A Freshwater Classification Approach for Biodiversity Conservation Planning

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Abstract: *Freshwater biodiversity is highly endangered and faces increasing threats worldwide. To be complete, regional plans that identify critical areas for conservation must capture representative components of freshwater biodiversity as well as rare and endangered species. We present a spatially hierarchical approach to classify freshwater systems to create a coarse filter to capture representative freshwater biodiversity in regional conservation plans. The classification framework has four levels that we described using abiotic factors within a zoogeographic context and mapped in a geographic information system. Methods to classify and map units are flexible and can be automated where high-quality spatial data exist, or can be manually developed where such data are not available. Products include a spatially comprehensive inventory of mapped and classified units that can be used remotely to characterize regional patterns of aquatic ecosystems. We provide examples of classification procedures in data-rich and data-poor regions from the Columbia River Basin in the Pacific Northwest of North America and the upper Paraguay River in central South America. The approach, which has been applied in North, Central, and South America, provides a relatively rapid and pragmatic way to account for representative freshwater biodiversity at scales appropriate to regional assessments.*

Key Words: classification, conservation planning, freshwater biodiversity, representative

Un Método de Clasificación de Agua Dulce para Planificación de Conservación de Biodiversidad

Resumen: *La biodiversidad de agua dulce está en peligro y enfrenta amenazas crecientes en todo el mundo. Para ser completos, los planes regionales que identifican áreas críticas para la conservación deben incluir componentes representativos de la biodiversidad de agua dulce así como especies raras y en peligro. Presentamos un método espacialmente jerárquico para clasificar sistemas de agua dulce para crear un filtro grueso que capte a la biodiversidad de agua dulce en los planes regionales de conservación. La estructura de la clasificación tiene cuatro niveles que describimos utilizando factores abióticos en un contexto zoogeográfico y localizamos en un sistema de información geográfico. Los métodos para clasificar y trazar mapas son flexibles y pueden ser automatizados, donde existen datos espaciales de alta calidad, o desarrollados manualmente cuando tales datos no están disponibles. Los productos incluyen un inventario completo de unidades mapeadas y clasificadas que pueden ser usadas remotamente para caracterizar patrones regionales de ecosistemas acuáticos. Proporcionamos ejemplos de procedimientos de clasificación en regiones ricas y pobres en datos en la cuenca del Río Columbia en el noroeste de Norte América y del Río Paraguay en Sudamérica central. El método, que ha sido aplicado en Norte, Centro y Sudamérica, proporciona una forma relativamente rápida y pragmática de contabilizar biodiversidad de agua dulce representativa en escalas adecuadas para evaluaciones regionales.*

Palabras Clave: biodiversidad de agua dulce, clasificación, planificación de conservación, representativo

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Introduction

The Nature Conservancy (TNC) is engaged in the process of ecoregional assessment, the purpose of which is to identify a set of conservation areas that best represents the native species, communities, and ecosystems of an ecoregion and the underlying ecological processes that sustain them (Groves et al. 2002). Freshwater biodiversity must be included in this process because freshwater species and ecosystems are a major component of biodiversity that is highly endangered (Master et al. 1998; Ricciardi & Rasmussen 1999) and that faces significant threats worldwide (Allan & Flecker 1993; Revenga et al. 2000). An approach for classifying and mapping patterns of freshwater environments is an indispensable tool for ecoregional assessment (Higgins 2003). We present the freshwater classification approach that TNC has developed to support ecoregional assessments.

The primary aim of the classification is to generate coarse-filter conservation targets. "Targets" refers to those elements of biodiversity that are a focus for conservation planning or action. The Nature Conservancy uses a coarse- and fine-filter approach to comprehensively represent the biodiversity of an ecoregion, which includes all ecosystems (coarse filter) and a subset of species and communities (fine filter; Groves 2003). The coarse-filter premise is that conserving representative ecosystem units conserves many common species and communities, the ecological processes that support them, and the environments in which they evolve (Hunter 1991). Using this approach for freshwater biodiversity conservation allows us to move beyond a focus on species and to begin protecting ecosystems and habitats on a systematic basis (Moyle & Yoshiyama 1994; Angermeier & Schlosser 1995). Coarse filters are generally used in conjunction with available species and community data to identify targets that are not adequately captured by the coarse filter. In areas of the world where species data are deficient, the coarse filter is the primary tool for representing biodiversity in regional conservation planning. The coarse-filter approach is effective for terrestrial and marine biodiversity planning (e.g., Oliver et al. 2004; Ward et al. 1999), but at the inception of TNC's ecoregional planning in 1994, an analogous freshwater coarse filter had not been developed.

An examination of existing freshwater classifications convinced us that existing schemes are—by themselves—not sufficient for ecoregional assessment (for reviews see Hudson et al. 1992; Leach & Herron 1992; Naiman et al. 1992; Maxwell et al. 1995; Hawkins et al. 2000). These earlier classifications were designed for purposes other than large-scale conservation planning and did not meet our criteria of providing a biodiversity context, being applicable across large regions, and requiring only data that are readily available, mappable, and at the right scale for ecoregional assessment. A key distinction between these previous approaches and the methods adopted and developed by TNC is that our approach provides the capacity to remotely identify and inventory actual units, where previous approaches exist only as a conceptual framework (e.g., Maxwell et al. 1995).

The classification framework we present satisfies these requirements and builds on existing classification concepts and methods (e.g., Maxwell et al. 1995, Seelbach et al. 1997), thus creating a practical framework for generating freshwater coarse-filter targets.

The methodology used to implement the classification is driven largely by the practical needs of ecoregional assessment. The urgency of conservation work and the limited funds available for conservation planning dictated that the classification be relatively rapid to implement and compatible with readily available data. Additionally, because TNC is conducting ecoregional assessment in a variety of locations worldwide, it was necessary to develop a classification framework that could be tailored to a wide range of ecological settings and that could be implemented with geographic information system (GIS) data of various levels of quality and scale. Indeed, a key strength of this classification approach (and others implemented in a GIS) is that a spatially comprehensive inventory of mapped and classified units is allowed. We describe the classification framework and present two case studies of classifications that we developed for ecoregional assessment.

Classification Framework

Our hierarchical classification framework has four spatial levels: an aquatic zoogeographic unit; ecological drainage units (EDUs) within one aquatic zoogeographic unit; aquatic ecological systems (AES) within one ecological drainage unit; and macrohabitats within one aquatic ecological system (Fig. 1). This framework is a more widely applicable and improved version of the classification approach that TNC first applied in the Great Lakes ecoregion (Higgins et al. 1998). In areas where GIS data are of inadequate scale or quality, the finest spatial level (macrohabitats) can be omitted. We chose these four levels because there are spatial data available to classify and map ecological patterns at scales known to shape freshwater biodiversity patterns. Although additional hierarchical levels could be added (e.g., Maxwell et al. 1995), pragmatism played a role in our selection. We believe that these four levels serve as a minimum set to describe key scales of ecological patterns.

MacNally et al. (2002) suggest that ecosystem-based planning units be developed as hierarchies to adequately capture representative biodiversity. A hierarchical classification structure is necessary to capture the patterns and processes that influence freshwater biodiversity at multiple spatial and temporal scales. Landscape patterns and

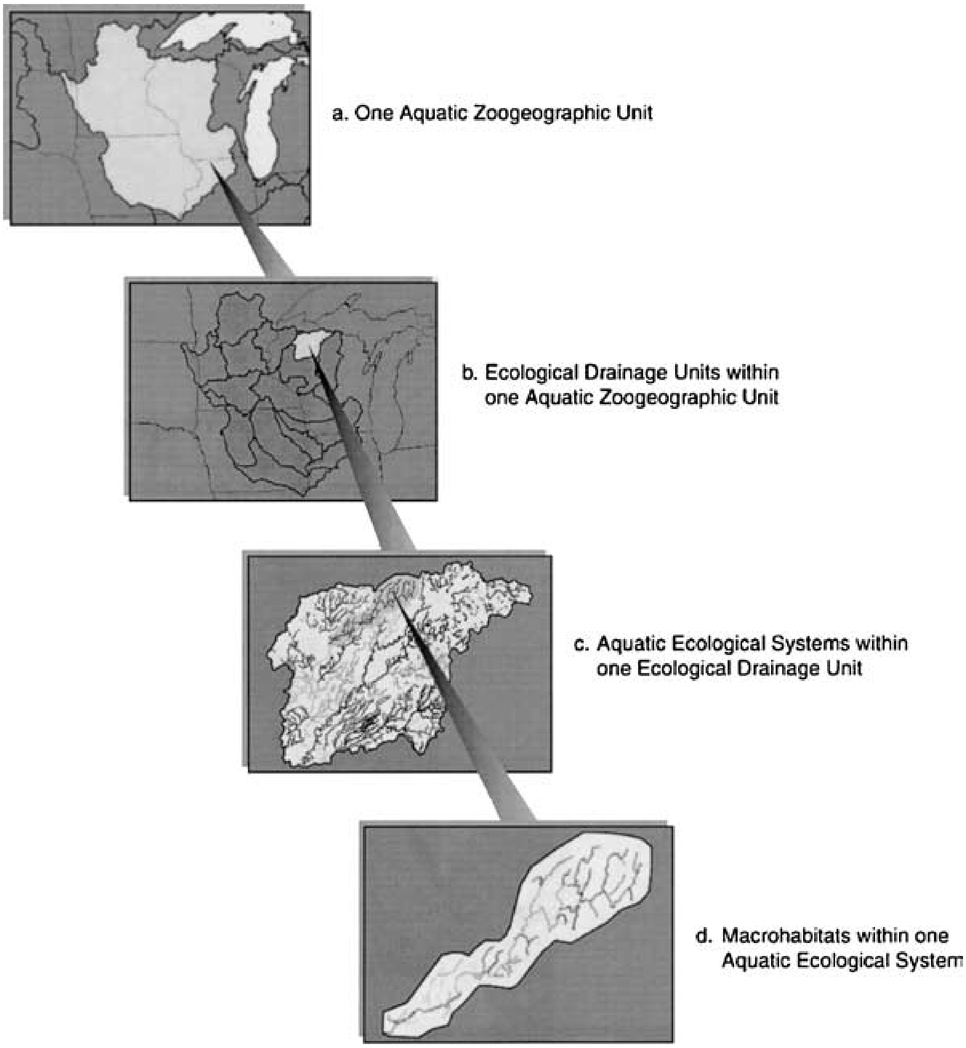

Figure 1. A four-tiered, hierarchical freshwater classification framework. The highest level is (a) aquatic zoogeographic units (approximate scale 1:26,000,000). (b) Ecological drainage units are nested within aquatic zoogeographic units (approximate scale 1:26,000,000). (c) Aquatic ecological systems are nested within ecological drainage units (approximate scale 1:4,000,000). (d) Macrohabitats are nested within aquatic ecological systems (approximate scale 1:1,200,000). (Adapted from Fig. 10.2, chapter 10 in Groves 2003. Copyright © 2003 Island Press. Reprinted by permission of Island Press, Washington, D.C.).

processes tend to be hierarchical, where large-scale patterns and processes constrain those at fine scales (Allen & Starr 1982; O'Neill et al. 1986). Our approach to classification has grown out of two bodies of work that address the hierarchical organization of freshwater ecosystems. The first body postulates that many freshwater biodiversity patterns, habitats, and ecological processes are shaped by a hierarchy of spatial and temporal processes (Frissell et al. 1986; Tonn 1990; Maxwell et al. 1995; Poff 1997; Mathews 1998; Jensen et al. 2001). The four levels of the classification are thus nested, with the upper levels shaping the expression of the finer scale units. The second body of work developed classification frameworks that combined hierarchies of fish zoogeography and landscape features (e.g., Pflieger 1989; Moyle & Ellison 1991; Maxwell et al. 1995). The concept of this work is particularly reflected in the design of the top two levels of the classification framework.

The highest level in the classification, the aquatic zoogeographic unit, is the overall planning unit. Planning units delineate the area to be classified for a particular project, and basing them on large-scale ecological differences makes more sense than using geopolitical boundaries because such units contain relatively distinct biotic assemblages (Groves 2003). The second highest level, EDU, represents a finer scale of physiographic and zoogeographic diversity, which allows the selection of rivers and lakes for conservation to be stratified. Distributing the selected conservation targets across the planning region's environmental gradients is one strategy for safeguarding against natural catastrophe and for helping to conserve the genetic and ecological variation that occurs in targets (Groves 2003).

The lower two levels in the classification generate the coarse-filter targets. The two levels consider how the physical environment shapes more local distribution patterns of aquatic organisms and are described using only abiotic variables. Aquatic ecological systems are the third level of the classification and are the coarse-filter targets. The fourth level, macrohabitats, represents finer scale classification units that can be used to create the AES. Macrohabitats are usually generated only in places where the resolution of hydrographic data is fine enough and of adequate quality to facilitate automated processing (see TNC-FWI [2000] for a description of data requirements).

Aquatic Zoogeographic Units

Aquatic zoogeographic units conform to drainage boundaries, generally 10,000–100,000 km^2, but are not always true watersheds because of the need to subdivide very large river basins into smaller nonoverlapping units. They are distinguished by differences in continental and regional patterns of zoogeography, which result from differences in initial zoogeographic sources, patterns of drainage connections, and biotic changes over time in response to climatic and geologic events (e.g., Hocutt & Wiley 1986; Tonn 1990).

When available, we directly adopted these units from other sources, sometimes subdividing them to create a more tractable unit of analysis. Sources in North America include Maxwell et al. (1995), who defined a hierarchy of zoogeographic subregions based on fish species, and the World Wildlife Fund, which modified these subregions by adding information on crayfishes and mussels to create 76 freshwater ecoregions of North America (Abell et al. 2000). Mobile taxa with life histories that include nonaquatic stages such as amphibians, reptiles, and insects do not correspond as closely as fishes to these unit boundaries, so the relevance of these units to these organisms needs to be evaluated separately. Where these units do not already exist, they can be drafted with guidance from experts on biogeography and available large-scale data on continental drainage patterns, climate, landform, and geology.

Ecological Drainage Units

Ecological drainage units represent regional biodiversity distinctions within aquatic zoogeographic units, and are generally 1,000 to 10,000 km^2. At this scale the interactions between watershed boundaries, landscape features (e.g., landform, geology), and climate influence broad patterns of aquatic ecosystem characteristics such as channel morphology and hydrologic, temperature, and nutrient regimes (Lotspeich 1980; Jensen et al. 2001). These features in turn influence the distribution and composition of freshwater fishes and invertebrates (e.g., Poff 1997; Angermeier & Winston 1999; Rabeni & Doisey 2000). As with aquatic zoogeographic units, EDUs are defined according to drainage boundaries but are not always true watersheds.

Ecological drainage units are delineated and classified by identifying areas with similar biotic patterns. Information on biotic patterns can be found in biogeography texts or derived from multivariate analysis of common species presence/absence data, when those data are available. Biotic data, however, are generally inadequate for conducting statistical analyses; therefore, we generally rely primarily on abiotic patterns when generating EDUs. Ecological drainage units thus conform to patterns of physiography, climate, and freshwater ecosystem connectivity (i.e., the networks formed by freshwater systems, including lakes, wetlands, glaciers, streams, and coastal waters). Ecoregion maps are one source for spatial data on landform, geology, and climate. Sources for North American ecoregions include Wiken (1986); Omernik (1987); McNab and Avers (1994); Keys et al. (1995), and Chapman et al. (2001). Similar maps are available for many countries around the world.

Ecological drainage units can range in size depending on the zoogeographic and physiographic complexity of a region. They are generally created from existing GIS data sets depicting watersheds or aquatic management units, such as the eight-digit hydrologic units delineated by the U.S. Geological Survey (Seaber et al. 1987) or similar units available for other countries. In regions where mapped hydrologic units do not exist, it is usually possible to manually delineate the boundaries of EDUs.

Aquatic Ecological Systems

Aquatic ecological systems are stream and lake networks representing a range of areas with distinct geomorphological patterns tied together by similar environmental processes (e.g., hydrologic, nutrient, and temperature regimes; Groves et al. 2002). Patterns of environmental conditions that determine the characteristics of freshwater ecosystems and influence biotic patterns are used to classify AES. Aquatic ecological system, as the name of a specific type of conservation target that we use as a coarse filter, should not be confused with the more generically and broadly applied term, ecosystems. Aquatic ecological systems are typically classified using available GIS data on stream and lake hydrography, surficial geography, land surface elevation, and other ecologically relevant factors. Sizes of aquatic ecological systems typically range from 100-km^2 headwater stream, lake, and wetland complexes to the largest riverine catchment in an ecoregion.

Freshwater ecosystem attributes such as water-body size, hydrologic and temperature regime, chemistry, drainage network position, local connectivity, elevation, and gradient can result in distinct aquatic assemblages and population dynamics between and within streams and lakes (e.g., Tonn & Magnuson 1982; Osborne & Wiley 1992; Poff & Allan 1995; Lyons 1996; Lewis & Magnuson 1999). Despite regional differences in the importance of specific abiotic variables to ecosystem characteristics and biotic patterns, in most locations some combination of these variables can be derived from existing GIS data at a scale that is relevant for classification. See Table 1 for a description of typical classification attributes.

Table 1. Standard attributes used to classify aquatic ecological systems and macrohabitats.

Variable	*Rationale*	*Typical classes*
Stream gradient	correlated with flow velocity, substrate material, channel unit morphology and in-channel habitat types (e.g., pools, riffles, plunge pools) (e.g., Rosgen 1994)	low, medium, high, and very high
Stream and lake elevation	influences climate and vegetation patterns, which in turn affect nutrient inputs and hydrologic and temperature patterns	foothills, montane, alpine
Stream size	measured as drainage area, stream link, or stream order, size is a correlate for channel morphology, types and ratios of habitats, habitat stability, and flow volume (e.g., Vannote et al. 1980; Mathews 1998)	headwater/creek, small river, medium river, large river; small, medium, large lakes
Stream local connectivity/drainage network position	measured as the type and size of macrohabitat immediately upstream and downstream; downstream connectivity captures local zoogeographic variation by considering differences in the species pool in downstream habitats; upstream connectivity captures effects from upstream segments on hydrologic regime and chemistry; both types of connectivity can influence refugia during different seasons or extreme climatic periods, or both (e.g., Tonn & Magnusson 1982; Osborne & Wiley 1992; Riera et al. 2000).	upstream and downstream connectivity to various size classes of lakes or streams (e.g., headwater, small, medium, large streams, large rivers, coastlines, glaciers, or unconnected)
Stream and lake geology (catchment and local)	incorporates the influence of geology on multiple ecosystem attributes; geology influences the sources of water (groundwater/surface water), temperature, chemistry, geomorphology, substrate and hydrologic regime characteristics of streams and lakes (Winter 1977; Lotspeich 1980; Cupp 1989 Montgomery & Buffington 1993; Ries 1994; Maxwell et al. 1995; Seelbach et al. 1997; Jensen et al. 2001; Winter 2001)	porous, nonalkaline bedrock (e.g., granitic, basaltic, shale, volcanic); nonporous, nonalkaline bedrock (sedimentary sandstone); porous, calcareous bedrock (e.g., sedimentary limestone, dolomite); coarse, porous, nonalkaline glacial and riverine deposits (e.g., alluvium, ice contact, colluvium, coarse moraine); low permeability, neutral-acidic surficial deposits (peat and muck, lake plain, fine glacial deposits)
Stream hydrologic regime	hydrologic patterns constrained first by climate; within climatic regions, hydrologic regime is influenced by catchment area, drainage density, surficial geology, bedrock geology, and elevational relief, which control relative surface and groundwater contributions to streams and lakes (Winter 1977; Jensen et al. 2001; Winter 2001); stream gage data can also be used to create empirical models of hydrologic regime based on these factors (Ries 1994); presence or absence of glaciers, wetlands, or lakes can define distinctions in hydrology and temperature and sediment regimes	groundwater dominated, mixed surface water/groundwater, surface water dominated, wetland/lake influenced, glacially influenced
Lake size	lake size often correlates with lake depth, stability, thermal stratification regime, habitat complexity, and species composition and diversity (Busch & Sly 1992; Magnuson et al. 1998)	small, medium, large, very large
Lake drainage network position	describes landscape placement of lakes in relation to connectivity to streams; influences species diversity through connectivity and refugia (Tonn & Magnuson 1982; Riera et al. 2000; Lewis & Magnuson 1999) and degree of riverine hydrologic influence (as with flow-through lakes)	unconnected, headwater lake (outlet only), flow-through lake (inlet and outlet stream number can be classified to further describe drainage network position)
Lake shoreline complexity	corresponds to degree of shoreline habitat diversity (Busch & Sly 1992)	simple (round, elongate), complex, very complex

Bottom-Up Aquatic Ecological System Classification Based on Macrohabitats

In regions with fine-scale, high-quality hydrographic data and digital versions of other relevant data layers, an automated, unsupervised, bottom-up classification approach can be conducted to map AES. Macrohabitats are river valley segments (typically 1–10 km in length) and small- to medium-sized lakes or lake basins (typically 10–1000 ha) that are relatively homogeneous with respect to the abiotic factors that shape freshwater system structure and functions and influence the distribution of biota. We based our approach to classifying and mapping macrohabitats on work by Cupp (1989), Busch and Sly (1992), and Seelbach et al. (1997). Macrohabitats can be used to represent the diversity of environmental settings within a watershed.

The classification is implemented by mapping relevant classification attributes onto the stream arcs and lake polygons in the hydrographic data with a set of automated GIS tools created specifically for this purpose. The Nature Conservancy's Freshwater Initiative Web site describes the technical details of the GIS processing and the requirements that hydrographic data must satisfy for the tools to work (TNC-FWI 2000). The GIS tools can be used with a variety of data sets, including, but not limited to, the Environmental Protection Agency's (EPA) Reach File data (1994), the National Hydrography Dataset (EPA & USGS 2000), and British Columbia's Watershed Atlas (BC Fisheries 1996). Additional data sets usually used in macrohabitat processing are digital elevation models and coverages of surficial geology.

Once the raw classification attributes are developed, the next step is to translate them into ecologically significant classes. For example, raw stream-gradient values calculated for each stream arc are used to create a series of discrete classes (e.g., low, medium, high, or very high gradient). The exact classes for this and other variables are derived through literature review, consultation with experts, and other research to identify the important classes for the area in question. Other variables are classified in a similar manner (Table 1). Lastly, each stream and lake is assigned a macrohabitat type. Each combination of class values constitutes a unique macrohabitat type. So, if streams are being classified according to stream size, gradient, elevation, upstream geology, and local connectivity, each unique combination of the class values for these classification variables is assigned a different macrohabitat type.

The final step is to create the AES, which are generated for a series of size classes that are likely to correspond to important transitions in physical characteristics such as habitat size, stability, and complexity, which in turn affect biotic composition. River and stream sizes can be classified using either stream order or watershed area, and the size classes used for AES are usually identical to the size classes used for macrohabitats. The AES classification is implemented by creating a series of nested watersheds that correspond to these size classes. Each of these watersheds represents an AES and is classified into different system types according to the variety of macrohabitats they contain.

Implementing such a classification over large areas can be facilitated by using a statistical clustering algorithm (e.g., McCune & Mefford 1999) to identify watersheds with similar patterns of macrohabitats. Multivariate analyses are typically viewed as preliminary classifications and should be reviewed and adjusted to better reflect important ecological distinctions.

Top-Down Aquatic Ecological System Classification

Top-down classification is conducted in areas where GIS data are insufficient for conducting a bottom-up classification. Here the macrohabitat classification is omitted, but AES are defined based on similar environmental attributes. Several methods exist to create a top-down classification. In some cases GIS data will exist, but the scale will not be fine enough to classify macrohabitats or of high enough quality to permit automated processing. In other cases, paper maps must be used. The general top-down approach is to assign AES types to groups of streams or lakes (on either digital or paper maps) after considering available information and expert opinion on hydrologic regime, physiography, geomorphology, vegetation, and drainage patterns. Predefined watersheds can also be used as is or aggregated to create AES if fine enough units are nested within the boundaries of the higher levels of the classification. The top-down approach to describing and mapping AES results in more general and qualitative descriptions than the bottom-up approach, but important distinctions among units can still be made based on available information.

Case Studies

Bottom-Up Approach in the Columbia and Willamette River Basins

The Columbia River Basin is a major river basin in western North America, and the Willamette River is a major tributary to the Columbia, covering 31,080 km^2 (Uhrich & Wentz 1999). The Columbia River Basin is composed of glaciated and unglaciated aquatic zoogeographic units (Abell et al. 2000; Fig. 2). We discuss the classification of EDUs in the unglaciated zoogeographic unit and the application of the bottom-up approach to classify AES in one of the two EDUs encompassing the smaller Willamette River Basin. This project was conducted as part of TNC's ecoregional assessment for the Georgian Strait-Puget Trough-Willamette Valley ecoregion. The primary GIS data used

Figure 2. Columbia River Basin, Pacific Northwest, North America, showing the (a) Columbia glaciated aquatic zoogeographic unit, (b) Columbia unglaciated aquatic zoogeographic unit, and (c) the Upper Snake aquatic zoogeographic unit. Within (b) we show the 11 ecological drainage units (1, Lower Columbia; 2, Willamette; 3, Deschutes; 4, John Day–Umatilla; 5, Grand Ronde; 6, Powder–Burnt; 7, Owyhee–Malheur; 8, Weiser–Payette–Boise; 9, Clearwater; 10, Salmon; 11, Bitterroot–Blackfoot).

for this classification were the National Hydrography Dataset (EPA & USGS 2000), geology (Walker & MacLeod 1991), and digital elevation models (USGS 2002*a*).

We classified 11 EDUs in the unglaciated aquatic zoogeographic unit based on patterns of fish zoogeography (Hocutt & Wiley 1986; Maxwell et al. 1995; Abell et al. 2000; NMFS 2002), climate, and physiography (McNab & Avers 1994; Pater et al. 1998; Fig. 2). We defined EDU boundaries by visually aggregating U.S. Geological Survey eight-digit hydrologic units (Seaber et al. 1987) based on similarity in physiography and climate; descriptions of fish zoogeography and multivariate cluster analysis of native fish historical distributions (NatureServe [www.natureserve.org], unpublished data); and patterns of watershed connectivity (i.e., the networks formed by freshwater systems, including lakes, wetlands, streams, and coastal waters).

Based on a literature review (Altman et al. 1997) and discussions with experts, we developed a conceptual model to describe and map five key aspects of freshwater ecosystem variability: geomorphology, hydrologic regime, temperature, chemistry, and local zoogeographic patterns as represented by connectivity to other freshwater features such as lakes, large rivers, and oceans. We represented geomorphology with measurements of water-body size, gradient, and dominant geology, which also influence flow regime and chemistry. Empirical data were used to confirm relationships between ecosystem attributes and modeled variables. For example, more than 60 geological types have been mapped in the Willamette Basin (Walker & MacLeod 1991). We aggregated these into eight geological classes according to patterns of natural stream flow regime by applying guidelines from Quigley and Arbelbide (1997) on geologic influences on stream flow, along with U.S. Geological Survey stream-gage data (Slack & Landwehr 1992). Finally, we identified macrohabitats by combining the classes of the five variables. We defined 624 macrohabitat types across nearly 20,000 km of stream.

We classified AES for the Willamette River EDU with a multivariate hierarchical classification (McCune & Mefford 1999) that grouped watersheds based on macrohabitat membership. Four size classes of AES were defined using the same watershed areas as those used for macrohabitat size classes. These were used to assess macrohabitat diversity and classify ecological systems. An agglomerative cluster analysis based on Sorenson's distance measure and Ward's group linkage method was applied to create draft AES (McCune & Mefford 1999). We determined the final set of AES after expert review and comparisons with units developed by Pater et al. (1998). The expert review evaluated whether units derived through automated, statistical methods corresponded to meaningful ecosystem patterns. More than 600 watersheds were classified into 27 AES types and mapped in a GIS for this single EDU (Table 2, Fig. 3).

As part of the process of ecoregional assessment, we typically identify future research needs that will improve the classification. For the AES and macrohabitat classification in the EDU discussed here, future needs include further development of empirical relationships between ecosystem attributes (e.g., stream temperature) and modeled variables (e.g., elevation and geology), exploration of covariation between variables, and evaluation of relations between physicochemical attributes and biological composition.

Top-Down Approach in the Upper Paraguay River

The Upper Paraguay River Basin covers more than 600,000 km^2, intersecting portions of Brazil, Bolivia, and Paraguay, and represents one of the most aquatically diverse yet threatened watersheds in the world (Olson et al. 1998; Hamilton 1999; Mittermeier et al. 1999). The basin includes the 140,000-km^2 Pantanal, the world's largest floodplain wetland. We developed a freshwater classification for the Upper Paraguay River Basin through a series of workshops with regional experts. The basin is a unique biogeographic unit (Olson et al. 1998) and was used as the aquatic zoogeographic unit. Regional experts

Table 2. Examples of ecological systems from the Willamette River Ecological Drainage Unit.

System size	*Number of types*	*Number of occurrences*	*Example types*	*Example occurrences*
Headwaters/creeks (<100 km^2)	14	509	Cascade Crest headwaters: elevation >1000 m for most of watershed; most slopes > 0.10; volcanic geology dominant; small alpine lakes often present; high flow variability with year-round snow pack	Separation Creek headwaters in the McKenzie Basin
			prairie/foothill tributaries: moderate and lower gradient systems progressing from small "islands" of Columbia basalt formation geology to lakeplain and mainstems; elevation <100 in valley to ~ 300 m on outcrops; connectivity to mainstem important for spawning grounds and floodplain processes	Palmer Creek watershed near the confluence of Yamhill and Willamette rivers
Small rivers (100–1000 km^2)	8	52	coastal range sedimentary rivers: influenced by sedimentary geology, low (0.005–0.020) gradient; mid and low elevations (100–1000 m)	Marys and Long Tom rivers
Medium rivers (1001–10,000 km^2)	4	9	Cascadian volcanic rivers: influenced by volcanic geology, low (0.005–0.020) gradient, progressing from high (~1000 m) to low (<100 m) elevations with confinement decreasing downstream	North and South Santiam rivers
Large rivers (>10,000 km^2)	1	1	main-stem rivers: low (<0.005) gradient, low (<100 m) elevation, influenced by mixed geology	lower Willamette River

developed conceptual models for freshwater ecosystem variability and qualitatively described and mapped EDUs based on data on geology, landform, vegetation, and climate (e.g., Ministériodas Minas e Energia 1982; Bezerra et al. 1996; Hamilton et al. 1996; Programa Nacional de Meio Ambiente 1997; Hamilton 1999; Willink et al. 2000). The Plano de Conservação da Bacia do Alto Paraguai (Programa Nacional de Meio Ambiente [1997]) provided some base data in a GIS at a scale of 1:250,000, predominantly for the Brazilian portion.

We drew distinctions first between those EDUs in the floodplain (i.e., the Pantanal) and those in the upland (headwater) regions. Patterns of timing and duration of the annual flood pulse (which correlates strongly to patterns of fish migrations), and upstream influence from headwaters further distinguished floodplain EDUs. In the uplands region, we based the EDUs on major watershed boundaries; changes in geology, landform, and climate; and expert knowledge of zoogeography. We defined 21 EDUs, 11 in the Pantanal proper and 10 in the surrounding uplands (Table 3, Fig. 4).

Because of limitations in the scale and completeness of GIS data, we conducted a top-down classification to identify AES types. In the upland EDUs, we first distinguished mainstem rivers from tributary systems and then further classified AES types with geologic and physiographic maps and expert knowledge of patterns of stream gradient, chemistry, channel type, seasonal flows, and biological composition. In the floodplain EDUs, stream size, which is often irrelevant because many streams are distributaries and flow only seasonally or are contiguous with other streams during floods, was not a primary classification variable. We classified 102 AES (44 in the Pantanal and 58 in the uplands, Fig. 5) in the Brazilian portion of the Upper Paraguay River Basin. Available data on surrounding vegetation, stream geomorphology, dominant hydrologic regime, and stream chemistry were summarized when possible as attributes (Table 4).

Like the Willamette River Basin, the Upper Paraguay classification approach was driven by expert-informed models of ecological variability. Without the fine-scaled (macrohabitat) information, however, it has lower spatial precision. Also, because extensive areas of the basin were poorly known by experts, AES mapped in the Upper Paraguay River Basin need to be ground truthed for spatial and descriptive accuracy. Data limitations in the Bolivian and Paraguayan portions also need to be addressed to create a comprehensive classification for the basin. Greater accuracy of the spatial data results in higher confidence and better preparation to carry out the next steps in place-based conservation planning and action. Working with existing, coarse-resolution data for regional assessments results in identifying conservation areas that are priorities for further data development.

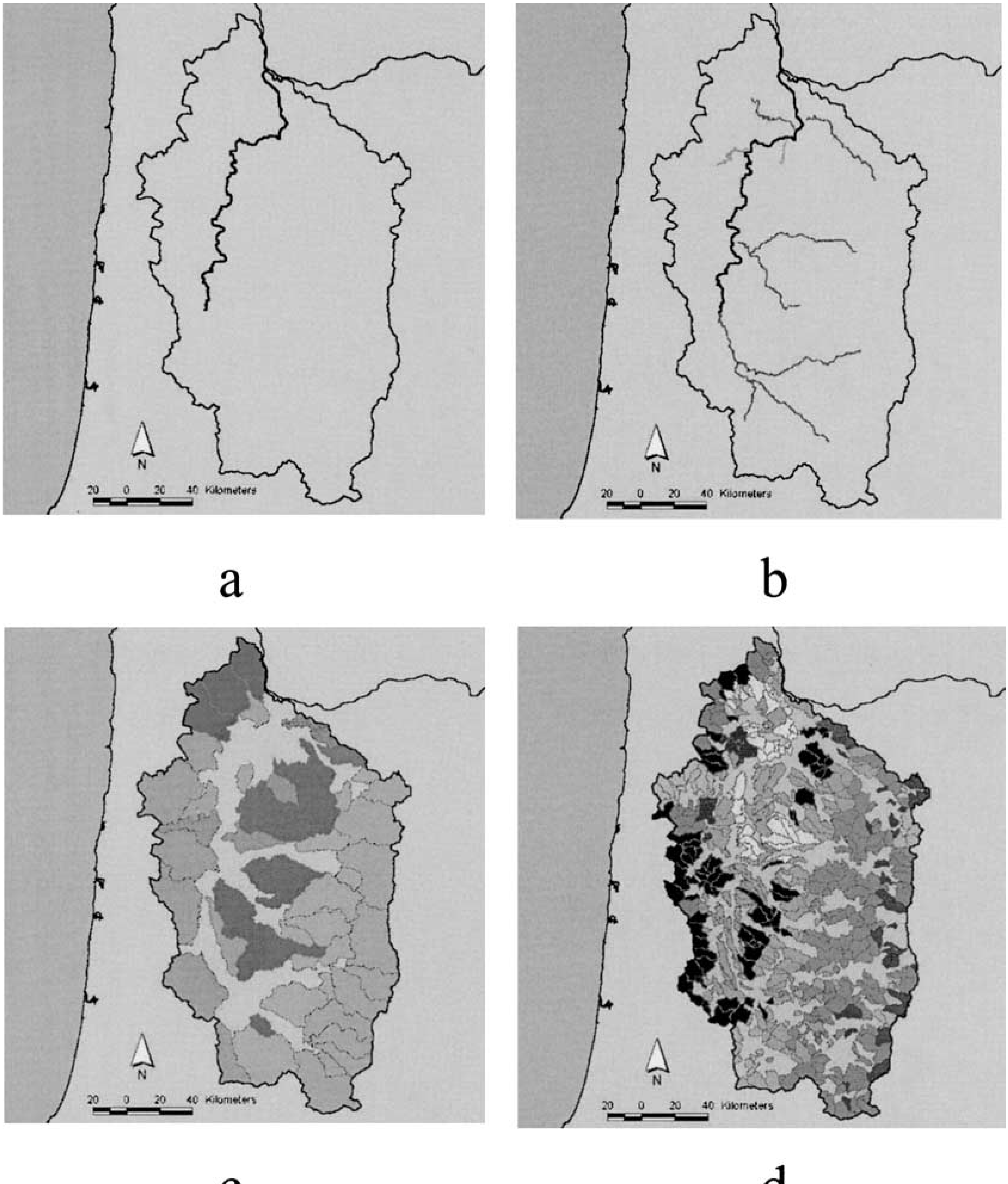

Figure 3. Four different scales of aquatic ecological systems in the Willamette River ecological drainage unit: (a) >10000 km^2 (large rivers); (b) >1000–10,000 km^2 (medium rivers); (c) >100–1,000 km^2 (small rivers); (d) >0–100 km^2 (headwaters and creeks).

Table 3. Examples of ecological drainage units (EDUs) in the upper Paraguay River Basin (data from Hamilton 1999 and Programa Nacional de Meio Ambiente 1997).

EDU (numerical code)	*Soil type/geology*	*Duration of inundation*	*Timing of peak inundation*	*General chemistry*	*Vegetation*	*Freshwater ecosystem types*
Alto Cuiabá (13)	concretionary stony soil, deep loam, deep sand, sandstone	upland, rainy season 3–4 months	upland, high flows, December–February	variable with geologic substrate	semideciduous forests; savanna	steep headwaters; medium sized rivers
Corixo Grande (1)	sand and loam deposits with iron intrusion, marble	3–6 months	March–April	high conductivity during dry season changing to blackwater during floods	park savanna without gallery; dense forest; grassland without gallery forest	permanent and intermittent streams, shallow (<2m) large lakes; disappearing streams/saline springs
Piquiri/São Laurenço (3)	sand and loam with iron intrusion; semi-consolidated sandstones	3–4 months	February	Piquiri mainstem is brown/red with high iron	alluvial forest with emergents; open forest without gallery	mainstem permanent streams; *vazantes*
Taquari Fan (5)	deep alluvial sand	3–4 months	February–March		dense forests with open grasslands	distributary streams, both intermittent and permanent; vazantes
Aquiduana/Negro (8)	loam and silt; un- and semiconsolidated sandstones; detritus	>6 months	February–June	blackwater year-round (acidic)	ecotone; park savanna	undefined mainstem channel in places; *corixos* and *vazantes*

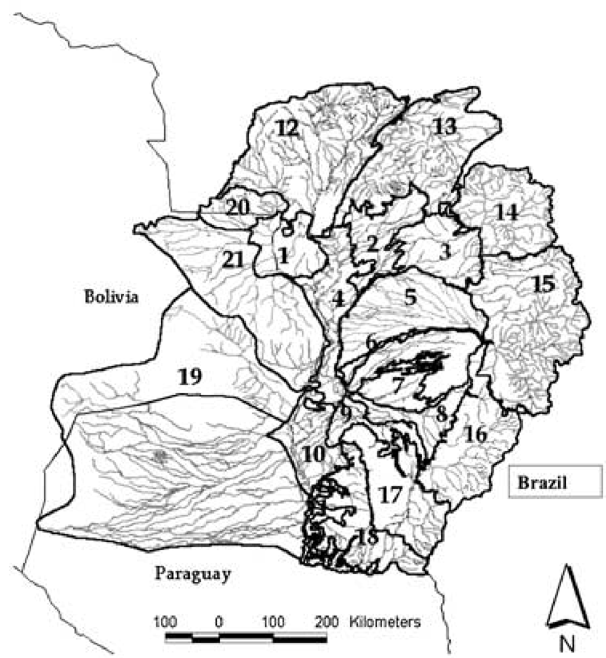

Figure 4. Ecological drainage units (EDUs) of the Upper Paraguay River Basin in Brazil, Paraguay, and Bolivia, South America. There are 21 EDUs shown for the basin. (Adapted from Fig. 10.4, chapter 10 in Groves 2003. Copyright © 2003 Island Press. Reprinted by permission of Island Press, Washington, D.C.).

Discussion and Conclusions

Our classification approach provides a relatively rapid and pragmatic way to organize information on freshwater ecosystems and biodiversity at scales appropriate for ecoregional assessment. The approach creates a spatially comprehensive inventory of mapped and classified units that can be used remotely to identify and differentiate spatial units to characterize regional patterns of aquatic ecosystems. This approach is being adapted by several pilot projects within the U.S. Geological Survey Aquatic Gap Analysis Program. In these projects, GIS data are being used to create hierarchical spatial classification units for characterizing aquatic ecosystem diversity (USGS 2002*b*). This classification framework has been applied to conservation planning efforts in North, Central, and South America. The classification products are the first ever developed for most of these regions and represent a major step forward in defining patterns of freshwater biodiversity.

Without the coarse-filter targets provided by the classification, the known location of rare and endangered species would drive most conservation priorities, which

Figure 5. Aquatic ecological systems (AES) types from a portion of the Alto Cuiabá ecological drainage unit in the upper Paraguay River Basin. Examples of 10 AES types are represented as stream networks. Multiple examples are represented as repeated numbers, stream network classes, or both.

would likely exclude numerous species and ecosystems representative of an ecoregion. This is especially important in regions that lack rare and endangered or endemic species. For example, Weitzell et al. (2003) identified the areas of freshwater biodiversity significance in the upper Mississippi River Basin necessary to represent the full regional aquatic biodiversity. Seventy-four percent of these areas were selected solely to represent coarse-filter ecosystem targets.

The case studies illustrate the flexibility of the classification framework. The bottom-up approach may be preferable because of its greater level of detail and the fact that macrohabitat data are useful for finer scale conservation planning. Flexibility is a key attribute because the classification can be tailored to specific regions. By framing smaller scale patterns of aquatic ecosystems within larger scale physiographic and biogeographic units, our approach identifies and maps attributes that influence the distribution of freshwater biodiversity at multiple scales. This information can be used to identify data gaps, inform sampling strategies, and develop predictive models of species distributions (e.g., Frissell et al. 2001; Sowa et al. 2001). The top-down approach lacks information on fine-scale patterns but is more quickly and easily developed for regional planning needs and can provide the same scale and diversity of classification units as the bottom-up approach.

The zoogeographic data used to define attributes, classes, and units is based mostly on fish species. There is evidence that the variables we use are relevant for other aquatic species, so it is likely that the classification is also providing useful information about these species. This uncertainty in the classification as it pertains to species other than fish needs to be accounted for when using our framework and when conducting future research to further develop the classification.

We do not claim that the classification units by themselves will predict biotic composition. The central hypothesis supporting the classification's use is that it will allow conservation planners to develop plans that more efficiently identify the areas within a planning region that comprehensively capture common and representative biota across environmental gradients than do plans that do not use such coarse-filter targets. A test for how comprehensively our method represents aquatic biodiversity and environmental variability should include an evaluation of a portfolio of conservation areas that results from using only species targets against one that results from using both species targets and aquatic system targets. MacNally et al. (2002) and Su et al. (2004) offer approaches for evaluating taxonomic coherence and congruence within and among classes of units. Variance partitioning can be used to evaluate the hierarchical, species-environment relationships of the tiered classification structure (Cushman & McGarigal 2002).

The classification products are first steps toward capturing common and representative biota across environmental gradients. Although we believe that implementing the classification is essential to initiating conservation planning in the face of imminent threats to biodiversity, our classification products may not be appropriate for all purposes. The classification framework produces an initial comprehensive coverage of ecological units, but it clearly remains vulnerable to the type, resolution, and overall quality of available spatial data. Experience thus far suggests that errors in the classification could be substantially reduced with improvements to existing hydrography and surficial geology data (in terms of increased spatial resolution and refined geology classes).

Accuracy will increase with additional data collection, tests of the classification framework, and improved GIS data and methods. Our current classification approach provides a means for assessing gaps in data availability and thus for organizing biotic sampling and assessing biotic integrity. As biotic data become more comprehensive, tests of the framework need to be conducted to help refine the approach. Biological data and subsequent inventory can provide information on the species composition of these coarse-filter targets to further inform conservation planning and to better integrate biotic attributes into classification units in the future. Hence, producing initial classifications for ecoregions is an essential component of a larger process of conservation planning and research that is necessary to conserve the freshwater biodiversity of the Earth.

Table 4. Sample descriptions of aquatic ecological systems in the Alto Cuiabá Ecological Drainage Unit.

Ecological system	*Location*	*Size*	*Gradient*	*Geology/soils*	*Hydrologic regime*
Confined streams with waterfalls	headwaters of the Rio Cuiabá	small	steep (1.6 m/km)	adamantine and calcareous soils; sedimentary rocks with high erodibility; high conductivity (200 μS/cm), high alkalinity, low nutrient concentration, maximum turbidity; 50 ntu, circumneutral pH	flood from December to February; torrential at times; gallery forests inundated
Confined streams with waterfalls	headwaters of the Rio Casca	small	moderate (~1 m/km)	substratum from Bauru geological group, prevailing fragile sandy soils, high permeability	flood from December to February; torrential at times; gallery forests inundated
Moderate-sized rivers	Rio Manso, extending to the confluence with the Rio Cuiaba	medium	moderate (1.1m/km)	Cuiabá geological group, low conductivity and low alkalinity; slightly acidic pH, medium sinuosity with sediment deposition	flood from December to February, remaining sometimes until March; outflow 550 m^3/s

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