Spatial Probability Mapping results later).

Flint Hills Field Data Transferred to Stream Reaches

The Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program conducts an aquatic field data collection program that consists of 1780 individual study sites across the state, of which 410 occur within the Flint Hills ecoregion project area (**Figure 12**). Although the survey sites are georeferenced, many of them were located away from streams (in terrestrial areas) and therefore it was not feasible to match all survey sites to specific stream reaches. Using a combination of proximity and stream names, 347 study sites are linked to individual reach segments in the Flint Hills synthetic stream layer; field data are available in 305 of them.

Field data consisted of both physical stream attributes and aquatic biota (fish species and animal numbers were available in 305 survey sites and mussel species were available in 225 sites). Lengths of survey sites ranged between 150 and 300 m (**Figure 13**). Each survey site was subdivided into 10 to 15 equal length segments and data collection occurred at each of those across channel (cross section). Each of the segments were further subdivided into ten equal sub-segments and data collection occurred along the thalweg (Figure 13). Physical data used in the Flint Hills stream classification included bankfull and summer hydraulic geometry (width and depth), substrate size classes (bedrock, boulder, cobble, gravel, sand, fines, bedrock), channel bed planform morphology (pools, riffles, glides, rapids, cascades) and woody debris abundance (none, sparse [0-10%], moderate[10-40%], heavy [40-75%], very heavy [>75%]).

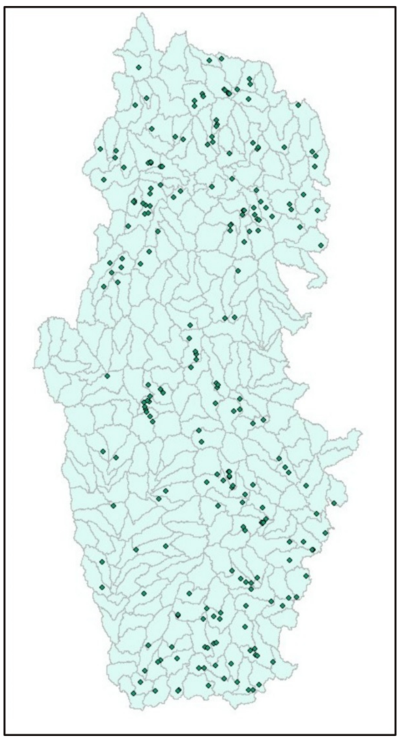


Figure 12. Field study site locations in the Flint Hills project area.

Field data were summarized in each survey site to explore relationships among the field data and synthetic network attributes; parameter plots are contained in Appendix 2. Summarized data in each survey site included: 1) most dominant substrate size class, 2) percentage of pools, 3) percentage of riffles, and 3) the average wood abundance. The complete field data (non-summarized) are used in the classification of habitat features (the third component of the Flint Hills classification system, Spatial Probability Mapping) described below.

Terminology for planform bed morphology used in the Flint Hills data collection is based on generally understood nomenclature (e.g., Rosgen 1996**,** Buffington and Montgomery 2013). "Riffles" encompass the sections of the channel bed with the steepest slopes and shallowest depths at flows below bankfull. Riffles typically occur at the transitions between inside and outside of meander bends and have poorly defined thalwegs. "Pools" are the deepest locations of a reach with the lowest velocities. Water surface slope of pools at below bankfull flows is near zero. Pools are often located at the outside of meander bends. "Glides" are located immediately downstream of pools or in areas that lack pools (over a length scale of say 100 m or more). The slope of the channel bed through a glide is negative while the slope of the water surface is positive. The head of the glide can be difficult to identify. "Rapids" are the steepest alluvial reaches (other than water falls) and are often referred to as "cascades" (Montgomery and Buffington 1997). According to the field data and based on the definitions above, the Flint Hills is dominated (92 to 99%) by alternating and interdigitated pools, riffles and glides. This is expected since the field data (including fish and mussel census) are restricted to channels with slopes of less than 0.02 (range 0.022 to 0.00005).

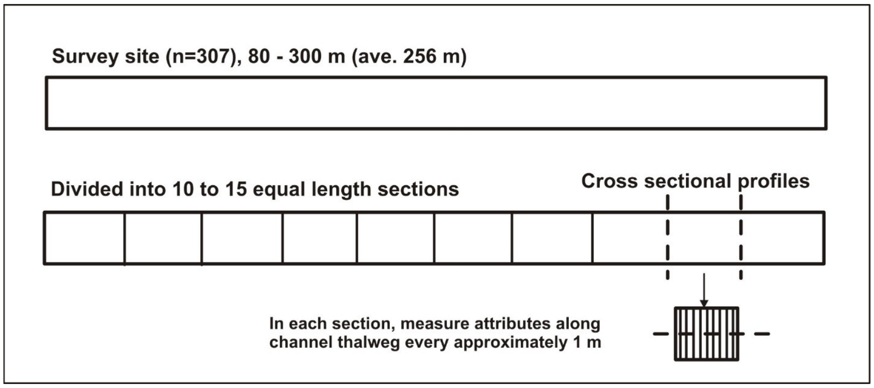


Figure 13. Flint Hills survey site sampling scheme.

Flint Hills Stream Geomorphic Stream – Aquatic Biota Classification System

The ultimate objective of the Flint Hills classification system is to couple landscape characteristics to channel physical features and ultimately to aquatic assemblages. Since the aquatic component of the Flint Hills classification system is not a part of this study scope, the approach taken is to build a system that allows for customizable and iterative classification of channel segments rather than on building a-priori classification systems. However, three new classification systems are built and two existing ones are applied in the Flint Hills.

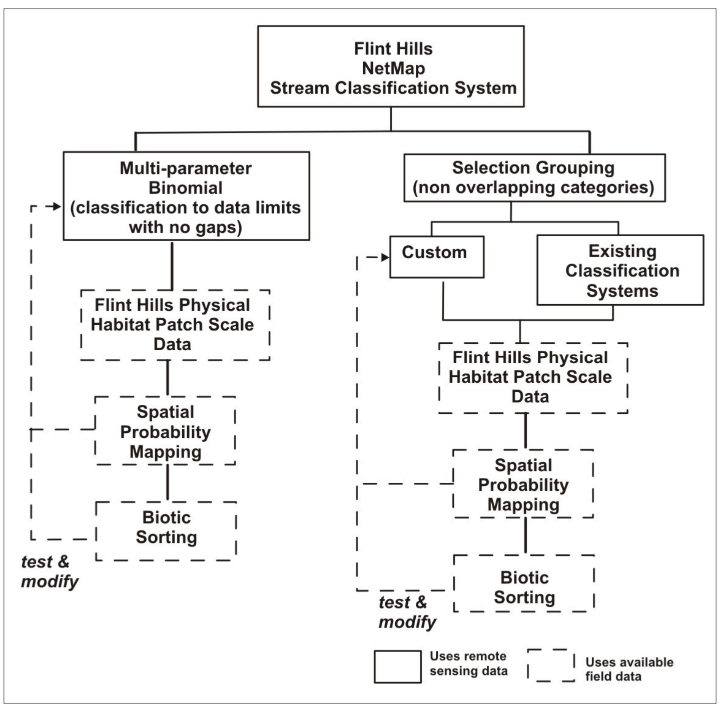


Figure 14. Flint Hills multi-faceted and flexible classification system.

A multi-faceted design to stream classification is used in the Flint Hills ecoregion (**Figure 14**). It is comprised of four principal components: 1) "Parameter Nesting" that uses nested sets of parameters to ensure classification to the upstream-downstream limits of river networks and data, 2) "Selection Grouping" that allows for customized classification using data ranges of remote sensing attributes, 3) "Spatial Probability Mapping" that converts field data on channel physical attributes to measures of attribute density (or probability) in all Flint Hills study reaches and its extrapolation across all channels, and 4) "Biotic Sorting" that categorizes species and their abundance by channel classes (species presence or absence and animal frequency and density for adults and juveniles, by species).

A key aspect of the four component Flint Hills classification system is that it supports customizable stream classification, applied in an iterative fashion, with the main objective of creating a taxonomy of landscape - channel– aquatic biota characteristics. The Flint Hills classification system is located in the NetMap suite of watershed analysis tools under 'Fluvial Processes' tab (**Figure 15**).

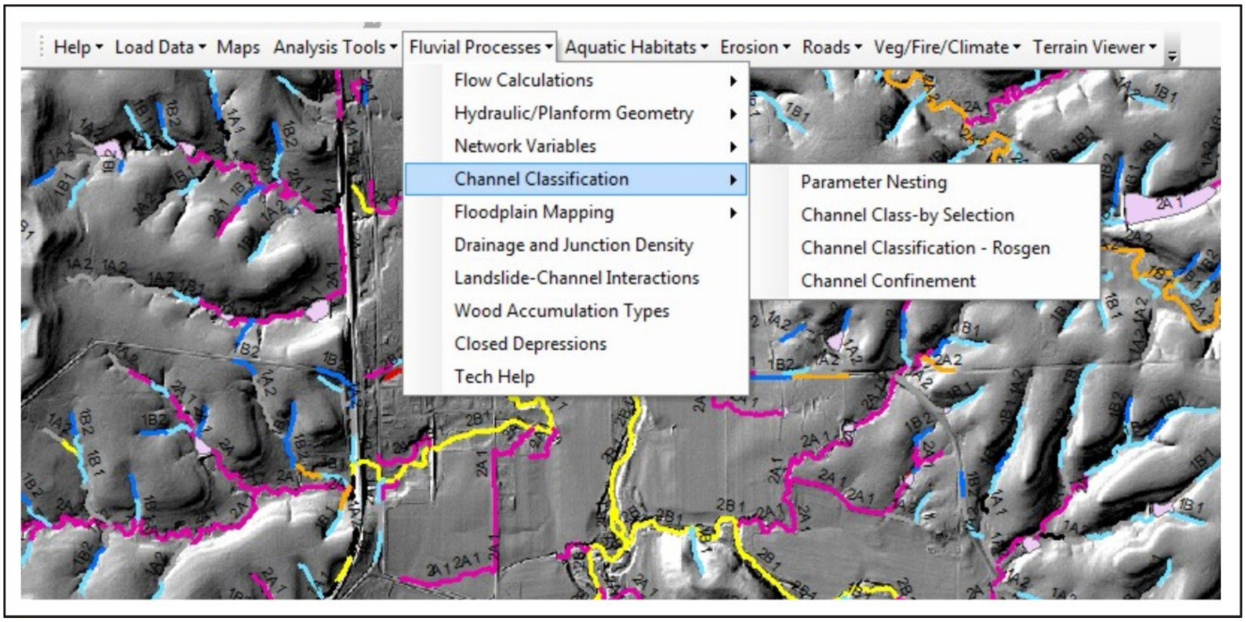


Figure 15. Flint Hills classification system in the NetMap Tools.

Component #1: Parameter Nesting

Parameter Nesting creates channel classes that extend to the limits of the channel network (e.g., no segments unclassified) and to ensure that there are no gaps in the classification (e.g., no unclassified channels). Parameter Nesting, that creates non overlapping channel class categories, defines a number of classes by:

$$N = C^P \quad (1)$$

where N is the number of channel classes, C is the number of numeric categories per classification parameter (continuous without gaps) and P is the number of geomorphic parameters. The number of class types increases with an increasing number of parameters and numeric categories. For example, three parameters and two categories per parameter create eight class types. Increasing the categories to three increases the total number of class types to 27, and so on. To create a reasonable number of channel classification types, a C = 2 and a P = 3 are used to create a maximum of eight channel classes (**Figure 16**).

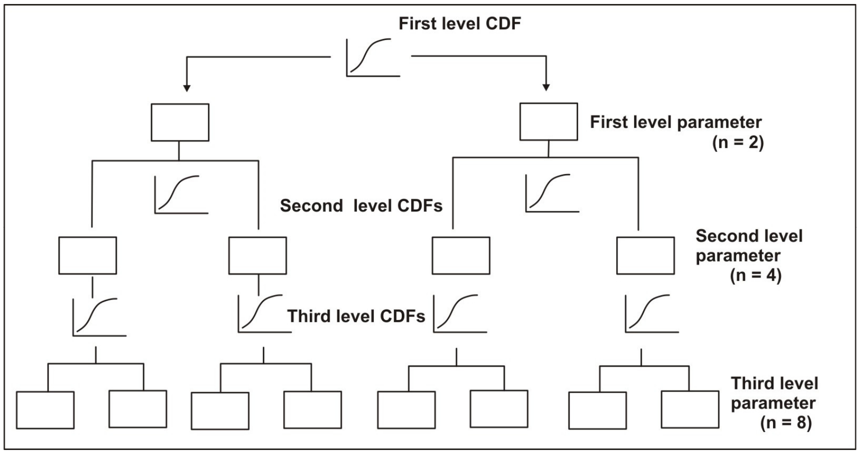


Figure 16. The Parameter Nesting classification system.

Using the Parameter Nesting interface in NetMap (**Figure 17**), an analyst selects from a drop down list of available parameters (Table 2) at each of the three parameter levels (**Figure 18**). Although geomorphic principles can be used to define category breaks in the Parameter Nesting, viewing cumulative distribution plots of parameters is recommended to define category breaks (**Figure 19**); a CDF tool is included in the classification interface. Parameter category breaks can be chosen where there is an abrupt change in slope of the CDF at each parameter level. Category breaks at each parameter level must be continuous; there are no gaps in the continuous data series. For example, two drainage area categories (for all channels greater than or equal to 1 km^2) might be 1km^2 to 10 km^2 and >10 km^2 to 2000 km^2 (the maximum basin area). Or a parameter of channel confinement that ranges from 1 to 10 might have categories of 1 to 4 and 4 to 6.

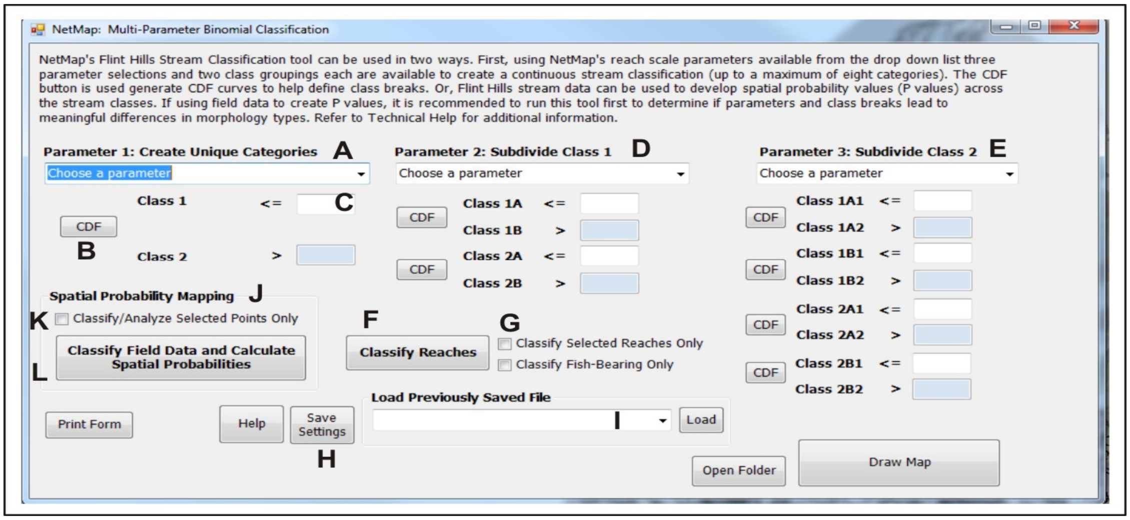


Figure 17. The NetMap interface for the Parameter Nesting classification tool. .

(A, D, E) Select attributes. (C) Set values. (B) Use CDF tool to help create data breaks. (L) Examine SPM results. (K) Use only a selection of field data. (F) Run classification. (G) Limit classification. (H) Save settings. (I) Load saved settings.

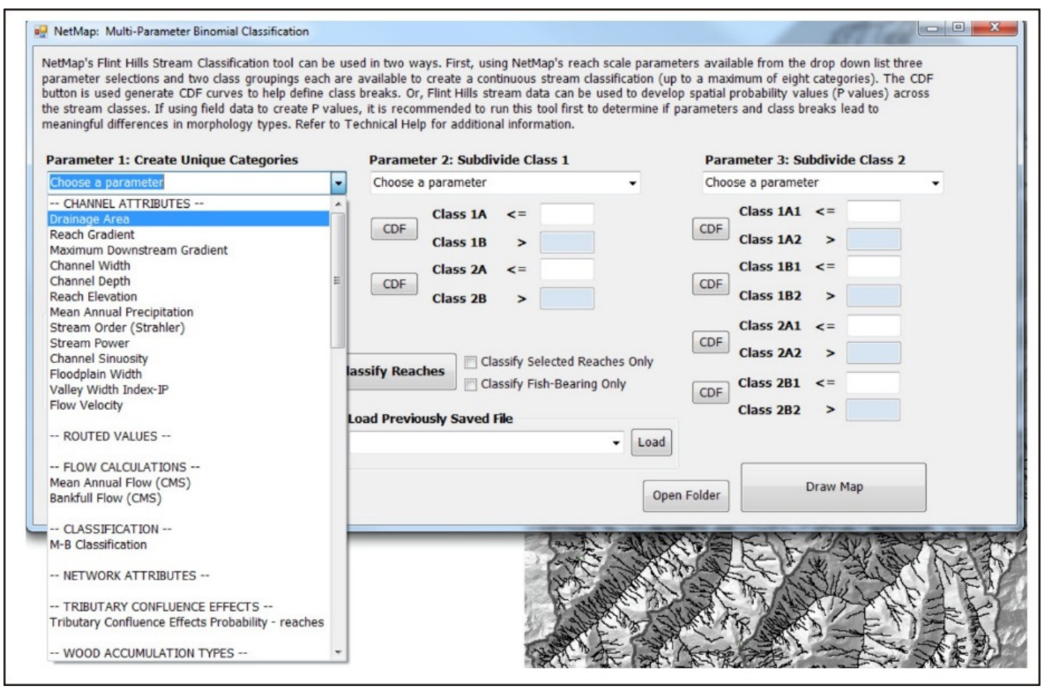


Figure 18. Attributes are selected for each parameter level in the classification tool.

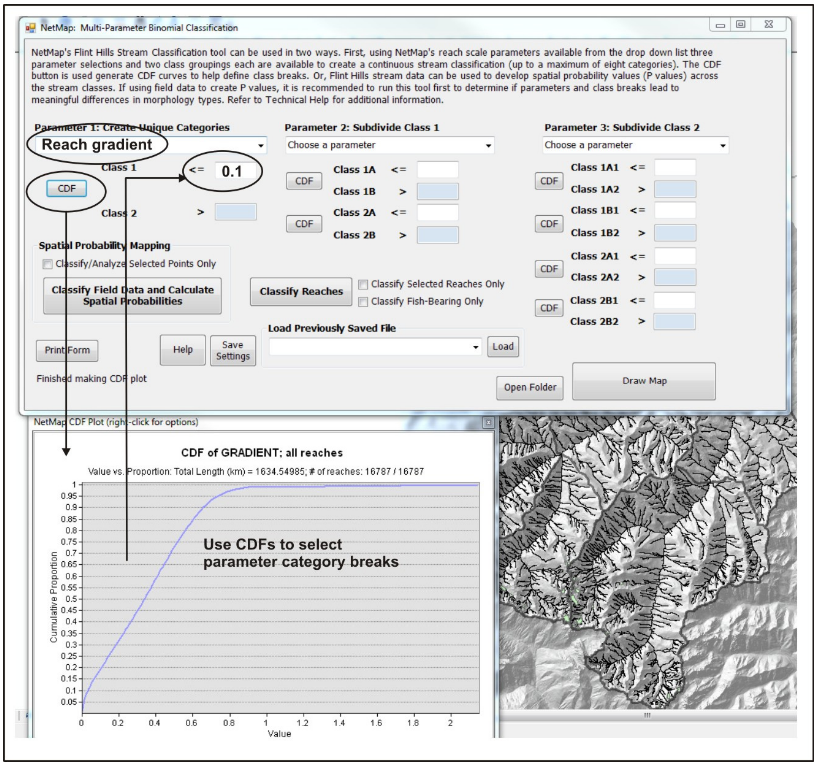


Figure 19. The CDF module in the Parameter Nesting interface aids in setting class breaks.

Since the Flint Hills ecoregion and the derived synthetic stream layer (Figure 10) extends across several distinct watersheds, unique classifications could be created at the scale of individual watersheds. Prior to selecting classification attributes from the drop down (Figure 18), a user selects a subset of reaches to classify, which is done in ArcMap by selecting only those channels encompassed within specific watershed boundaries; the Flint Hills landscape is subdivided into major watersheds and is included in NetMap's Flint Hill dataset (**Figure 20)**.

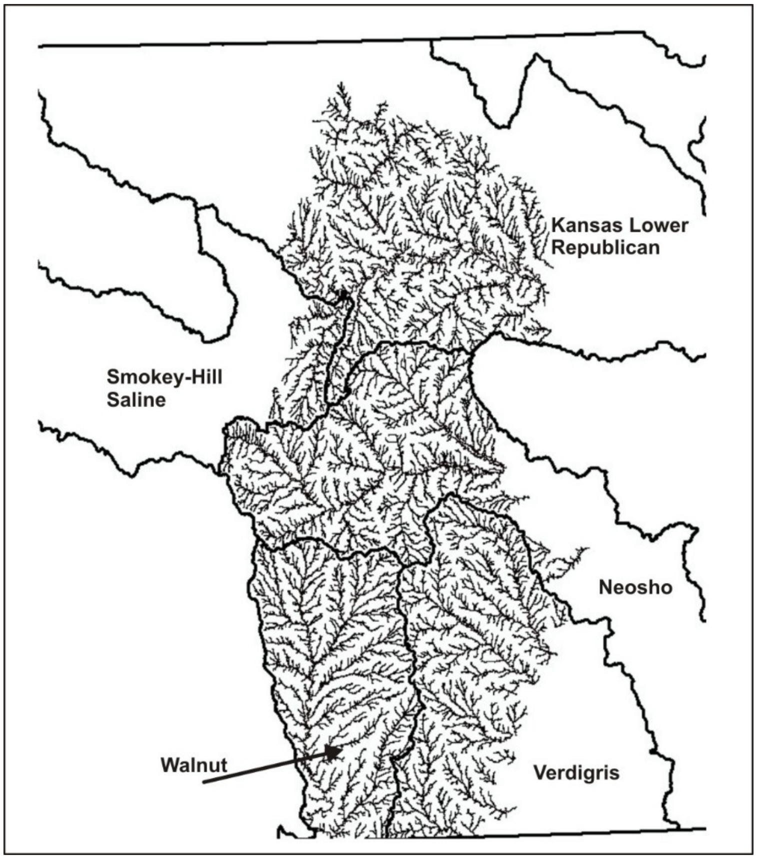


Figure 20. Major watersheds of the Flint Hills landscape.

Component #2: Selection Grouping

The Selection Grouping classification tool provides additional functionality. Users select any parameter and define selection criteria (e.g., range or minimum or maximum) (**Figure 21**). A classification builder is used via NetMap's interface and analysts create custom names for their classes, but limited to eight characters each. Although classification systems built using Selection Grouping can extend to the limits of the river network (e.g., no gaps in the classification), systems can be built that cover only a subset of channel segments (for example, see Buffington and Montgomery and Rosgen classification below). NetMap's CDF tool can be used to help determine appropriate parameter thresholds, similar to the Parameter Nesting method described above (Figure 19). In addition, classifications can be limited to and customized for specific watersheds (e.g., Figure 20). Selection grouping classification creates unique, non-overlapping channel classes.

Component #3: Spatial Probability Mapping

Survey sites in the Flint Hills (Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program), ranging in length from 150 to 300 m (e.g., Figure 12), are characterized by meter to decimeter scale variation in physical attributes including planform morphology (pool, riffle, glide, rapids, cascades), substrate size (fines, sand, pebbles, gravel, cobble, boulder, bedrock) and in-stream wood abundance (none, sparse, moderate, heavy, very heavy) (**Figure 22**). The presence or absence and number of different aquatic species in the Flint Hills channels likely responds to spatial variation in habitat conditions at these scales. Hence, for the purpose of developing a coupled stream geomorphic – aquatic biota classification system in the Flint Hills the survey site data are characterized by the relative proportions of the different attributes (**Figure 23**). Over individual survey reaches, the percentages of pools, riffles, different substrate categories and average in-stream wood abundance are calculated and are represented in the form of densities or spatial probabilities (referred to as “Spatial Probability Mapping” or SPM) (**Figure 24**).

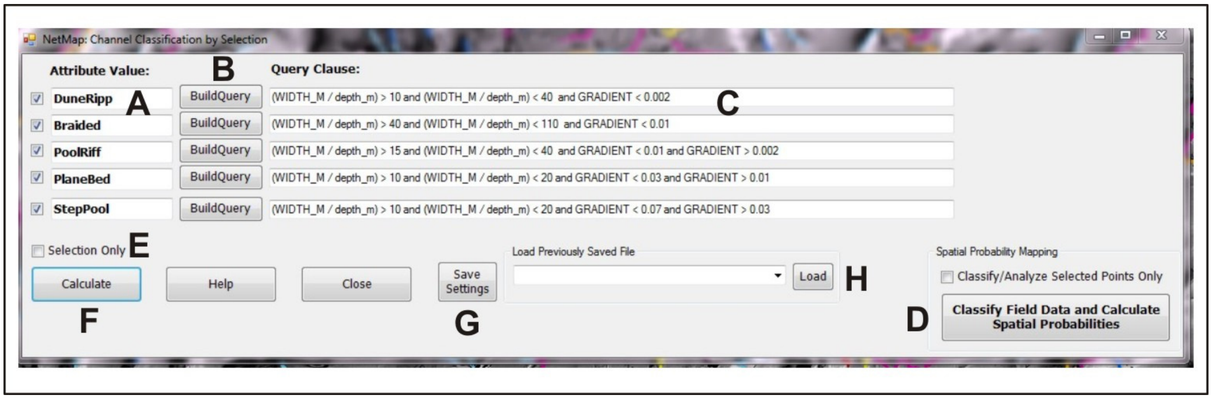


Figure 21. The tool interface for Selection Grouping classification.

(A) Names are assigned to different channel classes (8 character limit). (B) The selection is conducted using a query builder that produces the ranges of attributes to classify (C). (D) Spatial probability mapping is used to examine reach scale morphology with respect to channel classes. (E) Classification can occur on only a subset of channel reaches. (F) To conduct the classification. (G) Settings can be saved and reloaded (H).

SPM is coupled to the Parameter Nesting and Selection Groupings tools to extrapolate the spatial patterns of field data on aquatic habitats across the entire Flint Hills river network and can be used to evaluate various stream classifications. First, either the Parameter Nesting or Selection Grouping tool is used to create channel classes using the interfaces in NetMap Tools (including using the CDF tool and defining class breaks). Second, the tabular field data are spatially joined to NetMap’s synthetic stream reaches and the SPM is calculated for individual stream classes (**Figure 25**). If there are no field survey sites within individual MPB classes, no SPM is associated with that class (e.g., no Spatial Probability Mapping). This method is based on the hypothesis that the SPM of the 307 field study sites (morphology, substrates and in-stream wood abundance) can be extrapolated to other stream reaches within the same classification domains.

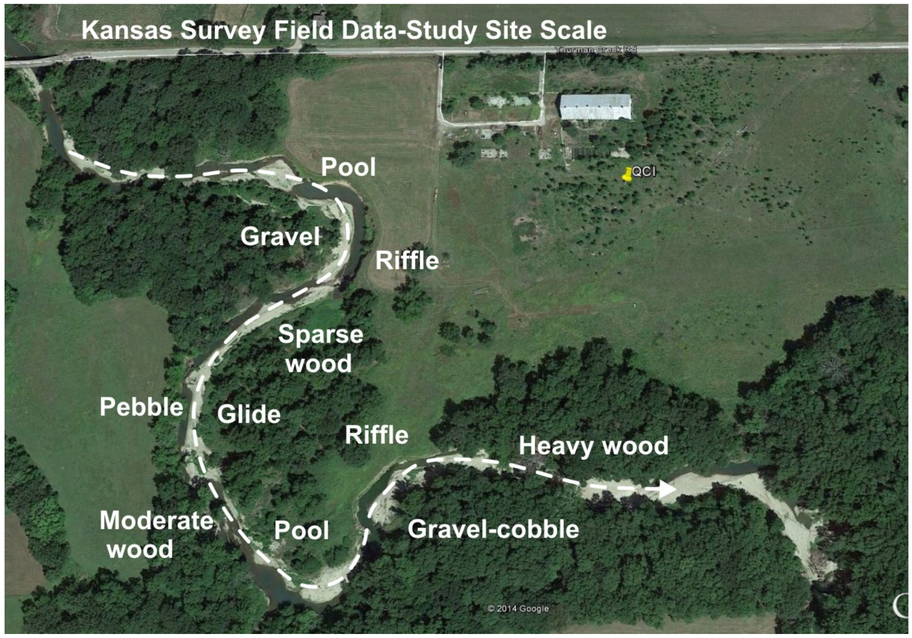


Figure 22. An illustration of Flint Hills channel morphology.

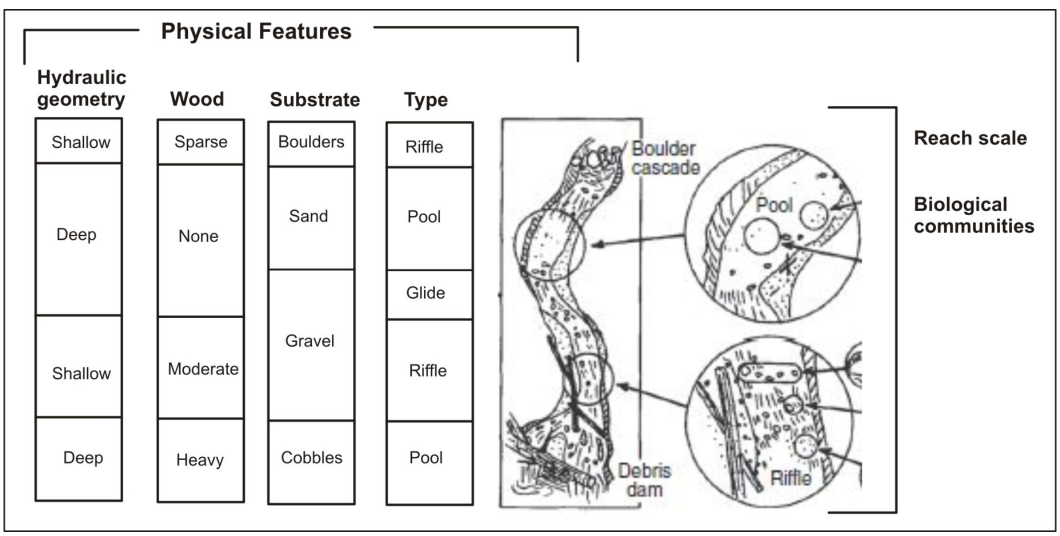


Figure 23. Morphology of reach scale study sites can be broken into micro habitat features.

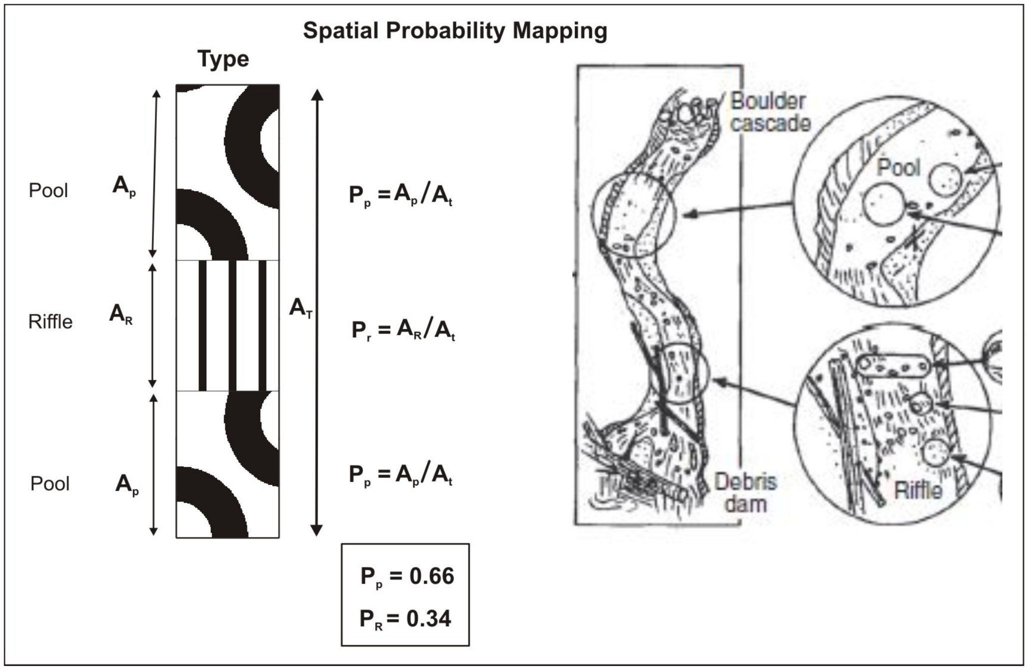


Figure 24. Micro habitat features in Spatial Probability Mapping.

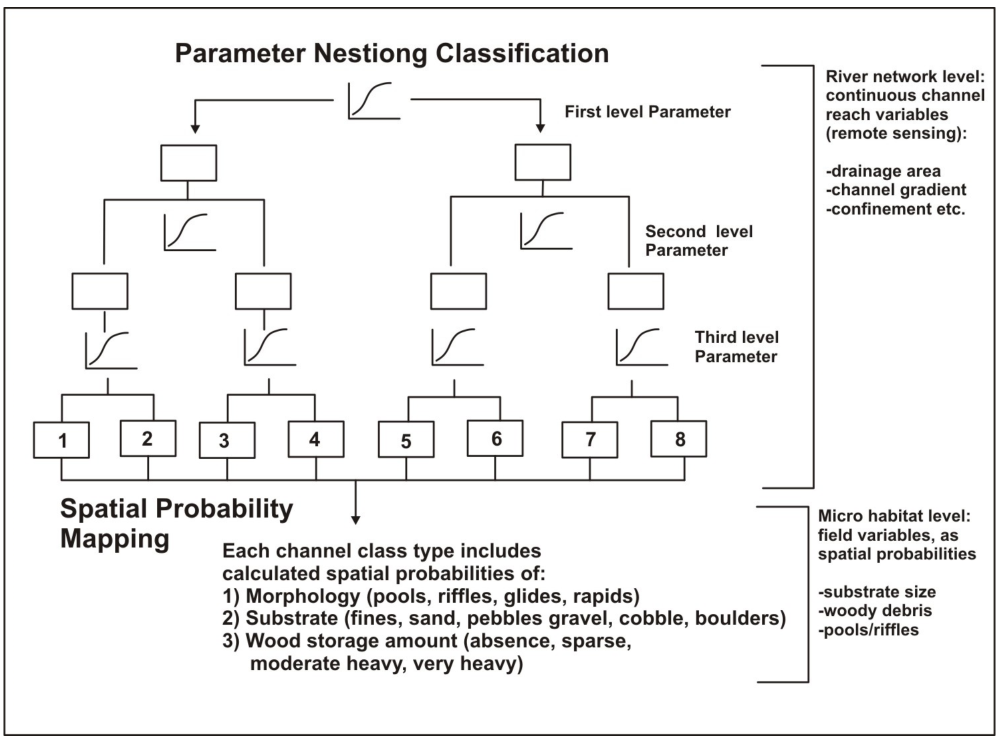
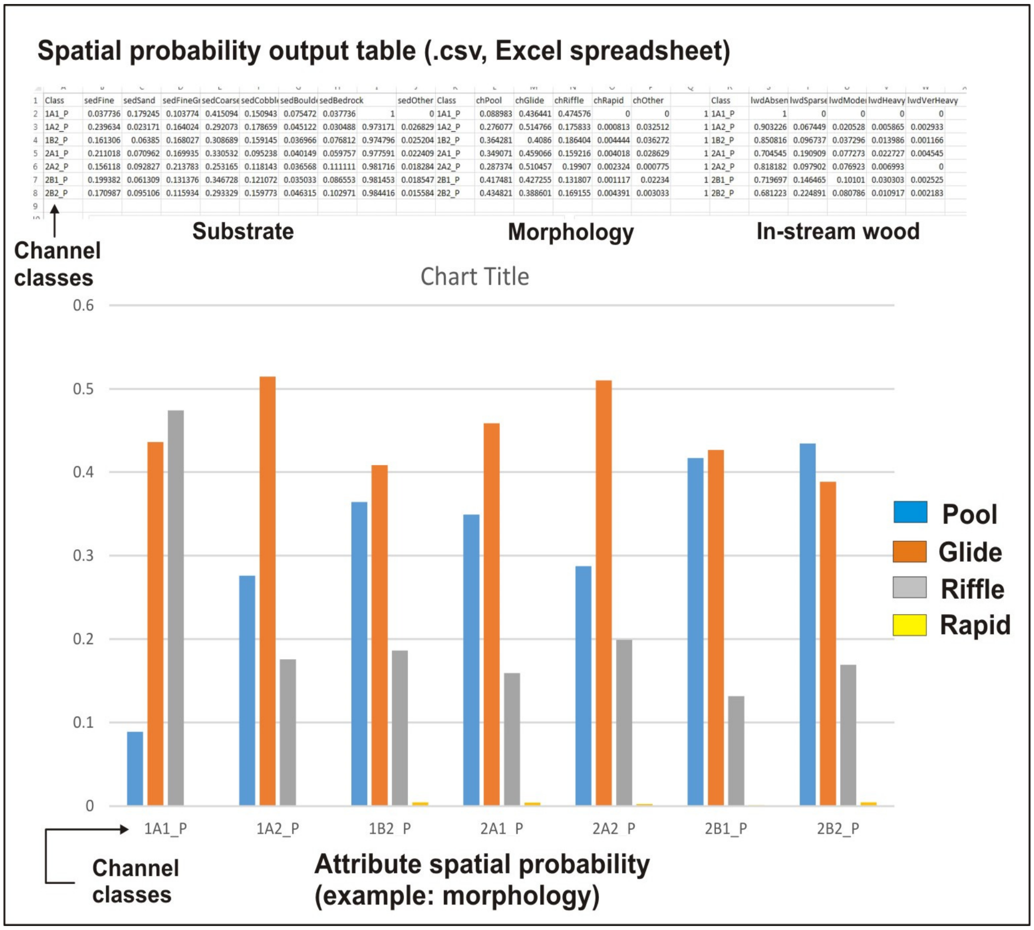


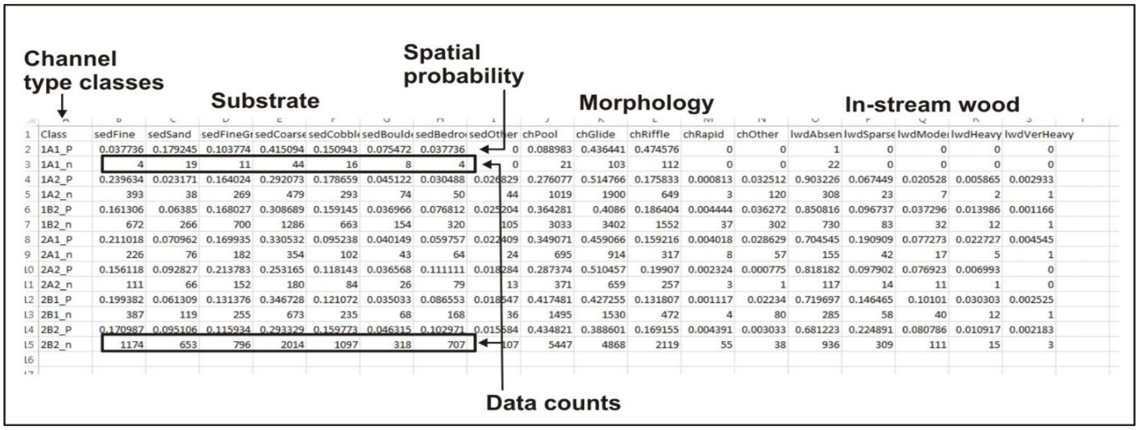
Figure 25. Spatial Probability Mapping (SPM) is linked to the Parameter Nesting classification tool.

SPM results are in the form of tabular data that cross references individual channel classes to spatial probabilities of morphology, substrates, and in-stream wood abundance (**Figure 26**). Additional output includes the number of field study sites (by length of channel) contained within individual channel classes; larger numbers of field study sites in individual stream classes indicate a more robust sample and thus strength of extrapolation (**Figure 27**).



Class	sedFine	sedSand	sedFineGr	sedCoarse	sedCobble	sedBoulde	sedBedrock		sedOther	Class	chPool	chGlide	chRiffle	chRapid	chOther		Class	lwdAbsen	lwdSparse	lwdModer	lwdHeavy	lwdVerHeavy
1A1_P	0.037736	0.179245	0.103774	0.415094	0.150943	0.075472	0.037736	1	0	1A1_P	0.088983	0.436441	0.474576	0	0	1	1A1_P	1	0	0	0	0
1A2_P	0.239634	0.023171	0.164024	0.292073	0.178659	0.045122	0.030488	0.973171	0.026829	1A2_P	0.276077	0.514766	0.175833	0.000813	0.032512	1	1A2_P	0.903226	0.067449	0.020528	0.005865	0.002933
1B2_P	0.161306	0.06385	0.168027	0.308689	0.159145	0.036966	0.076812	0.974796	0.025204	1B2_P	0.364281	0.4086	0.186404	0.004444	0.036272	1	1B2_P	0.850816	0.096737	0.037296	0.013986	0.001166
2A1_P	0.211018	0.070962	0.169935	0.330532	0.095238	0.040149	0.059757	0.977591	0.022409	2A1_P	0.349071	0.459066	0.159216	0.004018	0.028629	1	2A1_P	0.704545	0.190909	0.077273	0.022727	0.004545
2A2_P	0.156118	0.092827	0.213783	0.253165	0.118143	0.036568	0.111111	0.981716	0.018284	2A2_P	0.287374	0.510457	0.19907	0.002324	0.000775	1	2A2_P	0.818182	0.097902	0.076923	0.006993	0
2B1_P	0.199382	0.061309	0.131376	0.346728	0.121072	0.035033	0.086553	0.981453	0.018547	2B1_P	0.417481	0.427255	0.131807	0.001117	0.02234	1	2B1_P	0.719697	0.146465	0.10101	0.030303	0.002525
2B2_P	0.170987	0.095106	0.115934	0.293329	0.159773	0.046315	0.102971	0.984416	0.015584	2B2_P	0.434821	0.388601	0.169155	0.004391	0.003033	1	2B2_P	0.681223	0.224891	0.080786	0.010917	0.002183

Figure 26. Spatial Probability Mapping results in tabular and histogram form.



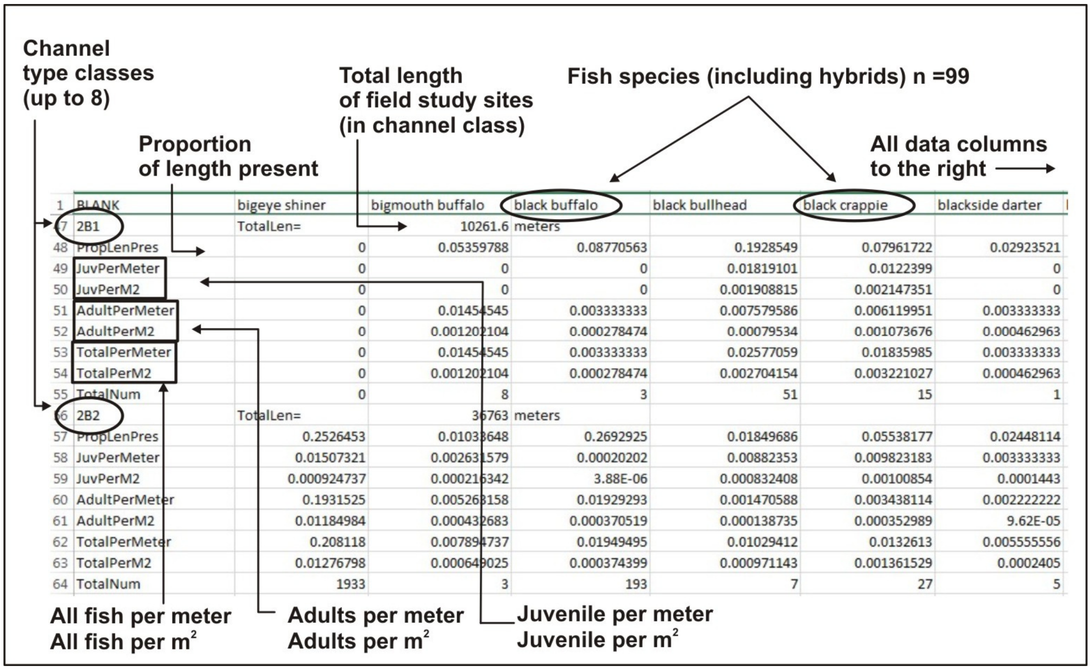
Class	sedFine	sedSand	sedFineGr	sedCoarse	sedCobble	sedBoulde	sedBedro	sedOther	chPool	chGlide	chRiffle	chRapid	chOther	lwdAbsen	lwdSparse	lwdModer	lwdHeavy	lwdVerHeavy
1A1_P	0.037736	0.179245	0.103774	0.415094	0.150943	0.075472	0.037736	0	0.088983	0.436441	0.474576	0	0	1	0	0	0	0
1A1_n	4	19	11	44	16	8	4	0	21	103	112	0	0	22	0	0	0	0
1A2_P	0.239634	0.023171	0.164024	0.292073	0.178659	0.045122	0.030488	0.026829	0.276077	0.514766	0.175833	0.000813	0.032512	0.903226	0.067449	0.020528	0.005865	0.002933
1A2_n	393	38	269	479	293	74	50	44	1019	1900	649	3	120	308	23	7	2	1
1B2_P	0.161306	0.06385	0.168027	0.308689	0.159145	0.036966	0.076812	0.025204	0.364281	0.4086	0.186404	0.004444	0.036272	0.850816	0.096737	0.037296	0.013986	0.001166
1B2_n	672	266	700	1286	663	154	320	105	3033	3402	1552	37	302	730	83	32	12	1
2A1_P	0.211018	0.070962	0.169935	0.330532	0.095238	0.040149	0.059757	0.022409	0.349071	0.459066	0.159216	0.004018	0.028629	0.704545	0.190909	0.077273	0.022727	0.004545
2A1_n	226	76	182	354	102	43	64	24	695	914	317	8	57	155	42	17	5	1
2A2_P	0.156118	0.092827	0.213783	0.253165	0.118143	0.036568	0.111111	0.018284	0.287374	0.510457	0.19907	0.002324	0.000775	0.818182	0.097902	0.076923	0.006993	0
2A2_n	111	66	152	180	84	26	79	13	371	659	257	3	1	117	14	11	1	0
2B1_P	0.199382	0.061309	0.131376	0.346728	0.121072	0.035033	0.086553	0.018547	0.417481	0.427255	0.131807	0.001117	0.02234	0.719697	0.146465	0.10101	0.030303	0.002525
2B1_n	387	119	255	673	235	68	168	36	1495	1530	472	4	80	285	58	40	12	1
2B2_P	0.170987	0.095106	0.115934	0.293329	0.159773	0.046315	0.102971	0.015584	0.434821	0.388601	0.169155	0.004391	0.003033	0.681223	0.224891	0.080786	0.010917	0.002183
2B2_n	1174	653	796	2014	1097	318	707	107	5447	4868	2119	55	38	936	309	111	15	3

Figure 27. Spatial Probability Mapping output.

Component #4: Biotic Sorting by Stream Classes

The ultimate aim of the Flint Hills – NetMap channel classification system is to define relationships between channel physical features (and therefore channel classification types) and aquatic biota. This component of the analysis, linking physical channel features with individual fish and mussel species or communities of species, is not part of the current study scope. However, NetMap's geomorphic stream-aquatic biota classification system is designed to link physical channel features with individual fish and mussel species or communities.

When an analyst creates a classification, the function that creates the SPM (L in Figure 17 or D in Figure 21) also sorts Flint Hills biological data by stream classes. All Flint Hills biological data on fishes and mussels (encompassing 99 species of fishes [includes hybrids] and 43 species of mussels) in the Kansas study sites are spatially joined to NetMap's stream segments that are contained within specific channel classes. The biological data are then categorized and represented in the different channel classes in the form of a .csv file (**Figure 28**). Channel class types are listed as rows; species of fishes and mussels (two different files) are organized by columns in the spreadsheet. For example, pertinent fish data in each stream class include: 1) individual species presence or absence according to the proportion of study site lengths contained within individual channel classes (e.g., presence of any individual animal, the total number does not matter; proportion is by length of sites, not by number of sites), 2) juveniles, by species, per meter length of study reaches, 3) juveniles, by species, per meter squared of study reaches, 4) adults, by species, per meter length of study reaches, 5) adults, by species, per meter squared of study reaches, 5) total number of animals, by species, per length, and 6) total number of animals, by species, per area (**Table 3**, Figure 28). Mussel data are described in **Table 4**.



1	BLANK	bigeye shiner	bigmouth buffalo	black buffalo	black bullhead	black crappie	blackside darter
47	2B1	TotalLen=	10261.6	meters			
48	PropLenPres	0	0.05359788	0.08770563	0.1928549	0.07961722	0.02923521
49	JuvPerMeter	0	0	0	0.01819101	0.0122399	0
50	JuvPerM2	0	0	0	0.001908815	0.002147351	0
51	AdultPerMeter	0	0.01454545	0.003333333	0.007579586	0.006119951	0.003333333
52	AdultPerM2	0	0.001202104	0.000278474	0.00079534	0.001073676	0.000462963
53	TotalPerMeter	0	0.01454545	0.003333333	0.02577059	0.01835985	0.003333333
54	TotalPerM2	0	0.001202104	0.000278474	0.002704154	0.003221027	0.000462963
55	TotalNum	0	8	3	51	15	1
56	2B2	TotalLen=	36763	meters			
57	PropLenPres	0.2526453	0.01033648	0.2692925	0.01849686	0.05538177	0.02448114
58	JuvPerMeter	0.01507321	0.002631579	0.00020202	0.00882353	0.009823183	0.003333333
59	JuvPerM2	0.000924737	0.000216342	3.88E-06	0.000832408	0.00100854	0.0001443
60	AdultPerMeter	0.1931525	0.005263158	0.01929293	0.001470588	0.003438114	0.002222222
61	AdultPerM2	0.01184984	0.000432683	0.000370519	0.000138735	0.000352989	9.62E-05
62	TotalPerMeter	0.208118	0.007894737	0.01949495	0.01029412	0.0132613	0.005555556
63	TotalPerM2	0.01276798	0.000649025	0.000374399	0.000971143	0.001361529	0.0002405
64	TotalNum	1933	3	193	7	27	5

Figure 28. Biotic Sorting data output.

Table 3. Data analysis descriptions for fishes included within NetMap's Biotic Sorting Tool.

Data Category (per individual fish and species)	**Data Analysis Description**	**Attribute name in .csv files**
Species presence or absence	The presence or absence of any species based on their occupancy in individual Kansas study sites; a single animal equals presence. The calculated value is the length of stream (in sites containing at least a single animal of the requisite species) divided by the total length of stream reaches of all 307 study sites.	PropLenPres
Juveniles per meter length of channel	For individual fish species calculated as a frequency, number per meter	JuvPerMeter
Juveniles per square meter (area) of channel	For individual fish species calculated as a density, number per square meter	JuvPerM2
Adults per meter length of channel	For individual fish species calculated as a frequency, number per meter	AdultPerMeter
Adults per square meter (area) of channel	For individual fish species calculated as a density, number per square meter	AdultPerM2
Total (juveniles and adults) per meter	For individual fish species calculated as a frequency, number per meter	TotalPerMeter
Total (juveniles and adults) per square meter	For individual fish species calculated as a density, number per square meter	TotalPerM2
Total Number	Total number of study sites that individual species were detected in	TotalNum

Table 4. Data analysis descriptions for mussels included within NetMap's Biotic Sorting Tool.

Data Category (per individual mussel species)	Data Analysis Description	Attribute name in .csv files
Presence or absence	Number of sites with live mussels	Livecount
Live mussels - frequency	Summed length of sites with live divided by the summed length of all sites in classification	LivePropLen
Recent mussels (recently deceased)	Number of sites with recent mussel shells	RecentCount
Recent mussel (shells) - frequency	Summed length of sites with recent divided by the summed length of all sites in classification	RecentPropLen
Weathered mussel shells	Number of sites with weathered mussel shells	WxCount
Weathered mussel (shells) - frequency	Summed length of sites with weathered divided by the summed length of all sites in classification	WxPropLen

Combining the Four Components of the Flint Hills Classification System

The overall objective of the Flint Hills classification system is to build one or more geomorphic stream classification systems that is able to differentiate among individual or communities of aquatic species (or guilds of species). Since the physical habitat requirements are not known for all 99 species of fishes and 43 species of mussels, it is not known a-priori which geomorphic stream classification system would be best suited to create a coupled stream – aquatic biota classification system. Thus, NetMap's Flint Hills stream classification system is designed to be used flexibly and iteratively to explore which classification provides the greatest explanatory power regarding the distribution of fish and mussel communities throughout the Flint Hills channel network.

The coupled stream classification-spatial probability mapping tools are designed to be used iteratively (Figure 14). First, analysts create a classification (Parameter Nesting or Selection Grouping) using a combination of fluvial geomorphic principles, CDFs of selected attributes and professional judgment. Next, SPM is conducted (J-L, Figure 17 or E-F, Figure 21). Prior to applying a classification across the full Flint Hills network, analysts examine the SPM results either as tables or histograms (Figure 26). Since the objective of stream classification is to distinguish among different channel types (morphologies), analysts search for differences in SPM results across the different channel classes. Differences in percentage of pools, riffles, and glides; differences in substrates; and differences in in-stream wood abundance across different channel classes indicate that the classification created a meaningful channel classification system (e.g., one that distinguishes among different morphologies). In contrast, absence of differences in SPM results across different channel classes indicates that the chosen classification did not distinguish among channel types, with respect to field measured attributes. If differences in SPM are indicated, an analyst can proceed with network wide classification using the interface (e.g., F, Figure 17). If no significant differences in SPM are indicated, then a new classification can be developed (using Selection Grouping or Parameter Nesting interfaces), and so on. Thus, the tools are to be used iteratively until the SPM results indicate that the chosen channel parameters and their domain boundaries yield meaningful differences in channel physical characteristics.

Alternatively, analysts may bypass SPM results and instead focus on how channel classification differentiates among fish and mussel species. For example, to determine which classification is most appropriate in the Flint Hills ecoregion, analysts will judge whether different channel classes correspond to different occupancy by different aquatic species, including collection of species or communities and aquatic biota density.

Five Channel Classification Systems in the Flint Hills

Although the Flint Hills classification system is designed to create customizable channel classes for diverse applications, five classification systems are applied during this study (**Table 5**). They include: 1) Parameter Nesting involving the drainage area attribute only, 2) Selection Groupings encompassing combinations of drainage area, gradient, channel confinement, summer habitat volume and tributary confluences, 3) Buffington and Montgomery classification system based on gradient and width to depth ratios and including a modified version to better match it to the Flint Hills landscape, and 4) Rosgen channel types that use entrenchment ratio, width to depth ratio and sinuosity. Evaluating whether these classification systems inform a taxonomy of channel geomorphic – aquatic biota in the Flint Hills is beyond the study scope. However, the five classification systems that extend to Spatial Probability Mapping and Biotic Sorting support the prime objective of the Flint Hills geomorphic stream – aquatic biota classification.

Table 5. Summary information regarding the five Flint Hills classification system.

Classification Type	Parameters	Method	Percent channels classified	Attribute Name in Reach Shapefile	SPM and Biotic Sorting .csv names (n=4)
Drainage Area	Drainage Area (Figure 29)	Parameter Nesting	100%	DrainA1	DrainageArea*.csv
Custom #1	Gradient, confinement and mean annual flow (Figure 34)	Selection Grouping	100%	Custom1	Custom1*.csv
Custom #2	Gradient, confinement, summer habitat volume (Figure 38)	Selection Grouping	100%	Custom2	Custom2*.csv
Buffington & Montgomery 2013 (modified)	Gradient Width to depth ratios (Figure 41)	Selection Grouping	87%[1]	BMmod	B_M-Mod_02*.csv
Rosgen	Entrenchment ratio, width to depth ratio, sinuosity	Rosgen tool	55%[1]	Rosgen	Na (too few classified to conduct SPM and Biotic Sorting)

[1] Channels only less than 0.022 in slope

Drainage Area Only: Role of Channel Size

Using the Parameter Nesting tool, a single parameter of drainage area is used in all three levels creating a classification system based on area alone (**Figure 29**). The resulting classification is denoted as 1A1, 1A2, 1B1, 1B2, 2A1, 2A2, 2B1 and 2B2, and it sub-divides the channel network into drainage area classes of 1-3 km^2, 3-8 km^2, 8-10 km^2, 11 – 40 km^2, 41 – 50 km^2, 51 – 60 km^2, 61 – 100 km^2 and 101 – 2000 km^2 (**Figure 30**). This classification is used to evaluate how channel size influence reach scale morphology and provides a basis for creating more complex classifications. In addition, the analysis of channel size is also used to help understand the apparent positive relationship among drainage area and species richness of fishes and mussels in the Flint Hills (see Discussion); a finding also supported by other recent studies in the Flint Hills (Martin et al. 2013, Trioa and Gido 2014).

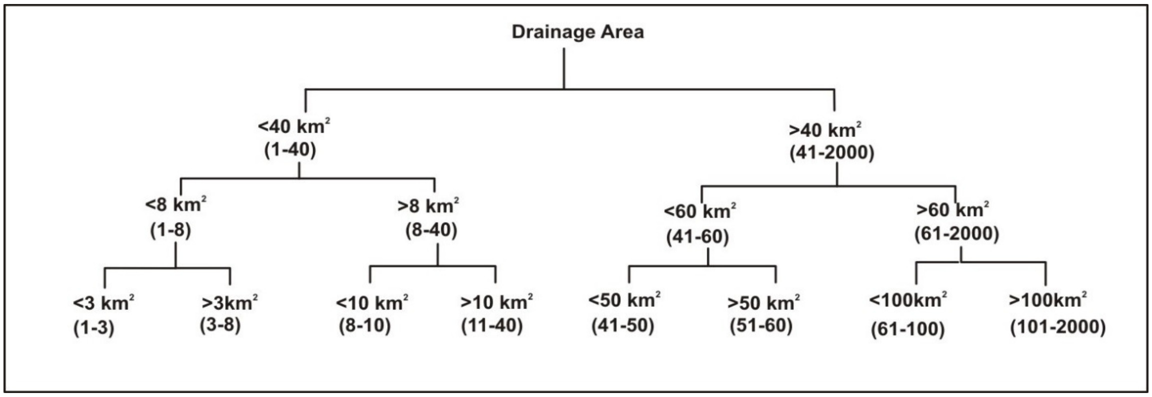


Figure 29. Drainage area classes used in the Parameter Nesting classification.

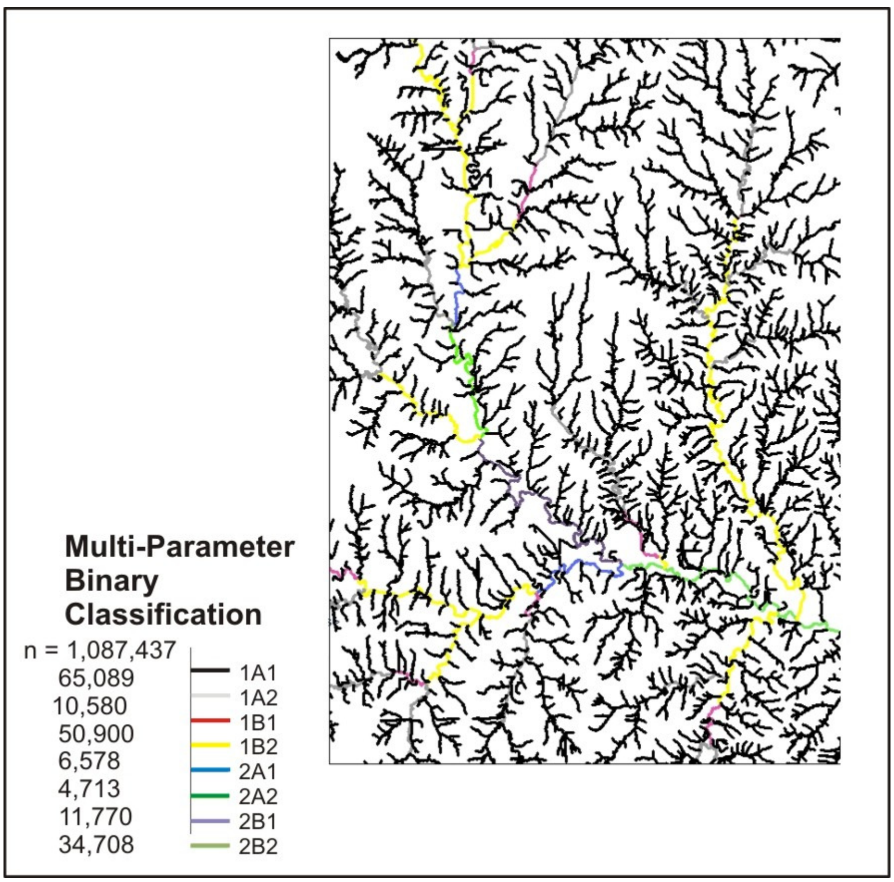


Figure 30. Map output of the drainage area classification showing the numeric legend (1A1 etc.)

The associated SPM analysis reveals watershed scale patterns of patch scale channel attributes. Using drainage area classes above, the proportion (spatial probability) of attributes changes downstream: the proportion of sand bedded channels decreases, the percentage of pools increases, the percentage of riffles decreases and in-stream wood storage increases (**Figures 31 through 33**).

This pattern suggests that pool dwelling species may increase downstream and species associated with woody debris may also increase downstream in the larger channels. Increased pool volume (and habitat volume) downstream may also lead to increasing number and diversity of species (e.g., species richness, see Discussion and see Troia and Gido 2014, and Martin et al. 2013).

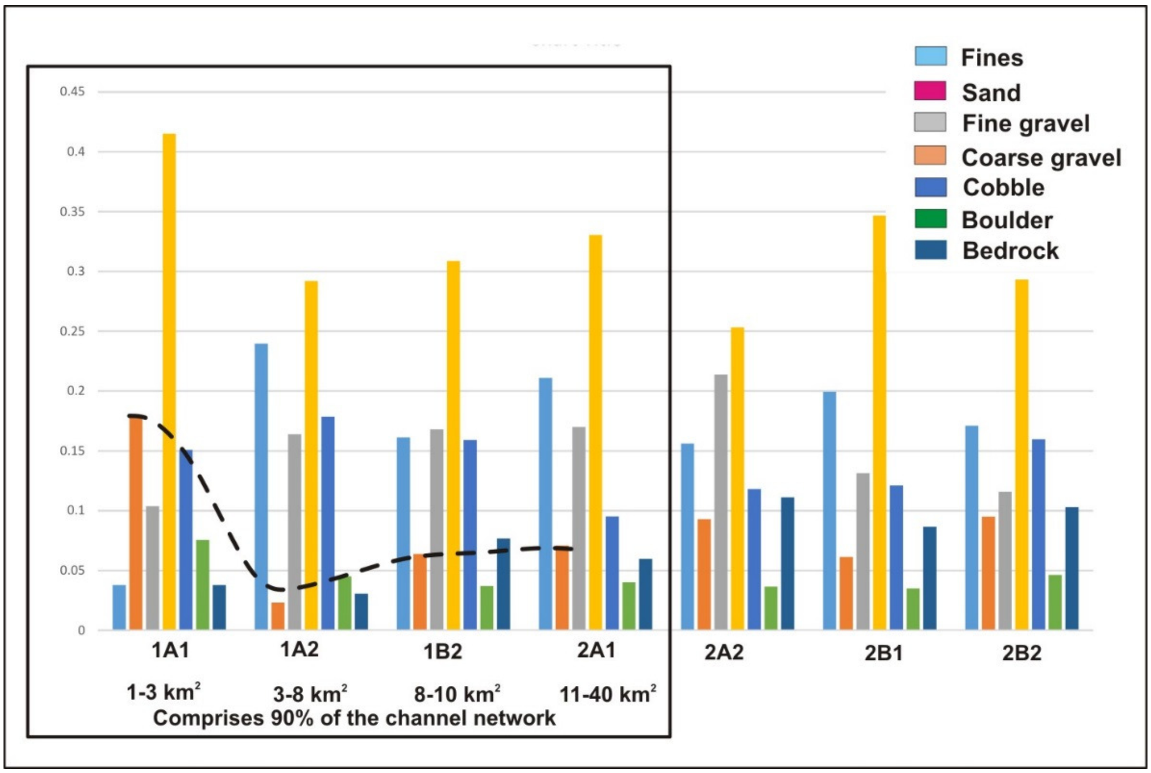


Figure 31. SPM output for substrates from the Parameter Nesting drainage area classification.

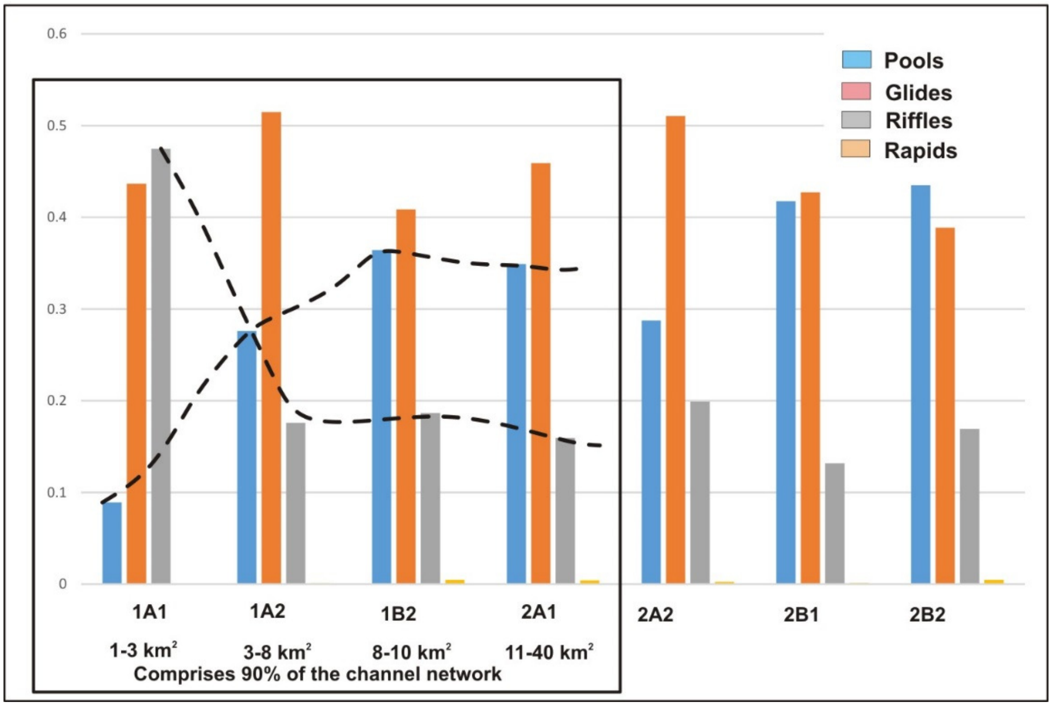


Figure 32. SPM output on channel morphology from drainage area classification.

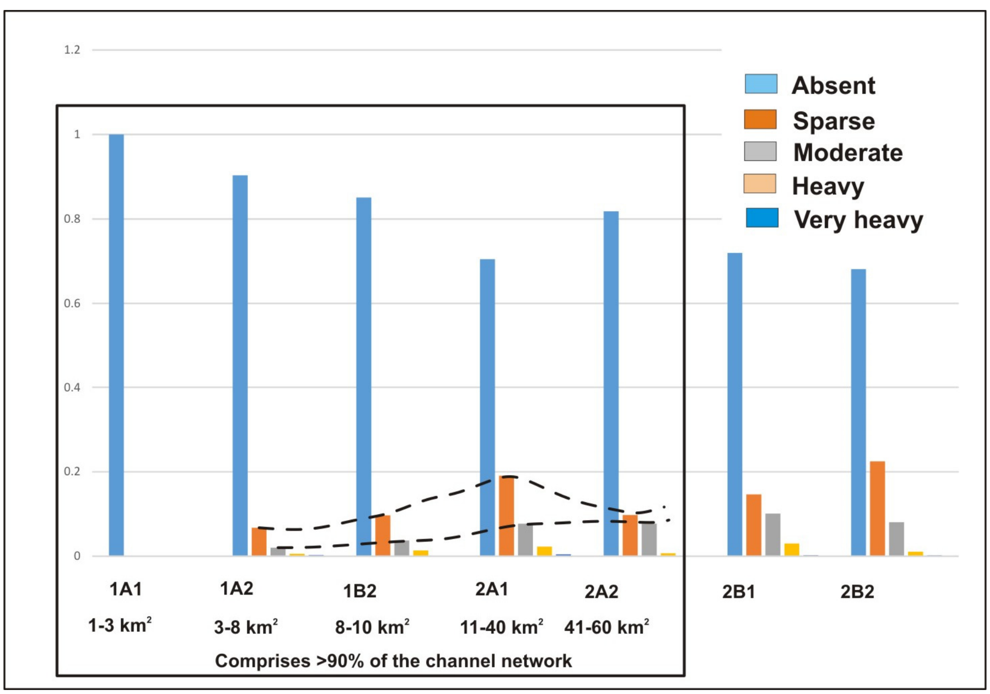


Figure 33. SPM output on woody debris from drainage area classification.

Custom #1: Drainage Area, Gradient and Confinement

A channel classification based on drainage area, gradient and channel confinement (channel confinement is floodplain width divided by channel width) was built using the Parameter Nesting tool (**Figure 34**). Classification and SPM results are shown in **Figures 35 and 36**. The classification reveals that there are distinct differences in the proportion of pools in a couple of the stream classes, notably 1B2 and 2B2 (Figure 36), defined as reaches less than 20 km^2, greater than 0.001 in gradient and relatively unconfined (>4) (Figure 35). Classification details are shown in **Table 5**.

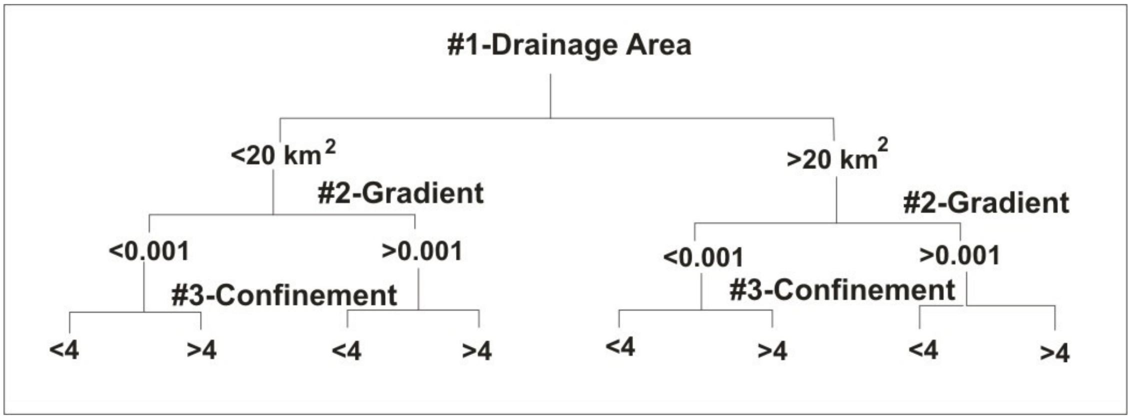


Figure 34. The parameters used and their class breaks using Parameter Grouping classification.

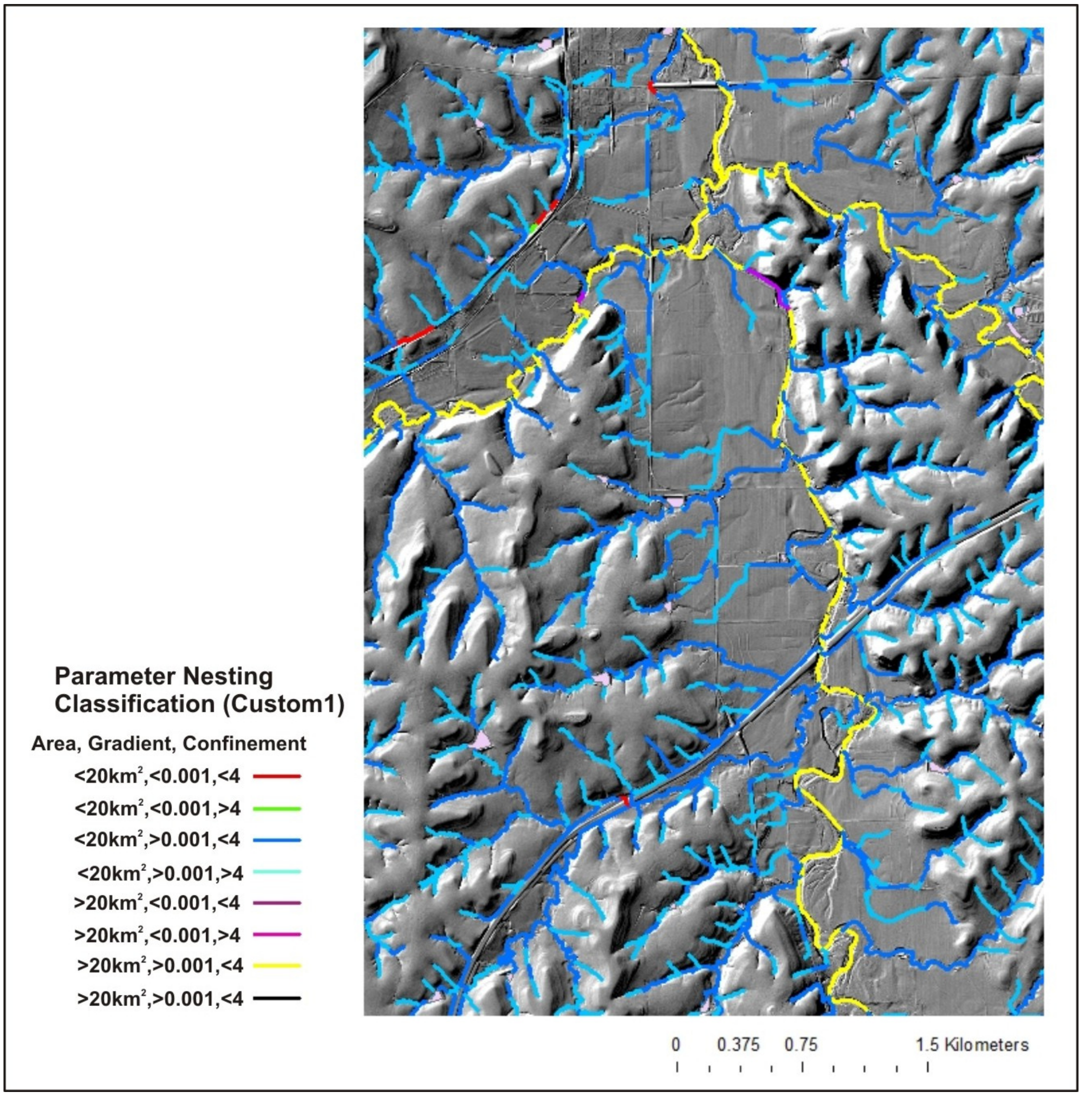


Figure 35. Custom #1 channel classification map.

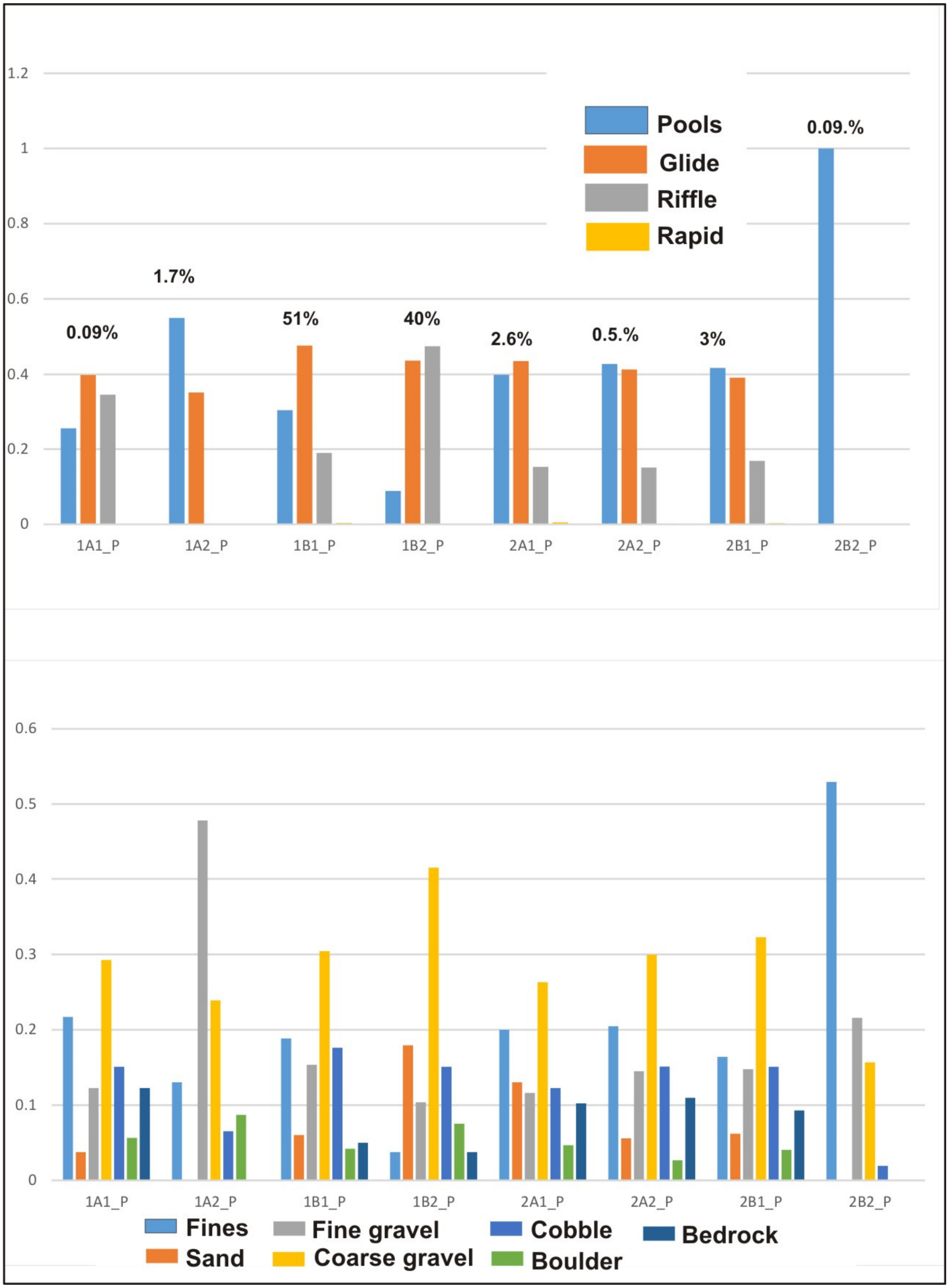


Figure 36. SPM output for the custom #1 classification.

To help interpret the results it is important to note that Flint Hills streams, in general, are dominated by confined channels (<4) in small to moderate drainage areas while the larger streams and rivers are mostly moderately confined (8-10); there are pockets of channels that are very unconfined (> 12) (**Figure 37**). Confinement, along with channel size (including summer habitat volume), appear to be important classification criteria.

The classification analysis is not extended to Biotic Sorting (beyond study scope) but the output files exist to examine results (**Appendix 3**).

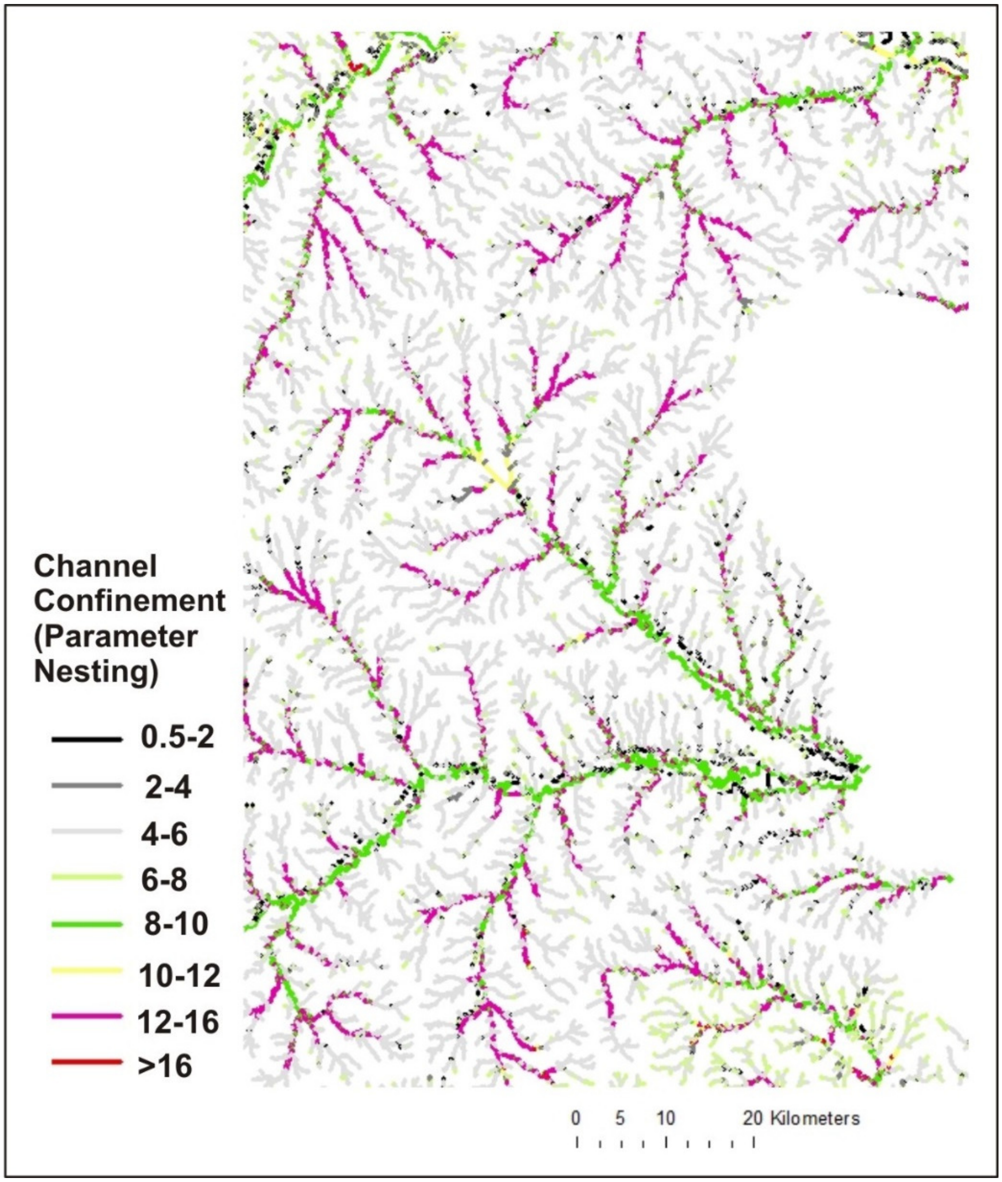


Figure 37. Map output for the Custom #1 classification.

The use of more diverse classification schemes, like Custom #1, or others that could be created by incorporating landscape features such as geology, valley morphology and erosion potential (Table 2), and their linkage to fluvial morphology (via SPM) or aquatic assemblages (using Biotic Sorting), could support building 'geomorphic guilds' that has proved informative in other landscapes (Watson et al. 1998).

Custom #2: Gradient, Mean Annual Flow, and Habitat Volume

Another channel classification is created using mean annual flow, habitat volume (summer habitat width multiplied by summer habitat depth multiplied by one meter of channel length), and gradient. This combination of parameters, theoretically, should have consequences for the distribution of fish and mussel species. This classification is an example of how SPM results can be considered secondary with the main emphasis on using the Biotic Sorting analysis.

Using the Parameter Nesting interface, the first level parameter is gradient (<=0.001 and >0.001); the second level parameter is mean annual flow (<=4m^3s^{-1} and > 0.05 m^3s^{-1}); the third parameter is summer habitat volume using four thresholds (4, 35, 0.5 and 20 m^3) (**Figure 38**). When combining diverse parameters like these, the selection of the first parameter division will impact the selection of the second and third level parameters, in ways that are not obvious. It is highly recommended that analysts use the CDF function in the Parameter Nesting interface to help determine appropriate parameter divisions. For example, note the diverse numeric values selected for the second and third parameters in the example above (based on using the CDF tool at all three levels in the classification).

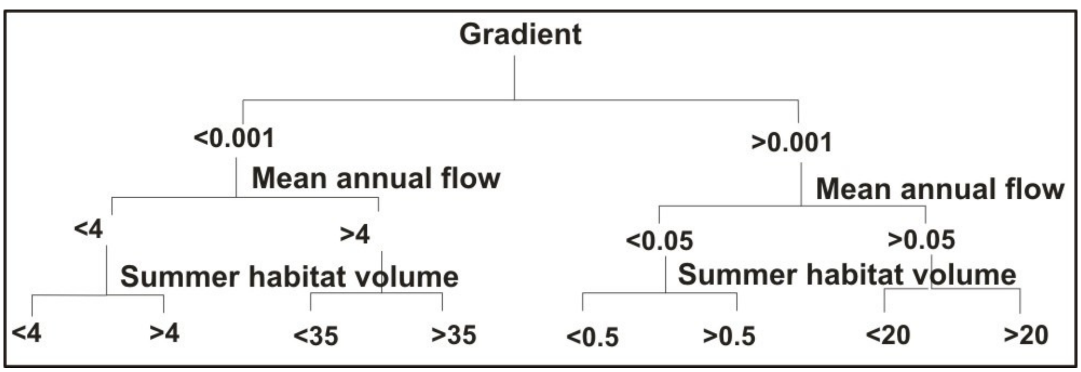


Figure 38. Parameters and class breaks for Custom #2 classification.

The SPM results only show four classes (1A1, 1B1, 2A1 and 2B1) (**Figure 39**). This is because there were no field study sites located in channels within four of the channel classes; e.g., where there are no field data in channel classes, there are no SPM results. Nevertheless, the SPM results (Figure 39) do show relatively large differences in the proportion of pools across the four classes. In particular, the first class (1A1) has significantly higher percentage of pools (48%) compared to classes 1B1 and 2A2 (e.g., double the percentage). The classification analysis is not extended to Biotic Sorting (beyond study scope) but the output files exist to examine results (Appendix 3).

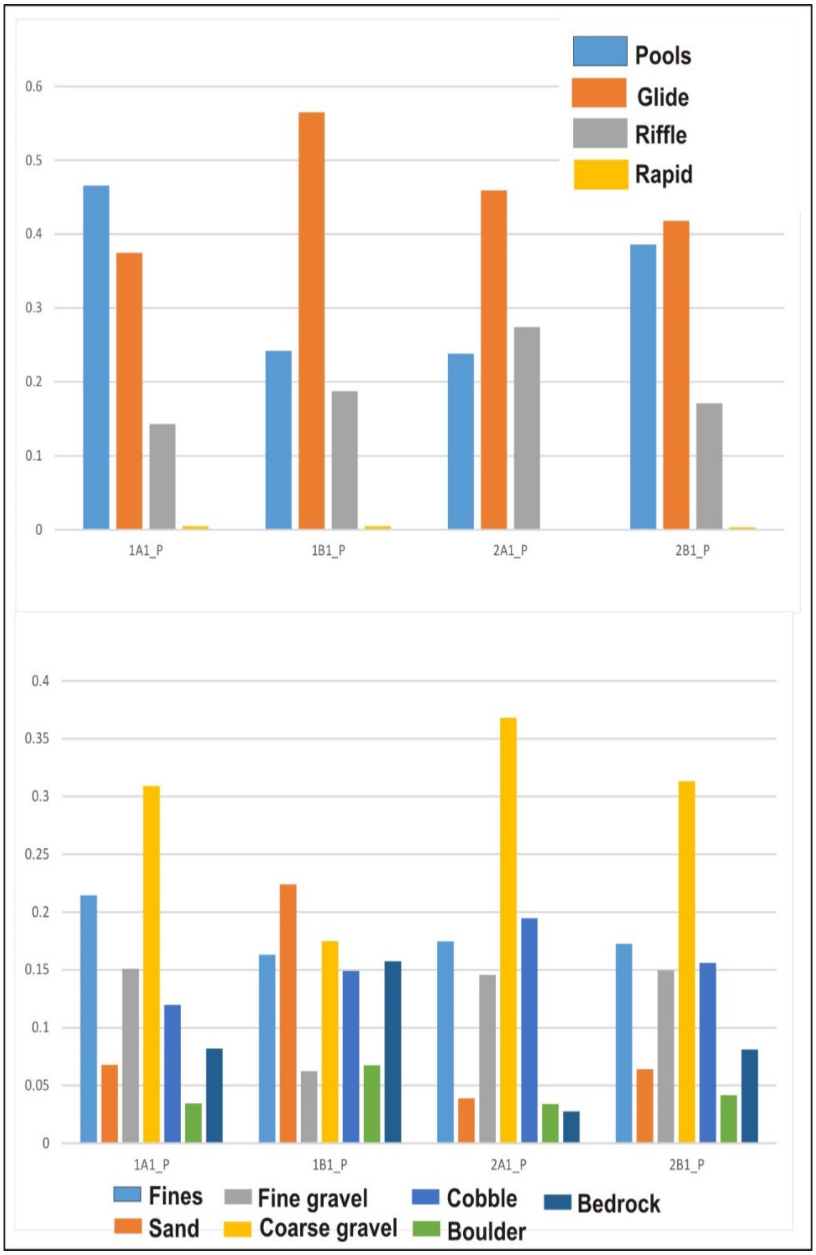


Figure 39. SPM output for custom #2 channel classification.

Buffington and Montgomery (2013) Classification System

The original Montgomery and Buffington (1997) classification system incorporated parameters of channel width, depth, sinuosity, gradient, gain size, valley confinement and sediment supply. These parameters, with the exception of grain size and sediment supply, are available from NetMap's synthetic stream layer (Table 2). A robust relationship between grain size and landscape parameters such as channel gradient, drainage area and lithology in the Flint Hills is not available (Appendix 2 and see SPM results in Figure 31). In addition, a sediment budget that would provide information about sediment supply to channels in the Flint Hills is also not available. Therefore, the updated Buffington and Montgomery (2013) classification system was used in the Flint Hills that relies only on width to depth ratios and gradients (e.g., Figure 5).

The Buffington and Montgomery (2013) classification domains of braided, dune-ripple, pool and riffle, plane bed and step pool have somewhat overlapping gradient and width to depth boundaries (Figure 5). Channel classification in the Flint Hills using remote sensing data on channel gradients and statistical regressions on hydraulic geometry (Table 1) using the Selection Grouping classification tool (Figure 21) requires non-overlapping boundaries. Thus, the Buffington and Montgomery (2013) classification domains were slightly modified to create non overlapping parameter boundaries (**Table 6**); additionally the dune-ripple channel class was eliminated because the Kansas field data did not reveal channels dominated by sand, even at the largest drainage areas and lowest channel gradients, as required by the Buffington and Montgomery dune-ripple classification (e.g., Figure 31).

Table 6. Buffington and Montgomery (2013) channel types defined by channel slope and width to depth ratios.

Channel Types	Channel slope (m m^{-1})	Width to depth ratio (m m^{-1})
Braided	0.0008 – 0.008	35 - 110
Pool riffle	0.002 – 0.01	16 - 35
Plane bed	0.01 – 0.03	12 - 25
Step pool	0.03 – 0.07	10 - 20

The classification system was applied to only those channels less than 0.022 in slope, those occupied by fishes and mussels according to the field data (61% of all segments in the synthetic network). Classes included braided, pool-riffle, plane bed and step pool (Table 6). Out of 776,990 channel segments, only 5% were classified (Table 7). Of the channels classified, pool riffle was the most common, followed by braided and plane bed. In general, braided channels were confined to the lower gradient mainstem; pool riffle channels classified the larger tributaries (**Figure 40**). There were no step pool channels classified; this may result from the classification being restricted to the lowest gradients (< 0.022) to match the channels that are occupied by fishes and mussels.

Table 7. The numbers and percentages of Buffington and Montgomery (2013) channel types for only those channel segments less than 0.022 in slope in the Flint Hills.

Buffington and Montgomery (2013) Channel Types	Number classified in channels > $1km^2$
Braided	11,998 (1.5%)
Pool riffle	24,598 (3.2%)
Plane bed	2,854 (0.4%)
Step pool	0 (0%)
Unclassified	737, 363 (94.9%)

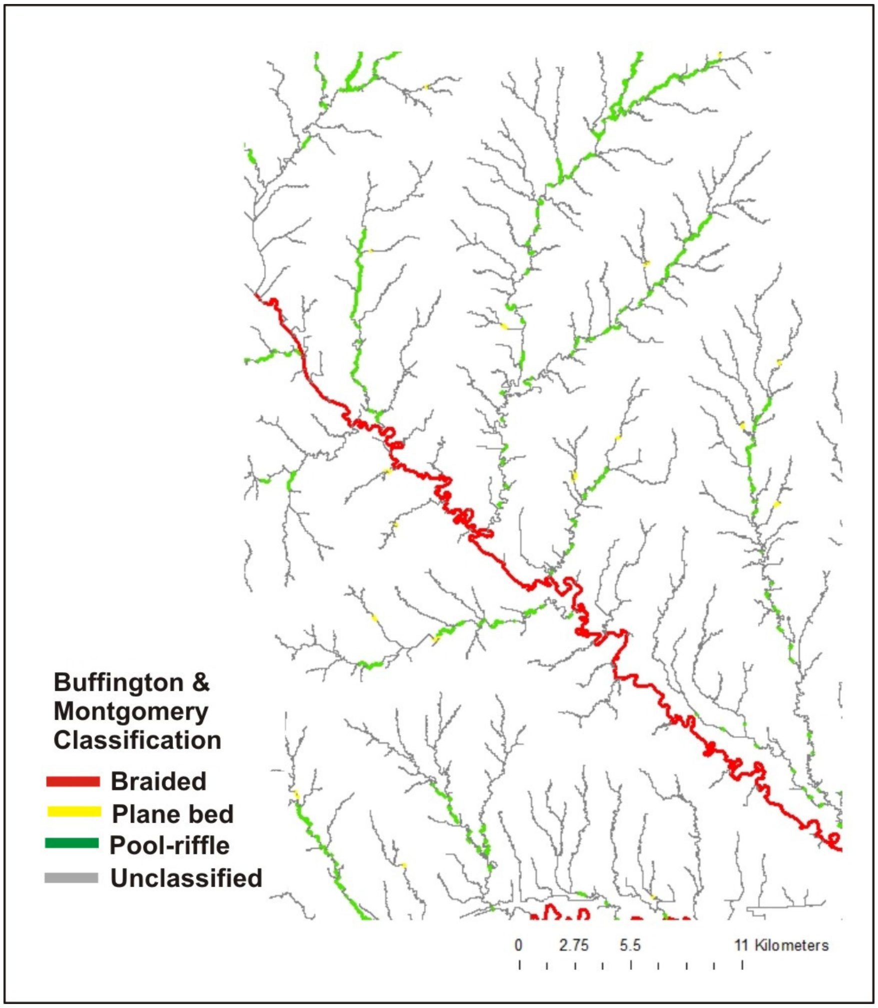


Figure 40. Map output for modified Buffington and Montgomery (2013).

The large percentage of unclassified channels using the Buffington and Montgomery (2013) classification system based on width to depth ratios and gradient categories (Table 7) was partly due to the range of width to depths and gradients in the Flint Hills that exceeded the classification parameter boundaries. Therefore, the Buffington and Montgomery (2013) classification was adjusted to reflect the Flint Hills landscape that included: 1) the absence of sand dominated channel segments (result: dune ripple class eliminated), 2) pool-riffle-glide morphology dominates based on SPM results in Figure 32 (result: pool-riffle limits extended to Flint Hill limits of width to depth ratios and extended by gradient into the braided domain), 3) width to depth ratios likely underestimated using width and depth regressions (result: extend braided and pool riffle categories), and 4) dominance of gravels and cobbles in field data and the presence of in-stream wood (based on SPM, see Figure 31) (result: plane bed category is subsumed within pool riffle and step pool categories); **Figure 41** shows the modified Buffington and Montgomery (2013) classification for the Flint Hills ecoregion. The adjusted parameter domains used in the selection grouping classification tool encompass braided, pool-riffle and step pool channel types applied to channels less than 0.022 in slope (**Table 8**).

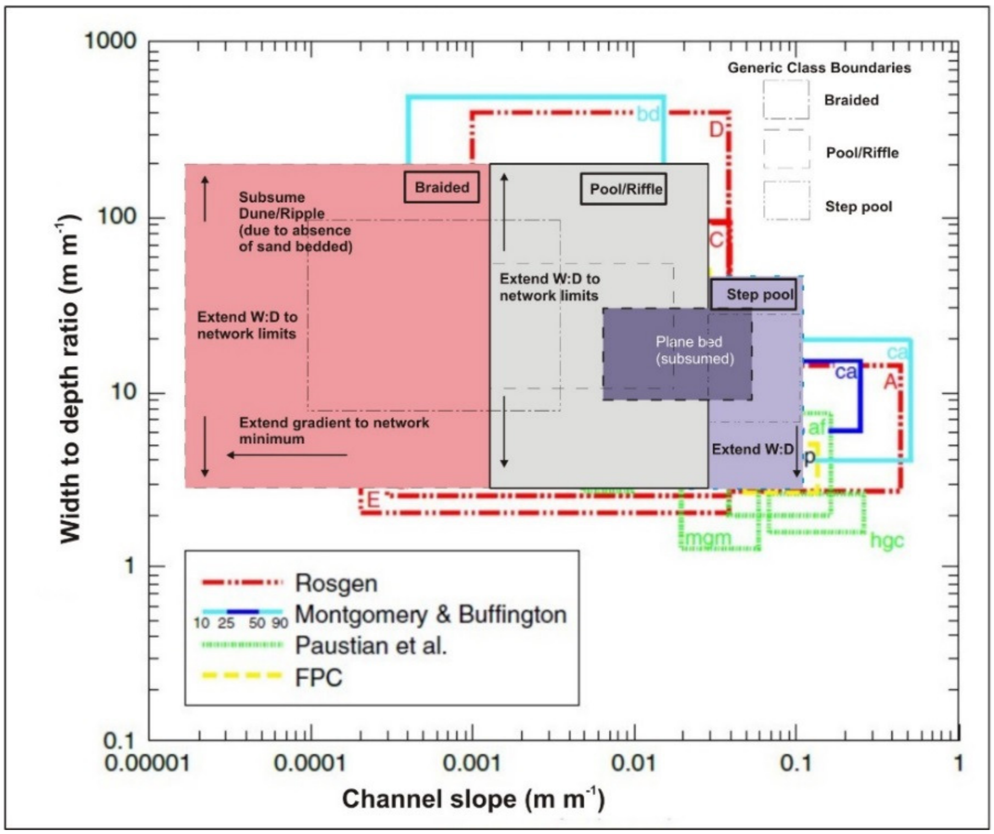


Figure 41. Modified Buffington and Montgomery (2013) classification domains.

Table 8. Modified domains of channel slope and width to depth ratios to better match Buffington and Montgomery (2013) classification to the Flint Hills landscape.

Channel Types	Channel slope (m m^{-1})	Width to depth ratio (m m^{-1})
Braided	0.0001 – 0.0015	3 - 110
Pool riffle	0.0015 – 0.03	3 - 110
Step pool	0.03 – 0.1	3 - 45

The modified Buffington and Montgomery classification in the Flint Hills is shown in **Figure 42**. The proportion of channel types in different classes is shown in **Table 9**; 86% of the channels less than 0.022 in slope were classified. To determine whether the Buffington and Montgomery classification, including its modified version, is suitable in the Flint Hills ecoregion, analysts would need to verify that its domains of channel classes (braided, pool riffle, plane bed and step pool) match field conditions. Available field data from Kansas Department of Wildlife, Parks & Tourism only includes the categories of percent pools, riffles, glides and rapids, thus its field classification does not directly correspond with the Buffington and Montgomery classification nomenclature.

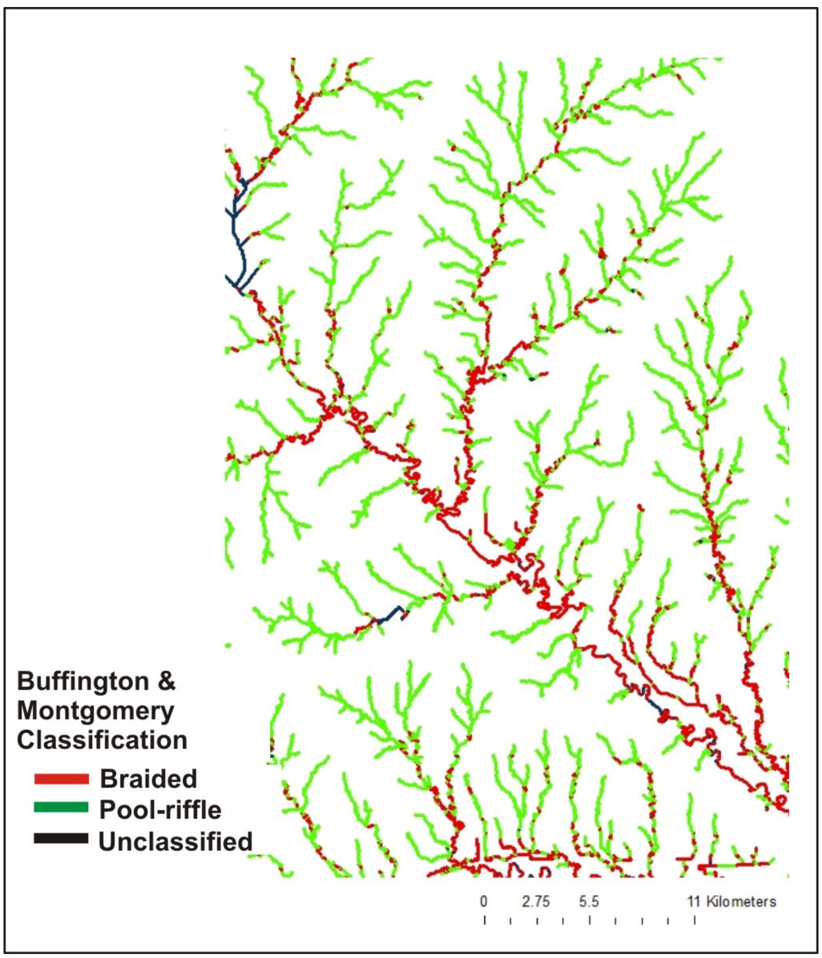


Figure 42. Map output for the modified Buffington and Montgomery classification.

Table 9. The numbers and percentages of Buffington and Montgomery (2013) modified channel types using only those channel segments less than 0.022 in slope.

Modified Channel Types	Number classified in channels > 1km^2
Braided	90,056 (11.6%)
Pool riffle	572,499 (73.8%)
Step pool	0 (0%)
Unclassified	114,217(14%)

Spatial probability mapping was used to make a preliminary evaluation of whether the modified Buffington and Montgomery classification corresponds to variation in habitat patch scale channel morphology. There is a higher percentage of glides and a lower percentage of riffles in the braided channel class compared to the pool-riffle class (**Figure 43**). The pool-riffle class had about an even distribution of pools and riffles and a smaller proportion of glides, as would be expected. The braided channels also had a much higher percentage of fine gravel and much lower percentage of cobbles compared to the pool-riffle class, again as would be anticipated. This suggests reasonable correspondence between the modified Buffington and Montgomery classification and patch scale habitat conditions in the Flint Hills; however, but limited to two channel classes (Table 9).

Rosgen Classification System (1996)

The Rosgen stream classification system uses entrenchment ratio (floodplain width divided by channel width), width to depth ratio, sinuosity, channel gradient and substrate size (Figure 6). The classification system subdivides channel types primarily by single to multi thread, cross sectional geometry, slope gradient and sinuosity.

The Rosgen classification system is applied to the Flint Hills ecoregion using the remote sensing data of entrenchment ratio, width to depth ratio, and sinuosity (using the NetMap tool interface, **Figure 44** that uses the Selection Grouping method). Adding bed substrate (D50) and channel gradient are options but not used due to the lack of river network wide substrate predictions in the Flint Hills. The Rosgen classification interface in NetMap tools is located under the 'Fluvial Processes' tab and under 'Channel Classification' (Figure 15).

Rosgen's classification system was applied to only those channel segments in NetMap's synthetic network greater than 1 meter in width (as per NetMap's Rosgen tool protocol). Classification encompassed 55% of the Flint Hills synthetic network, with most headwaters unclassified (**Figure 45, Table 10**). The majority of classified channels were type A (step pool and cascade), followed by type F (pool riffle or dune-ripple) and by type G (pool riffle or plane bed) (Table 10).

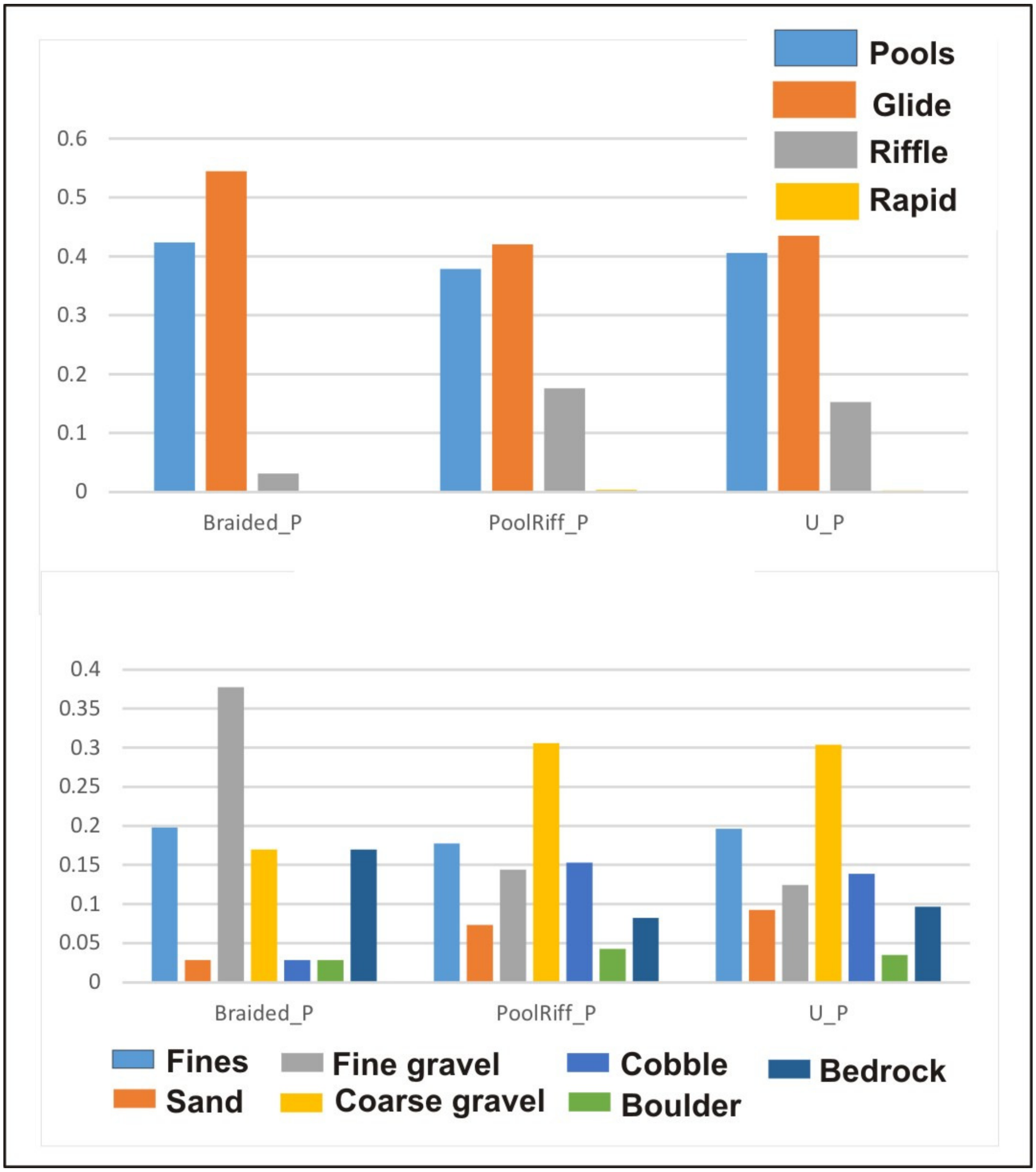


Figure 43. SPM output for the modified Buffington and Montgomery (2013) classification system.

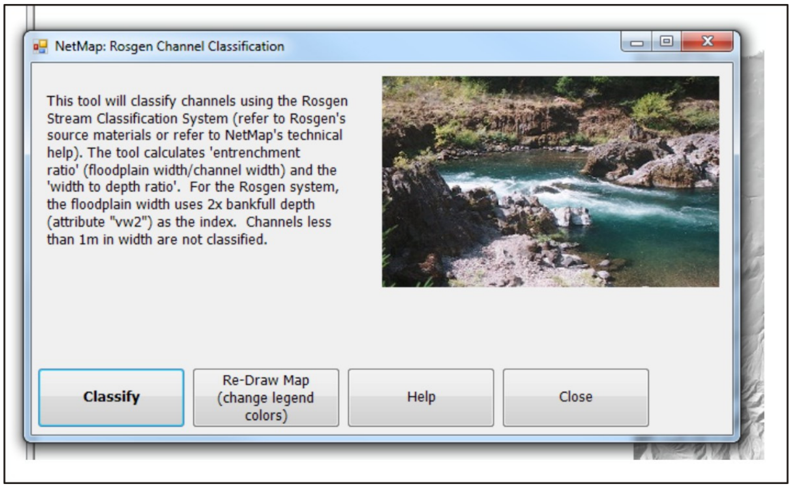


Figure 44. NetMap interface for the Rosgen classification tool.

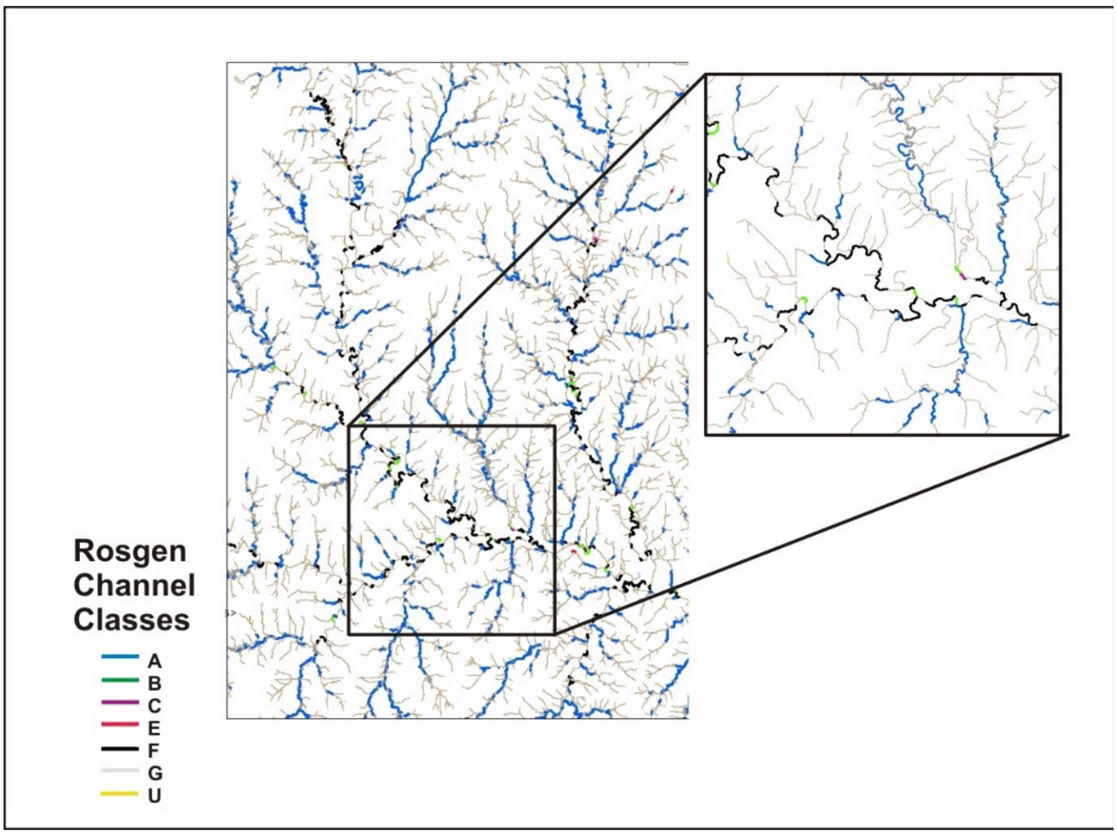


Figure 45. Rosgen channel types in a portion of the Flint Hills.

Table 10. Rosgen channel types that were classified using remote sensing data in the Flint Hills for all channels with channel widths greater than one meter (as per tool interface protocol).

Rosgen Channel Types	**Number classified in channels > 1 m width**
A (step pool and or cascade)	91,979 (30%); 57%
B (step pool and or plane bed or pool-riffle)	6,506 (2.15); 4%
C (Pool-riffle and or plane bed and or ripple dune)	7,022 (2.3%); 4%
E (pool riffle or ripple-dune)	107 (0.03%); 0.06%
F (pool riffle or ripple-dune)	36,386 (12%); 22%
G (step pool with some instances of plane bed forms	20,388 (6.8%); 13%
Unclassified	136,259 (45%)

The low number of classified streams is due in part to Rosgen's discontinuous parameter domains; entrenchment ratio is a continuous variable (<1.4, 1.4-2.2, and >2.2) while width to depth ratios and sinuosity are discontinuous variables (Figure 6). For example, an "E" channel has an entrenchment ratio of >2.2, a width to depth ratio of <12 and a sinuosity of >1.5; however, holding the entrenchment ratio and width to depth ratio the same, there is no classification for channels with a sinuosity of <1.5. This type of discontinuous classification domains led to many unclassified channels using the Rosgen method in the Flint Hills. Another limitation in the Flint Hills is the lack of channel network wide predictions of bed substrate which did not allow substrate and channel gradients to be used in the Rosgen classification.

Field validation of Rosgen channel types would be required to determine the efficacy of channel classification (A – G channel types) in the Flint Hills ecoregion. Available field data from Kansas Department of Wildlife, Parks & Tourism only includes the categories of percent pools, riffles, glides and rapids while Rosgen classes A-G include categories of step pool, plane bed, and ripple-dune.

The Rosgen classification has been used successfully in other areas of the U.S. However, because of its discontinuous parameter domains and its reliance on field identification of channel morphology (including substrate) its utility is likely compromised in the Flint Hills when using remote sensing data alone, including yielding only a partial classification of the channel network (e.g., 45% unclassified). It is likely that the Rosgen classification system is most usefully applied and accurate when it is based on field data and observations.

Discussion

Use of Remote Sensed Data in Channel Classification

Conventionally, channel classification relies on abundant field observations and measurements, in combination with general fluvial geomorphic principles. The empirical, field based approach is evident in numerous classification system used in the western U.S., Alaska and Canada (Paustian 1992, Rosgen 1996, Montgomery and Buffington 1997, Church 2006, Buffington and Montgomery 2013). Stream classification is not a precise science because physical descriptions of different channel types and their parameter domains can overlap, or there can be gaps in the parameter domains (e.g. Figures 5 and 6). Overlapping qualitative descriptions and overlapping parameter domains means that field observations or measurements are required to fit one channel segment into one channel type class or another. In addition, the temporally dynamic supply and storage of sediment and organic materials that affect channel classification can only be reliably determined in the field.

Although there are field data available at 307 study sites in the Flint Hills landscape (Figure 12), channel morphology naming conventions do not exactly match the nomenclature of other classification systems, such as the Buffington and Montgomery (2013) and Rosgen (1996) systems. For example, the Buffington and Montgomery system contains dune-ripple, pool and riffle, plane bed, step pool, cascade and colluvial types. The Flint Hills field data used pools, riffles, glides, rapids and cascades. Rosgen stream types are A through F can correspond to a mixture of stream types. For example, plane bed channels can be classified as C, E or F stream types (pool-riffle morphology, Rosgen 1996). Pool-riffle channels are classified as either B channels, riffle and plane bed morphology or A and G streams (step-pool and cascade) (Buffington and Montgomery 2013). Nevertheless, the Kansas field based nomenclature is informative and accurately reflects what appears to be the dominant channel type in the Flint hills, namely alternating and interdigitated pools, riffles and glides in channels less than about 2% in gradient occupied by fishes and mussels.

In addition, based on the objective of U.S. Fish and Wildlife Service, the Flint Hills classification system needs to be applied across all channel segments occupied by fishes and mussels. Thus, the classification system is dependent on remote sensing data, information that can be obtained from NetMap's synthetic stream layer built using LiDAR and 10 m DEMs (Figures 7 – 10). There are numerous remote sensing attributes that are derived from the synthetic river network, as well as the hydraulic geometry relationships that we developed from the field data (Tables 1 and 2).

The advantage of using remote sensing data is that it is spatially continuous across entire river networks or landscapes, like in the Flint Hills landscape. Moreover, difficult to obtain measurements such as floodplain widths, valley widths (e.g., channel confinement) and tributary confluence effects, are quickly evaluated using models and remote sensing data and can be used within a classification system. It also allows other potentially important land attributes to be included in stream classification such as vegetation, land use, climate, soils and geology. In NetMap, these types of terrestrial attributes can be summarized to stream reaches and routed downstream; this was done for climate (mean annual precipitation) and geology in the Flint Hills and they can be used in iterative classification.

The disadvantage of depending on remote sensing in channel classification is the lack of field observation and measurements that typically provide a strong empirical, real world component. For example, field measurements may target specific geomorphic settings believed to be important in controlling channel geomorphology (in the Flint Hills). These can include tributary confluences, alluvial fans, other large sediment sources, and log jams. Field observations and measurements might prove critical in linking specific types of planform morphologies to specific channel classes (pools and riffles, rapids), such as what combinations of channel gradient, width, depth, substrate and sinuosity lead to riffles, versus rapid channel types (Figure 5).

Use of remote sensing, including the development of synthetic river networks that are richly attributed (such as what is done in the Flint Hills using NetMap, e.g., Table 2) can provide the basis for developing channel and aquatic classification within a larger landscape classification framework. 'Geomorphic guilds' (Watson et al. 1998) could be built using NetMap's parameters and some combination of classification techniques that encompass both channels and the landscapes they exist within. However, the Flint Hills landscape and associated channel system do not appear to exhibit significant spatial variability and diversity, and thus the role of scale alone (such as channel size) could prove to be a dominant variable in classification frameworks (see below).

Necessity and Advantages of a Customizable and Iterative Stream Classification

The main objective of the Flint Hills stream classification system is to link channel physical characteristics to aquatic biota, including presence or absence of individual species, communities (or guilds) of species, and animal density. Since the aquatic component of the Flint Hills classification system is not a part of this study scope, a flexible and iterative classification system was developed rather than a-priori and fixed classification systems. This approach differs from more conventional stream classification approaches that impose a strict typology, often landscape specific (sensu Paustian 1992, Rosgen 1996, Montgomery and Buffington 1997, Church 2006, see Figures 5 and 6).

Advantages of a flexible and iterative classification system in the Flint Hills (Figure 14) include being able to explore how different combinations of stream attributes (Table 5) can be used to create customized classification systems and to evaluate their efficacy at differentiating among reach to habitat-patch scale channel morphology observations and data and ultimately aquatic biota. It also allows the system to be applied for different purposes. For example, the system that includes SPM can evaluate whether field measurement locations are located appropriately, reflecting the distribution of different channel and landscape conditions. For example, although tributary confluence areas may be important ecologically, including being part of an experimental classification system, they may be underrepresented in the field data.

Homogeneity, Channel Size, Habitat Volume and Species Richness

The Flint Hills channel network that is characterized by the Kansas field data and that contain aquatic species in channels less than 0.022 in slope, reflects a very narrow range of gradients. The field data plots (Appendix 2) and SPM results presented above reveal that physical channel attributes do not vary greatly across the Flint Hills channel system accessible to aquatic biota. Specifically, the SPM analysis that subdivides the Flint River network by drainage area classes (low to high) reveals that, although there are differences in the relative proportion of pools, riffles and glides, over 90% of the network can be characterized by alternating and interdigitated pool, riffle and glide morphology; there are a few rapids and almost no cascades.

However, there are discernable patterns in the SPM results that show that the proportion of pools increases downstream (and riffles decrease downstream). Substrate sizes also decrease downstream to some extent although all channels are mostly a combination of fine to coarse gravels and to a lesser extent cobbles. In addition, since channel width and depth increase downstream, as expected, summer habitat volume increases downstream (**Figure 46**).

The plots of fish species and mussel species counts versus drainage area indicate that species richness increases downstream (Figure 46). In addition, since the proportion of pools increases downstream, both available pool habitats and habitat volume appear to be important determinants in species abundance and likely in the overall animal frequency and density downstream.

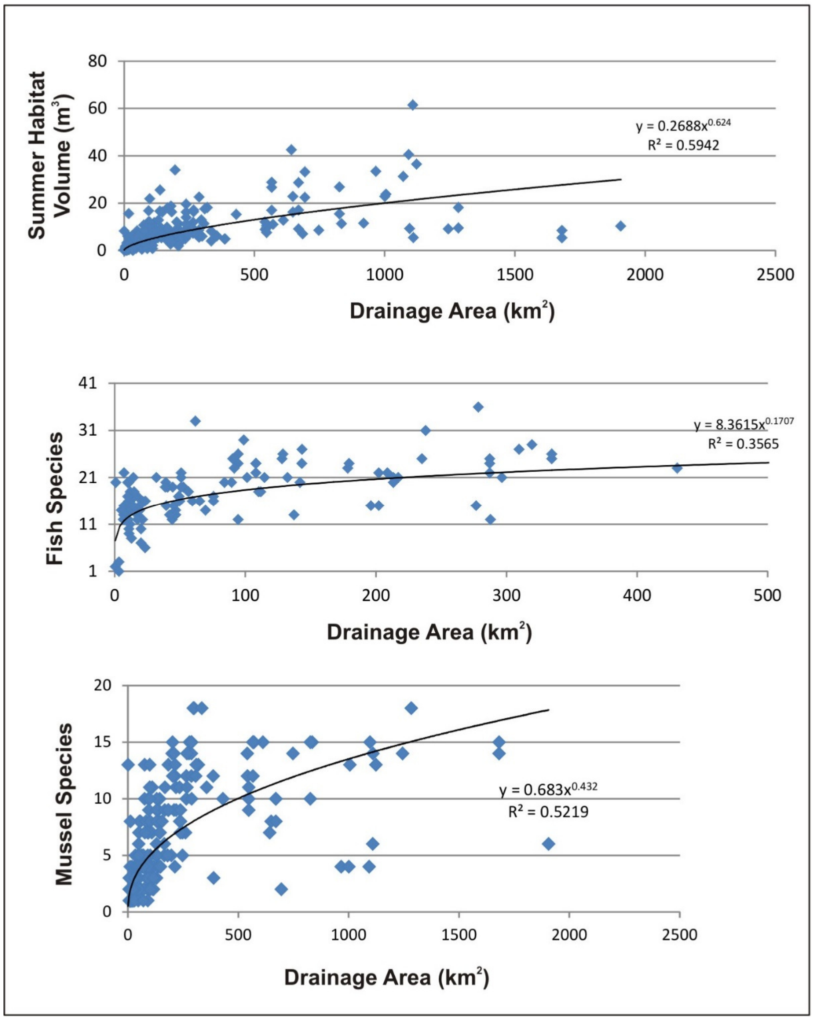


Figure 46. Summer habitat volume, species richness and drainage area.

This finding is similar to a recent analysis of prairie stream fish distributions in Kansas, including in the northern portion of the Flint Hills ecoregion. Troia and Gido (2014), in their analysis of congeneric cyprinids, found that stream size was the strongest predictor of species abundance and therefore species composition varied longitudinally along rivers. Furthermore, experiments revealed increasing temperature and food resources with increasing size that correlated with an increase in adult spawning success, juvenile condition and juvenile growth (Troia and Gido 2014). In another study in the Flint Hills ecoregion (Kings Creek in the Konza Biological Station and Fox Creek in the Tallgrass Prairie National Preserve), species richness of sampled fishes were strongly correlated with pool area and discharge (e.g., stream size) (Martin et al. 2013). Moreover, larger volumes of habitats had greater species diversity.

Within the hypothesized domain of stream size on fish and mussel species richness, different combinations of available parameters (Table 2), with different parameter breaks, may result in differences in SPM results, and more importantly, in differences in aquatic communities. Since it is not known a-priori how individual fish and mussel species, or communities of these species, are distributed according to channel physical properties, including as represented in channel classification schemes, NetMap's Flint Hills classification system should be applied in an exploratory and iterative fashion.

Conclusions

1. The principle objective of the Flint Hills classification system is to link channel physical characteristics to aquatic biota, including presence or absence of individual species, communities (or guilds) of species, and animal density; there are 99 species of fishes and 43 species of mussels in the Flint Hills channel system.
2. A one meter LiDAR digital elevation model (DEM) was available for approximately two thirds of the Flint Hill project area. The LiDAR DEM was merged (and warped) with the National Elevation Dataset 10 m DEM across the remainder of the landscape using NetMap. This produced a seamless, project-wide DEM that was resampled to 2 meter resolution.
3. NetMap was used to build a Flint Hills synthetic network consists of 1.27 million discreet channels reach segments of approximately 50 m to 150 m in length. The synthetic network was richly attributed with 24 landscape, fluvial geomorphic and hydrology parameters.
4. A portion of the Flint Hills field data was used to build statistical regressions for summer and bankfull widths and depths, and summer and winter flows.
5. Floodplains were mapped digitally using NetMap at 2, 3, 4, and 5 multiples of bankfull depths.
6. To build flexibility and analysis capacity into a Flint Hills stream geomorphic and aquatic biota classification system, a multi-faceted approach is used that consists of four components: 1) "Parameter Nesting" that uses nested sets of remote sensing parameters to ensure classification to the upstream to downstream limits of the river networks and data, 2) "Selection Grouping" that allows for flexible combinations of parameter ranges to build classifications, 3) "Spatial Probability Mapping" that converts field data on patch-scale habitat features to measures of feature density and for its extrapolation across all Flint Hill channel segments using remote sensing data, and 4) "Biotic Sorting" that categorizes field data on species and their abundance by channel classes.
7. Spatial Probability Mapping utilizes field data on patch scale aquatic habitat features available from Kansas Department of Wildlife, Parks & Tourism: Stream Survey & Assessment Program. Physical attributes included bankfull and summer hydraulic geometry (width and depth), substrate size classes (bedrock, boulder, cobble, gravel, sand, fines), bed morphology (pools, riffles, glides, rapids) and woody debris abundance (none, sparse, moderate, heavy, very heavy). Spatial Probability Mapping calculates the proportion (or density) of different field attribute values across the study reaches. Field sites are associated with individual channel classes and spatial probabilities of bed morphology, substrate and wood storage are extrapolated to all channel segments in each channel class.
8. Biotic Sorting is used to organize field data on species and their occurrence according to individual channel classes. Biological data are converted to indices of presence or absence of individual fish and mussel species and frequency and density of juveniles and adults, by species, within channel classes created by Selection Grouping or Parameter Nesting methods. This supports the ultimate objective of linking channel and landscape physical characteristics to aquatic biota in support of efforts such as the U.S. Fish and Wildlife Service's Surrogate Species initiative and other applications.

9. For Biotic Sorting, pertinent biological data in each stream class include: 1) individual species presence or absence according to the proportion of study site lengths contained within individual channel classes, 2) juveniles, by species, per meter length of study reaches, 3) juveniles, by species, per meter squared of study reaches, 4) adults, by species, per meter length of study reaches, 5) adults, by species, per meter squared of study reaches, 5) total number of animals, by species, per length, and 6) total number of animals, by species, per area.
10. Although the Flint Hills classification system is designed to create customizable channel classes for diverse applications, three new classification systems were built and two existing ones applied during this study. These include: 1) Parameter Nesting involving drainage area attribute alone, 2) Two Selection Groupings encompassed combinations of drainage area, channel confinement, gradient, habitat volume and network geometry via tributary confluences, 3) Buffington and Montgomery (2013) classification system based on gradient and width to depth ratios, and including a modified version to better match it to the Flint Hills landscape, and 4) Rosgen (1996) channel types that use entrenchment ratio, width to depth ratio and sinuosity.
11. Using the Parameter Nesting tool, a single parameter of drainage area is used in all three levels creating a classification system based on area alone. This revealed changing proportions (spatial probability) of attributes downstream including: proportion of sand bedded channels decreases, proportion of pools increases, proportion of riffles decreases and in-stream wood storage increases (slightly).
12. The Buffington and Montgomery (2013) classification that uses gradient and width to depth ratios results in only 5% of the channel network classified. The large percentage of unclassified channels was partly due to the range of width to depths and gradients in the Flint Hills that exceeded the classification parameter boundaries.
13. The Buffington and Montgomery (2013) classification was modified to better match it to Flint Hills channel characteristics. This resulted in 86% of the channel network classified but only in two classes, braided and pool riffle. A SPM analysis indicated that these two categories provide a reasonable depiction of Flint Hills streams.
14. The Rosgen classification system that uses entrenchment ratio, width to depth ratios and sinuosity only classified 55% of the network. The low number of classified streams is due in part to Rosgen's discontinuous parameter domains and the need for field based recognition of subtle channel attributes.
15. Evaluating whether the Flint Hills classification systems inform a taxonomy of channel geomorphic – aquatic biota in the Flint Hills is beyond the study scope because of the lack of a field based component. However, the five classification systems that extend to Spatial Probability Mapping and Biotic Sorting support the prime objective of the Flint Hills geomorphic stream – aquatic biota classification. In addition, since the aquatic component of the Flint Hills classification system is not a part of this study scope, the approach taken is to build a system that allows for customizable and iterative classification of channel segments rather than on building a-priori classification systems.
16. The advantage of using remote sensing data in the Flint Hills classification system is that it is spatially continuous across entire river networks or landscapes. Moreover, difficult to obtain measurements such as floodplain widths, valley widths (e.g., channel confinement) and tributary confluence effects, are quickly evaluated using models and remote sensing data and can be used within a classification system. It also allows other potentially important land attributes to be included in stream classification such as vegetation, land use, climate, soils and geology. The disadvantage of depending on remote sensing in channel classification is the lack

of field observation and measurements that typically provide a strong empirical, real world component. For example, field measurements may target specific geomorphic settings believed to be important in controlling channel geomorphology (in the Flint Hills). These can include tributary confluences, alluvial fans, other large sediment sources, and log jams.

17. The field data plots (Appendix 2) and SPM results reveal that physical channel attributes do not vary greatly across the Flint Hills channel system accessible to aquatic biota. Specifically, the SPM analysis that subdivides the Flint River network by drainage area classes reveals that although there are differences in the relative proportion of pools, riffles and glides, over 90% of the network can be characterized by alternating and interdigitated pool, riffle and glide morphology; there are a few rapids and almost no cascades. However, there are discernable patterns in the SPM results that show that the proportion of pools increases downstream (and riffles decrease downstream). Substrate sizes also decrease downstream to some extent although all channels could be considered as some combination of fine to coarse gravels and to a lesser extent cobbles. In addition, since channel width and depth increase downstream, as expected, summer habitat volume increases downstream. The plots of fish species and mussel species counts versus drainage area indicate that species richness increases downstream. Hence the increases in proportion of pools downstream and habitat volume appear to be important determinants in species abundance and likely in the overall animal frequency and density downstream. This finding is similar to other recent studies in the Flint Hills area (Martin et al. 2013, Troia and Gido 2014).
18. NetMap's multi-faceted classification tool that includes Spatial Probability Mapping of patch scale channel features and Biotic Sorting of species and their densities by channel classes provides a robust methodology to build a taxonomy of landscape - channel geomorphic – aquatic biota relationships. The tool can support application of the U.S. Fish and Wildlife Service surrogate species initiative as well as various monitoring, bio-census, resource management, conservation and restoration applications. In addition, the classification tools can be used to evaluate whether current monitoring programs are spatially distributed according to channel or habitat types of interest and their relative proportions across a watershed or landscape. The coupled tools can also be used to establish new field sampling protocols based on channel types and their representative populations within a watershed or landscape.
19. Channel classification that extends to aquatic assemblages can be integrated within larger landscape classification frameworks called 'geomorphic guilds' (Watson et al. 1998). In the present analysis in the Flint Hills, relevant landform characteristics can include hillslope erosion potential, valley confinement, floodplain size, networks via tributary confluences, geology and climate. However, Flint Hills landforms (mostly rolling hills of low relief and slope) and channel networks (with gradients less than 0.025 occupied by fishes and mussels) do not exhibit a high degree of spatial variability, and thus this limits the opportunity to link streams and aquatic assemblages to larger, spatially variable landscape features. This relatively low degree of heterogeneity may partially explain the recent analyses of fish communities in the Flint Hills that identified channel size alone as the most significant predictor variable of species abundance (Martin et al. 2013, Troia and Gido 2014), a finding also in accordance with this study.
20. The classification system presented in this report is designed to be applied manually using a combination of knowledge of the Flint Hills channel physical characteristics and aquatic biota, geomorphic and ecological principles, and professional judgment. However, the Flint Hills landscape is large (68,000 km^2) and potentially complex given its varying watersheds and 142 species of fishes and mussels (includes hybrids). Nevertheless, the integrated classification

components (including Spatial Probability Mapping and Biotic Sorting) lay a solid foundation for further numerical analyses. The potential exists, with additional funding, to automate and optimize via computer algorithms, a taxonomy of channel geomorphic – aquatic biota in the Flint Hills or in any landscape using statistical methods such as logistic regression, regression trees and cluster analysis. The automated system could also be used for other purposes such as designing monitoring and bio-census programs to reflect the range and relative abundance of different channel types across watersheds and landscapes.

Acknowledgements

We are grateful to Dr. Greg Watson, Chief, Office of Landscape Conservation U.S. Fish and Wildlife Service, Region 6 for the opportunity and funding to develop a coupled stream geomorphic – aquatic biota classification system for the Flint Hills landscape. We would also like to thank Mark VanScoyoc of Kansas Department of Wildlife, Parks & Tourism who provided access to Stream Survey & Assessment Program field data on channel physical properties and aquatic biota for their inclusion into the Flint Hills classification system. We also gratefully acknowledge Dr. Watson and Mark VanScoyoc valuable assistance and recommendations regarding classification system design.

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