Literature Review of Freshwater Classification Frameworks

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Introduction

Identifying aquatic ecosystems requires a classification of stream and lake features into recognizable entities or categories. Although a number of nationally recognized terrestrial community classifications exist, the most accepted being the National Vegetation Classification System (Grossman et al. 1998), currently there is no national or international standard for classifying aquatic communities or ecosystems. Despite the lack of a national aquatic community classification, aquatic ecosystem classifications and frameworks have been developed at a variety of spatial scales. Their goal is often to reflect the distribution of aqutic biological communities. Biological communities may be defined as an interacting assemblage of organisms, their physical environment, and the natural processes that affect them. These assemblages recur across the landscape under similar habitat conditions and ecological processes (Higgins et al. 2005). The methods used to develop aquatic ecosystem classifications vary widely, as do the biotic and abiotic variables considered in the classifications. The classifications generally fall into two broad categories: 1) taxonomic or bio-ecosystem classifications and 2) environmental or geo-physical ecosystem classifications (Rowe and Barnes 1994); however some classifications combine aspects of both.

Taxonomic Classification

Overview

Taxonomic or bio-ecosystem classifications emphasize biological data and are most often derived from analysis of patterns in species presence or abundance data. This species data often focuses on fish or macroinvertebrates which are more widely sampled, but sometimes includes algae, mussels, amphibians, and other freshwater biota. Many examples of taxonomic based classifications using species assemblage data exist at small to medium watershed scales (Bain 1995, Kingsolving and Bain 1993, Lobb and Orth 1991). These studies describe species assemblage patterns within a given small river system or watershed. Examples of taxonomic aquatic community classifications that exist at statewide or other large geographic scales are less common. In the northeast U.S. Appalachian LCC region these large geographic scale taxomonic focused classifications include the Fish Assemblages in the Conterminous USA (Herlihy et al 2006), the Pennsylvania Aquatic Community Classification (Walsh et al, 2007), New York Heritage Aquatic Community Classification (Reschke 1990, Edinger et al. 2002), and the Maryland Department of Natural Resources Aquatic Key Habitats (MD DNR 2012). These classifications are briefly described below.

Applications and Examples

Fish Assemblages in the Conterminous USA (Herlihy et al 2006)

This project compiled a national-scale database of lotic fish assemblages containing 5,951 sample sites from available national and state agency data. Cluster analysis (Bray-Curtis distance) and indicator species analysis were used to cluster the data, identify clusters, and describe them. They developed 12 national clusters of fish assemblage groups that were well described by indicator fish species and predicted using both discriminant function analysis and classification tree analysis. The groups were described qualitatively as associated with streams or rivers of major size classes, nutrient levels, temperature class, turbidity, and substrate. They also examined the relationship of ecoregion, physiography, hydrologic units, and geopolitical boundaries schemes to fish assemblage similarity. Existing schemes captured about half the within-group similarity expressed in biologically derived clusters. Cluster and mean similarity analyses were not strongly influenced by using data subsets that removed nonnative fish species and disturbed sites. This suggests that the underlying mechanisms responsible for controlling fish assemblage patterns at the national scale were fairly robust to the effects of nonnative species and anthropogenic disturbances.

Pennsylvania

The Pennsylvania Aquatic Community Classification Project classified streams and rivers based on community assemblages of macroinvertebrates, mussels, and fish (Walsh et al. 2007). Separate classifications were developed for each of the above 3 taxa groups. The project developed a database of comprehensive aquatic datasets for the state which enabled a large, statewide analysis of existing aquatic biological community survey data. Multivariate ordination and cluster analysis were used to determine initial community groups. Indicator Species Analysis, classification strength, and review by taxa experts helped to refine community types. Final community groupings include 13 mussel communities, 11 fish communities, 12 communities of genus-taxonomy macroinvertebrate communities, and 8 family-taxonomy macroinvertebrate communities. Seasonal influences on macroinvertebrate abundance and basin specificity of fish and mussels were used to define classifications. Datasets within a spring index period were used to classify macroinvertebrates. Three separate basin classifications were necessary to describe mussel communities (Ohio-Great Lakes, Susquehanna-Potomac, and Delaware), while two separate basin classifications were applied to fish communities (Ohio-Great Lakes, Atlantic Basin). Each group is described with a set of community indicator species, a set of species of conservation concern, a general description of the habitat, and habitat threats. By systematically evaluating fish, mussel, and macroinvertebrate communities, this project quantified for the first time these patterns of freshwater biodiversity and gave a better understanding to the composition and natural assemblages found within each of these 3 major freshwater taxa groups. The project also developed a GIS dataset which combined classes of bedrock geology, stream gradient, and watershed size in into physical stream types for each reach in the study area. Models were developed to predict community presence based on the reach and watershed attributes for all mussel, fish, and macroinvertebrate communities. Many of these reach to biological community relationships are many to one.

New York Classification

The New York Heritage Aquatic Community Classification provides another example of a biologically based classification (Edinger 2002).. This classification was designed to be used by biologists in the field to identify aquatic communities. Descriptions of aquatic communities and the indicator and representative biological taxa of these communities were developed by review of literature, species lists compiled from both qualitative and quantitative field surveys, and in some cases interviews with biologists. The New York Heritage Program currently uses this classification to assign each of its aquatic community survey locations to one of these community types. Most communities in the classification have some mapped known occurrence, although no aquatic community is yet comprehensively mapped. The New York classification provides a list of primary organisms used to define the community, and also when possible, main environmental characteristics to help distinguish the community. Riverine systems use fish as the primary organisms and watershed position and stream flow as the environmental characteristics. Community descriptions include dominant species (species with the greatest abundance), codominant species (species with relatively high abundance), and characteristic species (species that are commonly found in the community although not necessarily abundant). Some descriptions also include brief discussions of ecologically important environmental characteristics and disturbance patterns that distinguish the community. A state rarity rank and global rarity rank also accompany the classification based on the estimated number of occurrences and distribution of the community as well as its vulnerability to human disturbance or destruction. The 7 riverine system natural communities include rocky headwater stream, marshy headwater stream, mid-reach stream, main channel stream, backwater slough, intermittent stream, and coastal plain stream.

Maryland Key Riverine Habitats

The Maryland Department of Natural Resources Key Riverine Habitats provides another example of a biologically based classification, although similar to New York it also provides environmental setting descriptions for the types. This classification was developed for the State Wildlife Action plans and provides lists species of greatest conservation need and other wildlife associated with these types. Descriptions of the types and the species associated with them were developed by review of literature and both qualitative and quantitative analysis of field surveys. Community descriptions include rare and common fish, insects, reptiles and amphibians, crayfish, birds, and crustaceans. The description of the habitat includes geographic distributions which are often defined by terrestrial ecoregion or subsection lines, description of the water temperature, stream size, and in some cases slope, geology or soil types that help define these habitats. Each habitat is also described in terms of major threats, conservation actions, and inventory/monitoring/research needs for species of greatest concern. The habitats include coldwater streams, blackwater streams, Piedmont streams, coastal plain streams, limestone streams, highland streams, piedmont riverine, coastal plain riverine, and highland riverine.

Environmental Classification

Overview

Environmental or geo-ecosystem classifications give precedent in classification to environmental or physical factors and emphasize a streams' relationship to its physical environment across a wide range of scales in space and time (Frissel et al. 1986, Rowe and Barnes 1994). Environmental or geo-ecosystem aquatic classifications are based on the assumption that 1) physical factors such as climate and physiography constrain the observed range of aquatic ecological processes and 2) these factors can be used to predict the expected range of biotic community types (Tonn 1990, Jackson and Harvey 1989, Hudson et al. 1992, Maxwell et al. 1995, Angermeier and Winston 1998, Pflieger 1989, Burnett et al. 1998).

Much research has been done to support the relationship between environmental factors and patterns of freshwater biodiversity. For example, large continental aquatic zoogeographic patterns have been shown to be associated with drainage connections changing in response to major climatic and geologic events (Hocutt and Wiley 1986). Regional patterns in geomorphology and climate have also been shown to affect stream hydrology, sedimentation, nutrient inputs, and channel morphology that in turn alter stream form and function and control regional variation in stream systems (Hughes et al. 1994, Minshal 1994, Poff and Allan 1995; Hawkins et al. 2000). Within regions, there are finer-scale patterns of stream and lake morphology, size, gradient, watershed physiography, and local zoogeographic sources that are related to distinct aquatic assemblages and population dynamics (Frissell et al. 1986, Flecker 1992, Rosgen 1994; Maxwell et al. 1995, Angermeier and Winston 1998, Seelbach et al. 1997, Mathews 1998).

Environmental classifications are often developed within a spatial and temporal hierarchy. The interacting spatiotemporal factors define a system in terms of its potential capacity. Potential capacity is defined as all possible developmental states and all possible performances that a system may exhibit while still maintaining its integrity as a coherent entity (Warren 1979). System potential capacity is a theoretical concept that cannot be fully and directly measured empirically. The concept however provides direction on appropriate variables of classification. It suggests that for a system defined within a given spatiotemporal frame, the variables selected for classification should be those that are most general, invariant, and causal in determining the behavior of the system (Warren and Liss 1983). Classification should thus account for not only the present state and performances of the stream, but also its potential performances over a range of conditions that operate within that spatiotemporal scale (Warren 1979; Warren and Liss 1983).

For the spatial scales, within a regional biogeoclimatic geographic zone, environmental aquatic classifications often use a nested spatial hierarchy of drainage basins from small tributary catchments to largest basins. Smaller scale systems develop within constraints set by the larger scale systems of which they are part. Controlling or constraining environmental variables differ at different locations of the spatial hierarchy. Large watershed scale river systems are controlled by variables related to regional climate and physiography; while at medium scales valley segments and stream reaches reflect variations in geomorphology and mesoclimate; and fine scale channel units respond to variation in features such as substrate size and woody debris that change over periods of months to years (Maxwell 1995). For example, pool/riffle morphology of a reach is largely determined by the slope of the reach and input of sediments and water from the contributing drainage basin. Slope of the reach and pattern of sediment and water discharge are themselves controlled by coarse-scale, long-term variables like climate, lithology and structure, basin topography/area, and paleohydrologic history (Frisell et al 1986).

Temporal variation also significantly affects variation within aquatic ecosystems at every spatial scale. Temporal variation can have both relatively predictable components, such as seasonal variation, along with stochastic components (major geologic events, local invasions, disease, growth, decline of species) (Hawkins et al 2000). The time period over which any given aquatic ecosystem type is likely to persist within a given range of variation will vary, usually with the scale of the system. For example, the time scale of expected continuous persistence of an aquatic system is suggested to be 1-10 years for a pool/riffle system, 10-100 years for a reach system, 10-1,000 years for a segment system, to 1000-10,000 years for a watershed class (Maxwell et al 1995). Understanding the temporal component of potential classification variables can direct users to appropriate stable variables for a given spatiotemporal classification level. For example, as seen across geologic temporal time scales ($>10^5$ year) the slope of stream channel is a changing variable, yet viewed in a time frame of 10-100 years, channel slope is relatively invariant and slope could be considered an independent causal variable that controls on channel morphology and sediment transport at the reach system classification scale (Frissel et al 1986).

In addition to understanding the temporal and spatial hierarchy and appropriate classification variables, classification at any level involves two further steps: 1) delineate the boundaries between systems and 2) describe how the systems that have been delineated are similar or dissimilar by assigning them to some group within the total population based on their origin, development, and potential response to environmental changes. Boundaries between stream systems can be based on geomorphic features that constrain potential physical changes in the stream vertically, longitudinally, and laterally. Stream system boundaries can be based on catchment areas or drainage divides, basin relief, bedrock faults, and valley developments. Segment systems boundaries could similarly be based on tributary junctions, falls, bedrock, elevation, or other structural discontinuities or factors controlling lateral migration such as valley sideslope confinement (Frissel et al. 1986). For example, a stream reach dissecting a terrace with banks composed of gravel alluvium has a different capacity for bank erosion, channel morphology changes, or fish production than an adjacent reach cutting through clay cohesive soils (Frissel et al 1986). The boundary of the two reach systems would thus correspond to the location where bedrock or surficial geology substantially changed. In reality, communities will usually vary continuously on the landscape along ecological gradients which makes defining exact system boundaries extremely difficult; however defining draft boundaries or key factors that can be used to distinguish major transitions is necessary in classification.

Stream size is one of the most fundamental physical factors used to delineate system boundaries in environmental aquatic classification. Catchment drainage area, stream order, number of first order streams above a given segment, and flow volume are all recognized as measures of stream size. Although ecologically significant stream size class breaks may vary numerically between regions, the highly recognized "river continuum concept" provides a qualitative framework to describe how the growth of the physical size of the stream is related to major river ecosystem changes from headwaters to mouth (Vannote et al. 1980). The river continuum concept identifies predicable biotic changes along the longitudinal gradient from source stream to large major river as stream size and position along the longitudinal gradient change. Low order sites are small headwater streams where inputs of coarse particulate organic matter (CPOM) provide a critical resource base for consumer community. As a river broadens at mid-order sites, energy inputs are expected to change as CPOM inputs decrease and sunlight begins to reach the stream bottom to support significant periphyton production. Fine Particulate Organic Matter (FPOM) to the system increases and macrophytes become more abundant as river size further increases, and reduced gradient and finer sediments form suitable conditions for their establishment. In high order sites, the channel gets very large and the main channel becomes unsuitable for macrohphytes or periphyton due to turbidity, fast current, and lack of stable substrates. Autochthonous production by phytoplankton and other instream sources is limited by turbidity. Allochthonous organic matter inputs occurring outside the stream channel are again expected to be the primary energy source as processes such as inputs from the floodplain scouring increase and FPOM imported from upstream systems becomes less important. These changes in energy input along the longitudinal gradient of a stream system have profound consequences for the composition of consumer communities and the functioning of the ecosystem. For example, shredders should prosper in low order streams while grazers will prosper in mid-order streams (Allen 1995). Numerous studies have tested the river continuum concept and used it as a basis for general physical stream classifications across many biomes. (Minshall et al. 1983; Hawkins, Murphy, and Anderson 1982).

In addition to a measure of stream size, stream morphology has been integrated into many aquatic classifications to define system boundaries and classification types. Stream morphology characteristics of slope and sinuosity for example strongly affect hydrologic processes such as water and sediment yield, flow duration, and magnitude and frequency of floods. Straight, meandering, and braided physical stream patterns were used in an early classification by Leopold and Wolman (1957). Schumm (1963) delineated a reach classification based on channel stability (stable, eroding, or depositing) and mode of sediment transport (mixed load, suspended load, and bedload) based primarily on channel slope and then integrated a measure of size in channel dimension (Schumm 1977). Culbertson et al. (1967) used depositional features, vegetation, braiding patterns, sinuosity, meander scrolls, bank heights, levee formations, and floodplain types in a classification. Khan (1971) developed a quantitative classification for sand-bed streams based on sinuosity, slope, and channel patterns. Montgomery and Buffington (1997) proposed a reach-scale morphological classification for mountain stream channels that reflects the typical downstream progression of channel bedforms that occurs as stream gradient and bed material size decrease. Rosgen (1994, 1996) developed a comprehensive and widely used hierarchical stream classification system based on geomorphic variables including slope, sinuosity, width-todepth ratio, and substrate size.

Many environmental aquatic classifications have been implemented nationally and internationally and serve as a surrogate measure of aquatic biodiversity potential (Van Sickle and Hughes 2000, Oswood et al 2000, Waite et al. 2000, Sandin and Johnson 2000, Rabeni and Doisy 2000, Marchange et al 2000, Feminella 2000, Gerritsen et al 2000, Hawkins and Vinson 2000, Johnson 2000, Pan et al 2000, Bryer 2001, Smith et al 2002). Components of environmental classifications such as regionalization and use of stream size and temperature classes have also been used widely in bioassessment (Karr 1986, Hughes et al. 1994, Hawkins et al. 2000,, Frimpong and Angermeier 2010). Descriptions of major environmental classification frameworks that could be applicable to the Appalachian LCC Region are provided below and include the conceptual frameworks of Frissel, Rosgen, Maxwell, and Higgins, as well as examples of several applications of the Higgins approach.

Frissel

Frissel defines an environmental classification framework where stream systems are hierarchically organized on successively lower spatial-temporal levels into the following classes: stream system, segment system, reach system, pool/riffle system, and microhabitat systems (Frissel et al. 1986). Frissel's classification framework includes stream morphology and size as key classification variables, but suggests a variety of additional key physical structuring factors depending on the spatio –temporal hierarchy of the classification. Frissel suggest that larger regional scale stream system classifications should be defined by the watershed's biogeoclimatic region, geology, topography, soils, climate, channel shape and slope, and network structure. Frissel's smaller spatial scales systems of segments, reaches, and pool-riffles types are defined by distinguishing more local morphological characteristics. For example, segment systems are defined by channel floor lithology, channel floor slope, position in the drainage network, valley sideslopes, soil association, and potential climax vegetation. Frissel's pool/riffle systems are defined by bed topography, water surface slope, substrates immovable in < 10 year flood, and bank configuration (Frissel et al. 1986).

Rosgen

Rosgen's classification of natural rivers (Rosgens 1994, 1996) was developed using data from 450 rivers throughout the U.S, Canada, and New Zealand and is driven by stream morphology at each spatiotemporal scale. Stream pattern morphology is directly influenced and can be described by eight major variables including channel width, depth, velocity, discharge, channel slope, roughness of channel materials, sediment load, and sediment size (Rosgen 1994, 1996). Theoretically, a change in any one of these variables sets up a series of channel adjustments that leads to a change in the others, resulting in channel pattern alterations that influence aquatic habitats and thus aquatic species distributions (Rosgen 1994, 1996).

The Rosgen classification is divided into 4 hierarchical levels. Level 1 is a broad geomorphic characterization integrating the landform and fluvial features of valley morphology with channel relief pattern, shape, and dimension. It depends on lithology, landform, soils, climate, depositional history, basin relief, valley morphology, river profile morphology, and general river pattern. It uses measurements of cross-section morphology, longitudinal profiles, and plane view morphology to classify rivers into 9 broadly defined stream type categories. Examples of these categories include Aa+: very steep, deeply entrenched debris transport systems, A: Steep, entrenched, cascading, steep/pool high energy/debris transport systems, B: Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools, C: Low gradient meandering point-bar riffle/pool, alluvial channels with broad floodplains, or D: Braided channels with very wide channel and eroding banks (Rosgens 1994, 1996). Level 2 adds a morphological description that subdivides the initial stream types based on discreet slope ranges and dominant channel material. It depends on field measurements of channel patterns, entrenchment ratio, width/depth ratio, sinuosity, channel material, and slope. Level 3 is based on more detailed information including measurements of depositional patterns, meander patterns, confinement features, flow regime, debris occurrence, channel stability index, and bank erodibilty among others. Level 4 further subdivides the previous levels by finer scale variables such as sediment transport rates, bank erosion rates, aggradation/degradation processes, fish biomass, aquatic insects, and riparian vegetation.

Maxwell

In 1995, the USFS adopted the Hierarchical Framework of Aquatic Ecological Units (Maxwell et al. 1995) classification framework based on the principles of Rosgen, Frissel, and other geo-ecosystem classifications (USFS 2001). To date, this framework has been applied at a handful of state and sub-state level sites by the USFS (USFS 2001). This multiple scale framework is linked with terrestrial systems and complements the USFS hierarchy of terrestrial ecological unit classification developed in 1993. The USFS terrestrial and aquatic frameworks jointly classifies the stable (biophysical) components of terrestrial and aquatic ecosystems into a limited number of discrete units that, at any given scale, are mappable and distinguishable from one another by differences in various structural or functional characteristics, and biological and physical potentials (USFS 2001). In the USFS framework, separate information themes are developed for factors considered more transient such as current vegetation, wildlife, and fish distributions, road densities, insect infestations, and land use.

The USFS Hierarchical classification outlines the following 10 hierarchical classification mapping units: Subzone, region, subregions, river basins, subasins, watersheds, subwatersheds, valley segments and lakes, stream reaches and lake zones, and channel units and lake sites (Table 1). Subzones to Subbasins are defined at scales of 1:2,000,000+ by the physical features of regional climate, regional geology, river networks, and basin boundaries in combination with fish families and unique aquatic assemblages. Watershed and subwatershed types are defined a scale of 1:100,000 where physical features such as watershed boundaries, stream networks, geomorphology, and local climate define the map unit type according to the local geoclimatic, zoogeographic setting and morphological features. Valley segments are defined at a scale of 1:24,000 and reflect the valley geomorphology, climatic regime, and hydrologic regime. Stream reaches are defined at a scale of 1:12,000 and reflect channel morphology bedform/materials, bank condition, and woody debris. Channel units are defined at a scale of 1:1000 and reflect detailed habitat features, depth patterns, and debris patterns. The distinguishing physical features, disturbance patterns, biotic processes, and approximate persistence time of each spatial scale are defined in the table below.

Table 1: USFS Hierarchical Framework of Aquatic Ecological Units (Maxwell et al. 1995)

Mapping Scale	Riverine Patterns	Physical features	Disturbance pattern	Biotic processes	Approx. time for change/years
1:2,000,000	Subzones to Subbasins	Basin boundaries, river networks, regional climate, regional geology	Tectonics, glacial cycles	Speciation/extinction	>10,000
1:100,000	Watersheds, Subwatersheds	Watershed boundaries, stream networks, geomorphology, local climate	Local uplift, folding/faulting, flood cycles	Genetic variation	1,000-10,000
1:24,000	Valley Segments	Valley geomorphology, climatic regime, hydrologic regime	Valley filling, channel migration, stream incision	Population demographics	100-1000
1:12,000	Stream Reaches	Channel morphology, bed form, materials, bank conditions, woody debris	Peak flows, Sediment transport	Population dynamics	10-100
1:1,000	Channel Units	Habitat features, depth patterns, debris patterns	Hydrolics, Scour and deposition, bedload sorting	Behavior patterns	1 - 10

Higgins

In 1998 The Nature Conservancy (TNC) Freshwater Initiative Program integrated classification concepts from Maxwell, Rosgen, Frissel, and others to define a geo-ecosystem environmental hierarchical aquatic classification framework for use in its ecoregional planning effort. This standard classification framework can be implemented at ecoregional scales and emphasizes environmental gradients of climate, elevation, landform, and geology that are known to shape aquatic ecosystems at several spatial scales and influence the physical habitat diversity (Higgins et al 2005). The classification framework is based on four key assumptions about the connection between habitat structure and biological communities. (Higgins et al. 2005) 1) Large-scale physiographic and climatic patterns influence the distribution of aquatic organisms and can be used to predict the expected range of community types within these large zones (Tonn 1990, Jackson and Harvey 1989, Hudson et al. 1992, Maxwell et al. 1995, Angermeier and Winston 1998, Pflieger 1989, Burnett et al. 1998); 2) Aquatic communities exhibit distribution patterns that are predictable from the physical structure of aquatic ecosystems (Schlosser 1982, Tonn 1990, Hudson et al. 1992); 3) Although aquatic habitats are continuous, we can make reasonable generalizations about discrete patterns in habitat use (Vannote et al. 1980, Schlosser 1982, Hudson et al. 1992); and 4) By nesting small classification units (Aquatic Ecological Systems, macrohabitats) within the large climatic and physiogrpahic zones, we can account for community diversity that is difficult to observe or measure (taxonomic, genetic, ecological, evolutionary context) (Frissell et al. 1986, Angermeier and Schlosser 1995)

TNC has classified freshwater ecosystems in over thirty ecoregions in the U.S. and Latin America using these methods. The WWF, Aquatic GAP and others are also adopting TNC's methods for regional conservation planning (Higgins et al. 2005). The classification framework uses four hierarchical spatial scales: 1) Zoogeographic Region, 2) Ecological Drainage Unit 3) Aquatic Ecological System, and 4) Macrohabitat. Zoogeographic Subregions describe continental patterns of freshwater biodiversity. These units are distinguished by patterns of native fish distribution that are a result of large-scale geoclimatic processes and evolutionary history. For North America, TNC adopted the freshwater ecoregions developed by the World Wildlife Fund (Abell et al. 2000). Ecological Drainage Units (EDU's) delineate areas within a zoogeographic subegion and correspond roughly with large watersheds of 6-8th order major river systems (~3000-10,000 sq miles). EDUs are hypothesized to account for the variability within zoogeographic sub-regions due to finer-scale drainage basin boundaries and physiography. Aquatic Ecological Systems (AES) are defined within an EDU as networks of streams and associated lakes and wetlands that occur together in similar geomorphological patterns, are tied together by similar ecological processes or environmental gradients, and form a robust cohesive and distinguishable unit on a map. AES can be defined at multiple sub-scales within an EDU to represent for example types of 1) headwater to small river systems, 2) medium sized river systems, and 3) large river systems. Macrohabitats are the finest scale unit of classification and define stream reach types or lake types. Macrohabitats are based on abiotic variables known to structure aquatic communities at this reach or lake scale and that can be modeled in a GIS (Table 2). These variables include factors such as stream or lake size, gradient, general chemistry, flashiness, elevation, and local connectivity. The macrohabitat model is based on work done by Seelbach et al.1997, Higgins et al. 1998, and Sowa et al. 2004. Macrohabitats are relatively homogeneous with respect to energy and nutrient dynamics, habitat structure, and position within the drainage network. The physical character of macrohabitats and their associated biological composition are a product of the immediate geological and topographical setting and the transport of energy and nutrients through the systems (Higgins et al. 2005). The driving processes, measurable variables, and GIS datasets used to define macrohabitats are listed in Table 2.

Table 2: TNC Aquatic Classification Framework: Reach Scale Macrohabitat Ecosystem Attributes, Model Variables, and Spatial Data

Ecosystem Attribute	Modeled Variable	Spatial Data
Zoogeography	1) Region 2) Local Connectivity (to lake, wetland, ocean, large river, etc.)	1) Ecological Drainage Unit 2) Hydrography
Morphology	1) Size (drainage area) 2) Gradient	1) Hydrography 2) Hydrography and DEM
Hydrologic Regime	Stability/Flashiness and Source	Hydrography, Physiography, Geology
Temperature	1) Climatic Zone 2) Elevation	1) Ecological Drainage Unit/Ecoregions 2) DEM
Chemistry	Geology and Hydrologic Source	Geology

Applications and Examples

Freshwater Biodiversity Conservation Assessment of the Southeastern United States (Smith et al. 2002)
This project developed a stream classification as part of The Nature Conservancy's efforts to identify the most important areas for freshwater biodiversity conservation in the southeastern United States. The project covered four large freshwater ecoregions: Tennessee-Cumberland, Mississippi Embayment, South Atlantic, and Mobile Bay and was funded by the Charles Steward Mott Foundation. The project implemented a hierarchical classification of aquatic ecosystems using the Higgins classification approach to define and map the communities and ecosystems in the landscape. This classification helped planners identify "coarse filter" targets, which are large-scale ecosystems that capture multiple levels and types of biodiversity, including untracked common species, communities, and ecological processes. The classification systems was not meant to replace detailed data on the distribution and status of species and communities, but provided conservation planners with a tool to help deal with incomplete information.

Within the freshwater ecoregions, the project delineated Ecological Drainage Units (EDUs). EDUs facilitate evaluation of targets in the set of sub-regional ecological and evolutionary settings they occur. EDUs were defined as groups of watersheds (8-digit U.S. Geological Survey Hydrologic Units) within aquatic ecoregions with similar patterns of zoogeographic sources and constraints, physiography, drainage density, hydrologic characteristics and connectivity. Identifying and describing EDUs stratified basins into smaller units for more accurate evaluation of patterns of freshwater biodiversity, promotedconsideration of sub-regional differences in freshwater species pools, and guided conservation goals for targets across their environmental ranges.

Aquatic ecological systems were then mapped within EDUS. Aquatic ecological systems are rivers, streams, and lakes with similar geomorphological patterns tied together by ecological processes (e.g., hydrologic and nutrient regimes, access to floodplains) or environmental gradients (e.g., temperature, chemical and habitat volume), and form a distinguishable unit on a hydrography map. To identify aquatic systems, the project employed an approach developed by the Freshwater Initiative of The Nature Conservancy (Higgins et al. 1998, Groves et al. 2000) that uses a physically-based classification mapped in a Geographic Information System (GIS) to define the environmental patterns of freshwater ecosystems. While the systems defined by the same set of attributes may occur in several EDUs, they identified these system types as distinct because the context of each EDU is distinct. Aquatic system classification and delineation involved: 1. Determine physicochemical habitat variables that define environmental gradients and influence species distributions: stream size, gradient, elevation, downstream connectivity, and bedrock and surficial geologic characteristics (as they relate to hydrologic regime, water chemistry, stream and river geomorphology, and dominant substrate material; Seelbach et al. 1997). 2. Acquire and develop GIS data layers of these habitat variables or other data layers that can be used to model these variables and attach them to the EPA Rf3 1:100,000 stream reaches. 3. Determine classes for these variables that correspond to ecologically meaningful breaks in environmental gradients and attribute each stream reach with a value for the variables. 4. Classify the types of ecosystems by identifying all distinct combinations of physicochemical attributes. 5. Map aquatic systems by assigning system types to stream reaches at the small watershed scale. Aquatic systems of each size category were further distinguished by patterns in the other classification variables including Elevation, Gradient, Downstream Connection type, and Bedrock and Surficial Geology Classes . The detailed class breaks are shown in Table X

Table 3: Reach Classification Attributes from Freshwater Biodiversity Conservation Assessment of the Southeastern United States (Smith et al. 2002)

Category	**Range of Values**
Size	Link magnitude
Headwater	1-10
Creek	11-100
Small River	101-1000
Medium River	1001-2500
Large River	>2500
Elevation	Meters
Low	<300
Moderate	301-900
High	>900
Gradient	Rise/Run
Low	<0.01
Moderate	0.01-0.05
High	>0.05
Downstream Connections	Link magnitude
Streams	<100
Small and Medium Rivers	101-2500
Large Rivers	>2500
Lakes	NA
Ocean	NA
Embayment	NA
Bedrock and Surficial Geology	Recent river alluvium, Gravels, Sands, Mixed sands, silts, clays, Noncalcareous clays, Calcareous clays, Pleistocene terrace, Pleistocene valley-train, Loess, Marsh deposits, Loose limestone, shell, Alkaline sedimentary, Moderately alkaline mixture, Fissile shales, Erodible acidic sedimentary, meta-sedimentary, Resistant acidic sedimentary, meta-sedimentary, Erodible acidic, intermediate igneous, metaigneous, Resistant acidic, intermediate igneous, metaigneous, Erodible mafic igneous, meta-igneous, Resistant mafic igneous, meta-igneous

Virginia's Comprehensive Wildlife Conservation Strateg. (VADGIF Wildlife Diversity Division 2006). The Virginia Department of Game and Inland Fisheries (VDGIF) developed an aquatic habitat classification for use in the Comprehensive Wildlife Conservation Strategy. The methods used in this classification follow the basic structure of The Nature Conservancy aquatic community classification (Higgins et al. 2005) and the Missouri Resource Assessment Program's Aquatic GAP study (Sowa et al. 2005). The classification has been applied to riverine habitats only.

There were multiple goals of this classification effort. One was to provide a means to describe and catalog the diversity of stream habitats in Virginia. The second was to provide a dataset that can be used to describe species-habitat associations and predict species distributions at the stream reach level. The stream reach classification was also used to group all species of greatest conservation need into assemblages with similar patterns of habitat use.

This habitat classification is hierarchical and is based on an understanding of how habitat influences the composition and distribution of biological communities. The EDU dataset was used in this strategy to describe a layer of habitat classification within ecoregions, and as a unit of organization for the species of greatest conservation need and their habitats. The stream reach classification was the next level of the hierarchy applied. For the purposes of this classification, reaches were defined by confluences recognizing that stream habitats are continuous and most breaks we apply are artificial and/or subjective. The dataset used to depict streams was the USGS National Hydrography Dataset, or NHD. The reaches were then attribute with key variables related to size, gradient, elevation, and downstream connectivity. The key continuous variables they were divided into meaningful class categories. Stream temperature had been identified as another important factor to predict species distributions. However, it is difficult to predict in a landscape scale classification and attempts to assign temperature categories (cold vs. warm) based on some threshold elevation proved unsatisfactory so this variable was not included in the final classification. The classification used five categories for size, six categories for connectivity, and four categories for gradient as shown in the table below.

Table 4: Aquatic habitat classification categories used for continuous variables

Category	Range of values
Size:	Link magnitude:
Large river	> 999
Small river	200 - 999
Large stream	50 - 199
Stream	3 - 49
Headwater	1 and 2
Connectivity	Downstream link magnitude:
Connected to large river	> 999
Connected to small river	200 - 999
Connected to large stream	50 - 199
Connected to stream	3 - 49
Connected to headwater	2
Disconnected	Null and [Disconn] field=1
Gradient	Rise over run (m/km):
Very low	</= 4
Low	4 - 15

Moderate	15 - 40
High	> 40

A Framework for Assessing the Nation's Fish Habitat, National Fish Habitat Science and Data Committee (Beard and Whelan. 2006)

This framework defines aquatic habitat as a hierarchy of different attributes at several spatial and temporal scales corresponding to patterns of dominant ecological processes that affect fish distributions. For this national assessment and synthesis, it was critical that habitats were 1) classified and represented as mapped units at several different spatial scales, and 2) that the units were classified and mapped with relative consistency across the United States, given data limitations. By fulfilling these criteria, the units could be the basis for regional and national assessment and synthesis regarding their condition, and the type and severity of threats to them. (Beard and Whelen 2006). For this classification, the first major delineation in habitat was between inland and coastal habitat. Inland habitats are defined as waters above the head of tide. For inland habitats, the Higgins et al (2005) classification scheme was selected.

A simplified, consistent framework for the NFHAP was needed to allow the implementation of the assessment in a timely manner so the national framework was started at the landscape ecosystem level. The recommended simplified approach following was to initially use catchment size, average system gradient, and drainage network position. This differentiated true headwater stream and lake complexes from those that are small but are connected directly to large mainstem rivers. This established an initial national framework to characterize freshwater landscape ecosystems by size and stream power. Further refinement of size categories and all of the other attributes for a more detailed macro/meso habitat classifications can be conducted in the future by Fish Habitat Partnerships to better reflect more meaningful ecological breaks. Landscape ecosystems of different sizes were nested within Ecological Drainage Units (EDUs) (Higgins et al. 2005; Sowa et al. 2005, 2007). EDUs are nested within larger Freshwater ecoregions. EDUs were created using 8-digit USGS Hydrologic Unit Codes (HUCs), and 6-digit HUCs in Alaska, and are used to distinguish regional landscape and climate patterns that influence broad ecosystem characteristics such as lake and stream density, morphology, hydrology, temperature, and nutrient regimes.

Northeast Aquatic Habitat Classification and Map. (Olivero and Anderson, 2008)

This project developed a standard reach scale Northeastern Aquatic Habitat Classification (NAHCS) and GIS map for 13 northeastern states (ME, NH, VT, MA, RI, CT, NY, PA, NJ, DE, MD, VA, WV, and DC.) for the Northeast Association of Fish and Wildlife Agencies (NEAFWA). Stream and river flowlines were taken from the NHD Plus V1 1:100,000 dataset.

This classification and GIS dataset was designed to consistently represent the natural aquatic habitat types across this region in a manner deemed appropriate and useful for conservation planning by the participating states. This product was not intended to override state classifications, but was meant to unify state classifications and allow for looking at aquatic biodiversity patterns across the region. The NAHCS habitat classification was based on the biophysical aquatic classification approach of Higgins et al. 2005 and used four primary classification attributes that are key to structuring aquatic habitats at the reach scale. These variables include size (7 classes), gradient (6 classes), geology (3 classes), and temperature (4 classes) (Table 5). Ecologically meaningful class breaks within each of the four variables were developed and the resultant variables and classes combined to yield a regional taxonomy with 259 stream types. These types could be further nested within larger stratifications such as Ecological Drainage Unit and Freshwater Ecoregion.

Table 5. Variables and Classes used in Northeast Aquatic Habitat Classification System

Size Class	**Description**	**Definition (sq.mi.)**
1a	Headwaters	0<3.861
1b	Creeks	>=3.861<38.61
2	Small Rivers	>= 38.61<200
3a	Medium Tributary Rivers	>=200<1000
3b	Medium Mainstem Rivers	>=1000<3861
4	Large Rivers	>=3861<9653
5	Great Rivers	>=9653
Gradient Class	**Description**	**Definition (slope of stream channel (m/m) * 100)**
1	Very Low Gradient	<0.02%
2	Low Gradient	>= 0.02 < 0.1%
3	Moderate-Low Gradient	>= 0.1 < 0.5%
4	Moderate-High Gradient	>=0.5 < 2%
5	High Gradient	>=2 < 5%
6	Very High Gradient	>5%
Geology Class	**Description**	**Definition (index based on cumulative upstream geology; only applied to size 1a, 1b and 2 rivers)**
1	Low Buffered; Acidic	100-174
2	Moderately Buffered; Neutral	175-324
3	Highly Buffered; Calc-Neutral	325-400
Temperature	**Estimated Natural Temperature Regime**	**Definition**
1	Cold	Complex rules; see CART analysis and final rules on Temperature Metadata worksheet
2	Transitional Cool	
3	Transitional Warm	
4	Warm	

The full reach types could be simplified using recommended prioritization and collapsing rules. Providing the detailed types and recommended collapsing rules allowed the data to serve flexible and multiple purposes for the uses. For example, the detailed stream types have most recently been simplified for a regional assessment to 58 regional types and 23 major regional types in the Northeast Northeast Habitat Guides: A Companion to the Terrestrial and Aquatic Habitat Maps (Anderson et al 2013) and the Northeast Geospatial Condition Assessment (Anderson et al 2013). In this simplification, the full 259 reach types were collapsed to 58 types based on using simplified size (4 classes), gradient (3 for headwaters/creeks, 2 for rivers), geology (3 classes for headwaters through small rivers), temperature (3 classes), and tidal classes. For the general audience of the habitat guide, the 58 types were further collapsed into 23 major types. The 23 major types were created by merging the geology classes for headwaters through small rivers and merging the gradient classes for medium to large rivers. The simplified types were described in terms of their environmental setting, commonly associated fish species, associated rare species, and coded with summary condition information relating to impervious surfaces, dams, and riparian conditions.

New York Freshwater Blueprint (White et al. 2011)
The project goal was to develop GIS datasets that identify the locations and status of critical freshwater targets (habitats and species) in New York. The Northeast Aquatic Habitat Classification (NEAHC) System GIS datasets were used to develop a classification system for this project (Olivero and Anderson 2008). The NY Blueprint combined classes within each variable to simplify the NEAHC to reduce the number of aquatic habitat types in the study area. It derived collapsing rules within a variable from the NEAHC dataset once the Blueprint Team decided on parameters to use. The Blueprint Team relied heavily on the freshwater assessment of the Upper Delaware River basin as a model for determining how to simplify the NEAH classification. The NY Blueprint Team decided to use a size, gradient, geology, temperature, and tidal designation to assign unique types, however each type was not necessarily defined as differing in each of these 5 primary variables. For example, headwaters were split by gradient, geology, temperature and tidal class, however large rivers were lumped into only tidal and non-tidal types (not split by gradient, geology, or temperature). The Blueprint Classification used five size classes headwaters and creeks, small rivers, medium tributary rivers, medium mainstem rivers, and large rivers. It used three classes for gradient on headwaters and creeks, two gradient classes on small to medium rivers, and no gradient classes for large rivers. It used two geology classes on headwaters through small rivers and no geology classes for all medium and large rivers. It used two temperature classes for headwaters through medium rivers and no temperature classes for large rivers. It added a tidal designation to all segments. Combining these classes yielded 44 unique types which were used in the NY Freshwater Blueprint assessment.

Stream Classification Framework for the SARP Region (Sheldon and Anderson 2013)
The objective of this project was to develop some basic stream classification attributes for the entire Southeast Aquatic Resources Partnership (SARP) region (17 states) and to provide more detailed attributes in the eastern section of the SARP geography (9 states: AL, FL, GA, KY, NC, SC, TN, WV, VA) where additional data and modeling capacity was available. The final product was a mapped dataset of information linked to the NHD Plus medium resolution hydrography that can be used to classify stream reaches. The results of this work contribute to SARP's overall objective to develop a river classification framework database consisting of a hierarchical set of hydrologic, morphologic, and biotic parameters for NHDPlus river segments which can be used to identify ecologically similar types of rivers within the region according to the needs of the user. All reaches were attributed with stream size, gradient, freshwater ecoregion, and EDU. Reaches in the eastern section of the SARP geography were attributed with the additional attributes of baseflow index, bedrock geology, soils, surrounding landforms, landcover, and a modeled hydrologic class.

Conclusion

Many existing stream classifications fall into two major types, taxonomic or physical environmental classifications. Taxonomic based classifications provide descriptive information regarding aquatic species distributions and assemblage structure. By measuring the presence and abundance of taxa at a given location and time, these classifications emphasize the resident current biota and focus on the biotic expressions (taxa) that have resulted from the variety of interacting spatial, temporal, and biotic factors at the site. Biologists and managers often find taxonomic classifications easy to understand and useful in management, such as in biomonitoring, as these classifications depend upon readily identifiable biological entities that can be sampled and monitored at sites. However, taxonomic based classifications have been criticized because previous research has shown that classifications using strictly biological data or data about one type of organism, such as fishes, macroinvertebrates, or mussels, rarely represent the complexity inherent in aquatic communities (Higgins et al. 2005). For example, stream systems are extremely dynamic and their biological species composition can vary widely seasonally and over short temporal scales due to changes in environmental factors. The high temporal variation makes it difficult for researchers to obtain comprehensive collection data at sampling station or compare data collected at different times. Existing biological classifications of stream communities are also almost always based on data collected from wadable streams, that biases their representation of ecological diversity in terms of stream size, gradient, and scale. Historic data on distribution and abundance are rarely taken into account and the future evolutionary potential created by underlying environmental diversity is usually not considered in taxonomic classifications. In addition, biological classifications are not easily applied to map comprehensively all streams and rivers community types across a state or larger geographic area given lack of biological sampling in every stream and river.

Physical environmental classifications emphasize a stream's relationship to its physical environment. Physical factors have been shown to constrain the observed range of aquatic ecological process and biotic communities and are used as classification variables in these classifications. The classification variables often include measures of climate, physiography, bedrock and surficial geology, channel width, depth, and gradient, bed form, and bank conditions (Maxwell et al.1995, Frissel et al 1986, Rosgen 1994, Argent 2002). Envirornmental classifications are often designed within a spatial and temporal scale hierarchy. For example, a number of environmental classifications recognize a sequential spatially nested hierarchy of a small scale pool/riffle system units, reach level, reach systems, stream systems or subwatersheds, watersheds, subbasins, and subzones (Maxwell et l.1995, Frissel et al 1986, Higgins et al 2005). At any point in the hierarchy, the potential capacity or development of a smaller scale systems develop within the constraints set by the larger scale systems of that they are a part. For example, geology and climate factors associated with very large scale subbasins and subzones constrain the development of reach level physical habitat and biological structure through their large-scale controls on chemistry, hydrology, and sediment delivery (Hawkins et al 2000). The temporal scale or time during which a type at a given patial scale units are thought to continuously persist within a given range of variation defining their type will also vary. Smaller spatial levels of aquatic systems, such as a reach's arrangement of pools and riffles, are much more temporally dynamic than larger scale systems that are often only significantly altered after major geologic and climate processes occurring over much longer time frames. At any spatial or temporal scale, the variables selected for classification should be those physical entities that are most general, invariant, and causal for the given frame of time and space (Warren 1979, Warren and Liss 1983, Frissel et al 1986).

Both taxonomic and environmental classifications can provide useful approaches to structuring the continuum of aquatic biodiversity patterns that exist on the landscape. Use of one over the other can depend on the availability of comprehensive taxonomic sample data for the entire study area, the desire to comprehensively classify every aquatic feature (even those without collection sites), the desire to include physical habitat parameters as a surrogate to address unknown/unsampled aquatic biodiversity, and the desire to include the ecological and evolutionary context of the system in a structured hierarchical manner. Some classifications are beginning to combine aspects of both taxonomic and physical environmental classifications. For example, a number of taxonomically derived biological classifications attempt to relate assemblage structure to the underlying physical habitat parameters (Langdon et al 1998, Reschke 1990). Many environmental classifications are also beginning to describe their classes with biological entities (Van Sickle and Hughes 2000, Oswood et al 2000, Waite et al. 2000, Sandin and Johnson 2000, Rabeni and Doisy 2000, Marchant et al 2000, Feminella 2000, Gerritsen et al 2000, Hawkins and Vinson 2000, Johnson 2000, Pan et al 2000, Walsh et al. 2007, MD DNR 2012) or use physical classification variables to model and broadly map predicted habitat for certain species (McKenna and Johnson, 2011, White et al. 2011,)

PART II: Hydrologic Classification

Introduction

Hydrology varies extensively across regions, continents, and the globe (Kennard et al., 2010b; Haines et al., 1988), yet streams display reoccurring patterns in their streamflow (Acreman and Sinclair, 1986; Burn and Arnell, 1993; Poff et al., 1997). By their very nature, streamflow regimes are also multi-dimensional. The hydrologic signature of streams is measured by five key components: the magnitude, duration, frequency, timing, and rate of change of flow events (Poff et al. 1997). These repeatable multivariate patterns naturally predispose streams to hydrologic classification. However, the question remains, "Why do we care about classifying streams by their hydrology?" According to Melles et al. (2012), classifications depict our current state of knowledge about a subject area. In fact, classifications provide the structure and relationships within and among groups of objects (Sokal, 1974). These relationships provide a foundation for drawing inferences about the principles that govern relationships among different classes and how to interpret unclassified objects (Sokal, 1974). Thus, the best approach to characterize streamflow regimes is to classify them. Hydrologic classifications not only provide an understanding of how different streams operate, but also how they structure ecological communities. Riverine organisms have developed life history strategies adapted to the natural variation in stream flow regimes (Bunn and Arthington, 2002; Poff et al. 1997). The natural timing and magnitude of flooding establishes the template on which riverine habitats are created and then maintained (Trush et al. 2000), structures floopdlain riparian communities (Auble et al. 2005), and provides behavioral cues for the initiation of spawning and seasonal migrations for fish (Nesler et al. 1988; King et al. 1998). Studies have suggested that hydrology forms the habitat template (Schlosser 1987, 1990) or hierarchical filter (Jackson and Harvey, 1989; Tonn, 1990; Poff, 1997), which organizes tradeoffs among adaptive strategies for fish and macroinvertebrates. The wide range of natural flow conditions across the US continent (Poff, 1996) exerts different selective pressures that shape life history and reproductive strategies and result in regionally distinct river assemblages (Southwood 1988; Olden and Kennard 2010; Mims and Olden 2012).

With regard to river systems, stream classifications and their use in management have a fairly long history (Horton, 1945; Strahler, 1957; Pennak, 1971; Rosgen, 1994). However, the development of hydrologic classifications for use in environmental flow management has greatly expanded in recent years. In fact, hydrologic classifications have become so popular that Olden et al. (2012) compiled a literature review strictly on the subject. One of the primary justifications for developing hydrologic classifications is to provide a means for developing environmental flow standards to support the preservation of freshwater biodiversity and ecosystem services (Arthington et al., 2006; Poff et al., 2010). With growing water demands, infrastructure, and development (Poff et al., 2003), river managers are faced with a need to protect the key aspects of the natural flow regime. However, managing for the specific needs of every river is not only challenging, but also unlikely. Competing social, economic, political, and ecological demands on water typically result in simple and static flow rules that ignore the complexity of flow variability responsible for sustaining river systems (Arthington et al., 2006). For many states found within the APP LCC region, the practice of making environmental flow recommendations (e.g. water withdrawal criteria) has been to apply statewide criteria, treating all river types in a similar way. Obviously, this is inadequate for protecting the variability in flow regimes that support aquatic biodiversity. One practical approach to providing environmental flow standards is to form classes of rivers with similar hydrologic properties across regions from which standards for managing flow needs can be developed (Poff, 1996; Arthington et al., 2006). Classifications alleviate some of the complexity of environmental flow management by consolidating hydrologic variation into management units and managing for groups of streams rather than for the uniqueness of individual water bodies. The assumption is that rivers that behave similarly in terms of their hydrology should share similar patterns in ecology (Arthington et al., 2006) and respond similarly to a given anthropogenic stressor (Arthington et al., 2006; Poff et al., 2010). The latest paradigm in environmental flow science is the development of the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al., 2010), whose central design is based upon placing streams into hydrologic classes to provide a context for generalizing hydrologic disturbances, assembling and testing hypotheses regarding ecological responses to hydrologic disturbance, and lastly, developing environmental flow standards. In essence, hydrologic classes form the template for developing relationships between flow alteration and ecology (Poff et al., 2010). Comparisons of ecological patterns between natural and hydrologically altered streams within each class yield flow-ecological response relationships, which provide the basis for environmental flow standards (Arthington et al., 2006).

Major Approaches to Hydrologic Classification

According to Olden et al. (2012), two major approaches to hydrologic classification are available. *Deductive* techniques use regional boundaries, such as ecoregions, or environmental variables to infer areas of similar hydrologic regimes whereas *inductive* techniques use hydrologic data (either from stream gages or synthesized data) directly to inform and create classifications (Olden et al., 2012). In situations where hydrologic information is lacking, deductive approaches may be advantageous; however, these approaches have several assumptions: 1) features in the landscape adequately represent hydrologic variability, 2) the actual number of hydrologic classes and thus, total hydrologic variation, is already known, or 3) the structure of environmental variables in predicting hydrology is already known (Olden et al., 2012). In addition, deductive approaches often only include best professional judgment as criteria (e.g., such as using watershed boundaries) and may not accurately represent or predict streamflow patterns (McManamay et al., 2012c). By comparison, inductive approaches utilize the available hydrologic information (i.e. stream gauges) and classification techniques that group streams according to similarities in hydrologic metrics (Olden et al., 2012). Then, various predictors, including climate and features of the landscape, are used to understand differences among streamflow classes. The hierarchical importance of different predictors in discriminating amongst classes is extremely important and depends on the spatial extent of the hydrologic classification (McManamay et al. 2012). However, the hierarchical importance of these predictors is not known unless direct hydrologic observations are used in classifications. Based on the above reasons, inductive approaches to hydrologic classifications are obviously the recommended technique to support environmental flow standard development (Poff et al. 2010).

Within the last 2 decades, the majority of approaches to hydrologic classification (including approaches within the APPLCC) have used inductive methods (Table 1). Inductive approaches to hydrologic classifications have been created at multiple scales including states (Kennen et al., 2007, 2009; Turton et al., 2008; Henriksen and Heasley, 2010; Liermann et al., 2012), regions (Monk et al., 2006; Sanborn and Bledsoe, 2006; Chinnayakanahalli et al., 2011; McManamay et al., 2012b), continents (Kennard et al., 2010b; McManamay et al. 2013), and the world (Haines et al., 1988). However, one noteworthy example of a deductive approach was the creation of Hydrologic Landscape Regions (HLRs) by Wolock et al. 2004. HLRs were created by compiling information on landscape characteristics known to influence hydrology (climate, topography, and soil characteristics). These variables were summarized within > 12,000 catchments across the conterminous US and then used in a hierarchical clustering procedure to produce 20 different hydrologic-landscape classes. The purpose of HLRs were to stratify sampling designs for studies assessing nutrient loading (e.g. USGS NAQWA), with the rationale that study sites should represent the diversity of background hydrologic conditions (since hydrology influences nutrient loading). However, one major assumption was that the selection and structural importance of landscape characteristics were already known and adequately explained variation in hydrology. However, McManamay et al. (2012) showed that HLRs did a poor job of explaining hydrologic variation in the Southeast.

Inductive Hydrologic Classification Process

The inductive hydrologic classification process can be described as a 3-step procedure, symbolized by CCC: 1) Compile reference condition hydrologic information, 2) Compute statistics that summarize hydrologic information, and 3) Cluster streams according to similarities in hydrologic statistics.

Compile hydrologic information: One common approach in hydrologic classification is screening gauges for inclusion in a final 'reference' dataset (Olden et al., 2012). Because hydrologic classifications form the starting point for developing environmental flow standards, great care should be taken in selecting streams that represent the "baseline" or "reference" hydrologic condition. These reference streams are used for classification, but also they become important for measuring the degree of hydrologic alteration in areas of disturbance. Hence, if the baseline becomes contaminated with non-reference conditions, then natural hydrologic variation inferred from classes is likely spurious and an adequate appreciation of how streams should function in their natural or, in the least, semi-natural state is lost. However, ensuring high-data-quality standards often come at the expense of losses in hydrologic information, which may limit sample sizes of representative gages. Hence, conclusions regarding the true hydrologic variability (e.g., largest streams are likely to be the most disturbed – thus, large rivers are missing from the analysis); thus, selecting gages is a balance between The screening process typically includes evaluating landscape disturbances upstream of each gauge, the hydrologic record length, and the extent of overlap among hydrologic records (Olden et al., 2012). Because most hydrologic classifications are constructed from natural streamflow patterns, the standards for inclusion can be quite strict and exclusive (Poff, 1996; Kennard et al., 2010a; Olden et al., 2012), which may limit the sample size and variation represented in the final dataset. Thus, high-data-quality standards often come at the expense of losses in hydrologic information. The period of record (POR) needed for each stream gage is also important, as changes in climatic regimes will be reflected in hydrology. Thus, short PORs may cause incorrect classification, especially if including drought years or extremely wet years. Kennard et al. (2010a) recommends that at least 15 years of record is suitable for estimating hydrologic variables that are used to detect differences in the spatial variation, such as flow classifications. In addition, at least 50% overlap among all PORs is needed to ensure different classes are not an artifact of different climatic regimes.

Compute hydrologic statistics: Over 200 different hydrologic statistics are available to summarize stream flow. Statistics typically represent either measurements of one of the five key flow components (magnitude, frequency, duration, timing, and rate of change) or variation in one of the key flow components. Olden and Poff (2003) describe 171 different hydrologic statistics supported within the existing literature, including 94 magnitude indices, 14 frequency indices, 44 duration indices, and 9 rate of change indices. Hydrologic indices were subdivided into a total of 9 subcategories where magnitudes were divided into average (n = 45), low (n = 22) and high (n = 27) categories, frequency into low (n = 3) and high (n = 11) categories, and duration into low (n = 20) and high (n = 24) categories. The set of indices reported by Olden and Poff (2003) included the Indicators of Hydrologic Alteration (IHA), the most commonly used set of hydrologic metrics in streamflow analyses (Ricther et al. 1996; Olden and Poff 2003). IHA variables include 33 individual metrics and 33 associated measures of variation. Indices not included in Olden and Poff's assessment included commonly-used percentile flows from flow-duration curves(1%'tile-95%'tile) and indices protecting withdrawal limits, such as 7Q10 (the lowest 7-day average flow that occurs on average once every 10 years). However, these indices are likely captured in other metrics because of the high colinearity among hydrologic indices.

Because streamflow is a multivariate concept, the use of single hydrologic indices in characterizing streamflow regimes has been criticized because of either over simplification or being ecologically irrelevant (e.g. Poff, 1996; Richter et al.,1996, 1997). However, stream ecologists are now faced with the difficult task of selecting from among >200 hydrologic indices to characterize streamflow regimes (Olden and Poff 2003). In addition, hydrologic indices are highly redundant, i.e. many indices convey the same information because of mulit-colinearilty among metrics. Besides the need to simplify the logistics of characterizing streamflow regimes, selecting a subset of non-redundant hydrologic metrics is important to avoid the deleterious effects of multi-colinearity, such as biases in classification results and failure to identify the most meaningful patterns in data. Redundancy may bias classifications by providing more weight to variables with higher colinearity (i.e. more representation by redundant variables in clustering algorithms). One approach to identify and remove redundant variables includes examining correlation matrices among variables and removing those with highest correlation values, in favor of metrics that are more interpretable. An alternative and more robust approach is to use Principal Components Analysis (PCA) to reduce the redundancy in the dataset while also identifying variables that explain the most variation in streamflow regimes. Olden and Poff (2003) used this exact process to identify redundant patterns among 171 hydrologic indices and select the indices that explained predominant patterns in streamflow variation. However, one of their main conclusions was that the 66 IHA indices explained the majority of variation in streamflow regimes represented by all 171 indices. Thus, selecting the IHA variables for characterizing streamflow regimes would be a simpler alternative to running PCA analyses and then selecting subsets of variables. In addition, the variables are supported by scientific literature. If PCA is used, another simpler alternative is to use the principal component scores themselves (as opposed to variables with highest loadings) in future clustering procedures. This avoids the complication of selecting metrics.

Besides ensuring that hydrologic metrics are not redundant, there is a need to ensure that hydrologic metrics are "ecologically relevant". The term, "ecological relevance (ER)", when related to hydrology, places additional emphasis on indices that supposedly explain more variation in ecological patterns (e.g., fish assemblage structure). However, ER has been used quite loosely to justify the arbitrary selection of metrics due to preference, opinion, prior use, or simplicity. However, to date, very few studies have specifically addressed which hydrologic indices (out of >200) explain the most variation in ecological patterns, either related to natural or altered streamflows (Carlisle et al. 2011). Kennen et al. 2008 evaluated the ecological relevance of almost 80 hydrologic metrics in New Jersey streams using a series of steps: 1) conducting a PCA filtering out the metrics that were redundant and keeping those explaining the most variation, 2) Employing multiple linear regression models to identify the remaining subset of hydrologic variables driving differences in invertebrate assemblages across a disturbance gradient. In a similar approach, Knight et al. (2008) selected a subset of 16 hydrologic indices (out of 90 total) that best represented multivariate patterns in fish assemblages in the Tennessee River Basin. For obvious reasons, determining the ecological relevance of hydrologic metrics should be conducted at the same spatial scale in which the hydrologic classification will be developed.

Many software packages are now available to calculate hydrologic indices. The Indicators of Hydrologic Alteration are available from The Nature Conservancy (citation). In addition, the Hydrologic Index Tool (HIT) software is provided by the U.S. Geological Survey (USGS) and calculates the 171 variables used in Olden and Poff (2003), which also includes the IHA variables (Henriksen et al. 2006). The USGS also provides StreamStats, an online web-interface that provides up to 1264 different indices, which vary according to state (USGS 2014). Most states only provide <50 indices.

Cluster streams according to similarities in hydrology: Because multiple variables are selected to represent streamflow regimes, multivariate statistics are required to appropriately create hydrologic classes through ordination or clustering. Unfortunately, an exhaustive list of clustering procedures is available and the selected approach can have dramatic influences on the clustering outcome. Olden et al. (2012) provides a good overview and identifies five major types of classification techniques: 1) ordination, 2) hierarchical, 3) partitional, 4) fuzzy clustering, and 5) bayesian probabilistic clustering. For more detailed discussion of clustering approaches, see Everitt et al. (2001). Ordination techniques include principal components analysis or non-metric multidimensional scaling. While these approaches are convenient for allowing visual examination of similarities or dissimilarities among the data, they require manually separating classes based on visual patterns. The remaining four procedures are clustering procedures that produce groups of observations. Hierarchical classifications have been the most widely used in and include two major approaches: 1) the agglomeration approach, which starts with each stream gage and combines into the most similar groups until only one gage is left, or 2) the divisive approach, which splits larger clusters into smaller ones until all stream gages have been separated. Seven different algorithms are available to produce hierarchical classifications and while each differs in their pros and cons, describing all algorithms in detail is well beyond the scope here. The similarity among hierarchical classifications, however, is that smaller classes that nested within the larger classes that they comprise, which create a dendogram/tree-like structure. For most hierarchical applications, Olden et al. (2012) recommend using Ward's hierarchical classification because it is a space-conserving method, which means it balances distances between and within clusters proportionally that best represents the structure of the original data. In addition, this approach removes any relationships between the clustering solution (i.e., number of clusters) and group-size (we cannot assume that equal numbers of stream gages should be represented among groups).

In contrast to hierarchical classifications, partitional clustering techniques seek equal distinction among clusters rather than seeking clustering solutions represented by hierarchy. Partional approaches initiate with a random group of clusters where euclidean distances are measured from each observation to each cluster centroid (Olden et al. 2012). Observations with similar distance measures create new cluster cnetroids. The mean distance values from the previous iteration are used in subsequent iterations to create new clusters, until no changes occur in the observations. This approach is considered more efficient for larger datasets, because, unlike hierarchical approaches, the dissimilarity matrix among all observations is not needed. However, partitional approaches are sensitive to the initiation of the clustering algorithm and thus, the order of the dataset can influence the outcome. Partitional approaches also require the user to pre-define the number of clusters, whereas the number of clusters in hierarchical approaches is typically determined following the procedure by examining the dendrogram. However, in both cases, plots of the sum-of-squared distances (SSD) versus the number of clusters can be used to determine the most parsimonious solution. The number of groups in which SSD is minimized is typically used to determine the most parsimonious solution. At least four different partitional approaches are available and include k-means, k-median, k-modes, and k-medoids (Olden et al. 2012). Among approaches, k-means is the most widely used approach.

Both hierarchical and partitional approaches, in their raw form, are considered hard clustering procedures. Thus each observation is assigned to a given cluster under the assumption there is well defined boundaries between clusters and each observation fits neatly within its corresponding class (Olden et al. 2012). However, this is rarely found in nature and many streams tend to share overlap (in some regard) with multiple classes. Fuzzy clustering is a technique that uses ordination, along with hierarchical or partitional clustering solutions, to simultaneously assign probabilities of membership for all clusters to each observation. This provides an indication of strength of membership for a given stream to its assigned class, but also provides a mechanism to exclude only high-probability streams or identify no-analogue or novelty streams.

One of the main obstacles in clustering, especially with hydrologic data, is that the number of clusters and the multivariate shape of the clusters are unknown. Unfortunately, the choice of the number of clusters and distance measure/algorithm used is subjectively made by the user and this will certainly influence cluster solutions. However, Bayesian mixture modelling (BMM) presents an approach to overcome some of these obstacles. BMM models the observed data as a finite number of component distributions (number of clusters) (Gelman et al. 2004). Mixture modeling refers to probabilistic modeling where subpopulations are represented within an overall population; thus, subpopulations refer to hydrologic classes. The Bayesian approach models the number of clusters, the parameters describing each cluster (shape, orientation, etc), and membership of each stream to a cluster as completely probabilistic. The approach produces multiple classification scenarios and the most parsimonious solution is presented that has the highest probability of correctly describing the data (Gelman et al. 2004; Olden et al. 2012). Only two studies, Kennard et al. (2010) and McManamay et al. (2013), have used the BMM approach and created continental classifications for Australia and the United States, respectively.

Examples of Inductive Hydrologic Classifications overlapping with APP LCC

Based on our knowledge, at least 10 different inductive hydrologic classification efforts spatially overlapping with the APP LCC region have been publicized; however, only 6 are available in published materials, either as peer-review journal articles or reports. Four of the efforts were conducted for the conterminous or continental US. The first hydrologic classification for the conterminous US was produced by Poff and Ward (1989) and later expanded by Poff (1996), who documented 10 dominant streamflow types of varying intermittency, perennial flows, and timing in 806 streams (Figure 1). Over two decades of US Geological Survey (USGS) streamflow gauge information has become available since Poff (1996) produced his hydrologic classification (latest gauges used were from 1986). Recently, McManamay et al. (2013) created an updated classification for the US (including AK and HI) and Puerto Rico using 2618 reference condition stream gages in a hierarchical bayesian clustering method (mentioned previously). Fifteen hydrologic classes were represented across the US, with many showing similarities to classes created by Poff (1996) (McManamay et al. 2013). One similarity in the approaches by Poff (1996) and McManamay et al. (2013) is that streamflow patterns were not influenced by river size either through careful selection of metrics or by standardizing magnitude-related metric; thus, in both cases, classes tended to show high regional affiliation. Archfield et al. (2013) also recently completed a US hydrologic classification using 7 fundamental daily streamflow statistics (FDSS) in a Ward's hiearchical clustering procedure. Several classification solutions were created from 2 to 8 nested classes. The novelty of the approach was the development of the FDSS, hydrologic indices representative of moments of the streamflow distribution. However, one of FDSS was mean daily flow; thus, the resultant river classification was heavily biased by river size and failed to show any distinct regional affiliation (one of the main conclusions of their analysis). As opposed to multivariate clustering approaches, Environmental Flow Specialists produced a hydrologic classification for the continental US and Puerto Rico using a 'multi-univariate' approach (EFS 2013). The approach consists of a decision-tree design where multiple individual hydrologic variable thresholds are used to categorize streams into a series of classes, regardless of the reference condition of the gages. The approach is convenient in that the classification approach is easy to follow; however, the selection of hydrologic metrics and their threshold values to create classes are somewhat subjective and do not rely on natural patterns among streams. Mean daily flow is used to segregate classes based on size rather than standardize for river size.

Other efforts have been at the regional or state-wide level. McManamay et al. (2012) conducted a stream classification for an 8-state region of the southeast using 66 hydrologic statistics for 292 streams. Using a k-means clustering procedure, six flow classes showing regional affiliation were isolated that ranged from extremely stable to highly variable to intermittent. Konrad et al. (2013) developed a hydrologic classification for the Southeastern Aquatic Resources Partnership (SARP) region based on the seasonality of streamflow regimes (using monthly flow estimates) and 13 carefully selected metrics (based on discussion/expert review). In both of the above cases, magnitude-related metrics were standardized by mean daily flow; thus classes showed a high degree of regional affiliation. State-specific classifications within the APPLCC region have been conducted for New Jersey, Pennsylvania, and North Carolina. Kennen et al. (2007) classified 94 "least impaired" streams into 4 groups using 70 hydrologic indices within an average-linkage hierarchical clustering procedure. Using a k-means clustering approach, Henriksen and Heasley (2010) developed a hydrologic classification for 163 unaltered streams in North Carolina. Seven classes emerged, six of which were perennial and varied in stability and timing and one of which showed signs of intermittency. Five hydrologic classes were developed for Pennsylvania using 136 reference streams (Apse and DePhilip 2009).

Prior to clustering streams, hydrologic metrics must be selected explain the maximum variation in the data, but are also non-redundant. As stated previously, this can be achieved using PCA to determine which variables explain the majority of the variation and then correlation analysis can be used to remove redundant variables. Four of the regional/state-level studies above used PCA followed by correlated metrics to reduce the predictor dataset. McManamay et al. (2012) reduced 171 metrics to 66, Kennen et al. (2007) reduced 171 metrics to 70, and Henriksen and Heasley (2010) reduced 108 to 61 indices. Thus, while it is uncertain which metrics were used in all analyses, 60-70 indices seem to be the number of hydrologic statistics that are available, non-redundant, and explain the majority of variation in streamflow patterns.

Conclusion

The approach to hydrologic classification will vary depending on the objectives. If the objective is to describe patterns in streamflow, then an inductive approach that uses the CCC procedure is recommended. Because stream classifications are mean to represent the natural "baseline", building classifications using the best reference streams is also recommended. The choice of metrics is also pivotal in any clustering analysis; however, again, if describing natural patterns in flow variation is the objective, then selecting non-redundant metrics that describe the majority of variation is best. Alternatively, simply using scores from PCA can be an efficient and preferred alternative. Similar to choosing metrics, the selection of a clustering procedure can also have consequences on the final outcome. Because most managers desire simplicity and nested organization, a Ward's hierarchical approach may be best and is recommended by Olden et al. (2012), at least as the best approach when using hierarchical methods.

Despite the intense growth of hydrologic classifications, comprehensive testing of hydrologic classifications in generalizing patterns of disturbance and establishing environmental flow standards, one of the central precepts behind creating streamflow-based classes (Arthington et al., 2006; Poff et al., 2010), has not been fully addressed. Furthermore, with regard to ecological patterns, the predictive capacity of hydrologic classifications has received little attention (but see Monk et al., 2006; Chinnayakanahalli et al., 2011). The utility of any classification system lies, in part, on its ability to stratify analyses and generalize patterns in disturbance. Thus, the full utility of classifications will not be recognized unless we learn from them.

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