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A GAP ANALYSIS AND COMPREHENSIVE CONSERVATION STRATEGY FOR RIVERINE ECOSYSTEMS OF MISSOURI

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Abstract. North America harbors an astounding proportion of the world's freshwater species, but it is facing a freshwater biodiversity crisis. A first step to slowing the loss of biodiversity involves identifying gaps in existing efforts to conserve biodiversity and prioritizing opportunities to fill these gaps. In this monograph we detail two separate, but complementary, conservation planning efforts—a Gap Analysis (GAP) and a State Wildlife Action Plan (WAP)—for Missouri that address this first step. The goal of the Missouri Aquatic GAP Project was to identify riverine ecosystems, habitats, and species not adequately represented (i.e., gaps) within existing conservation lands. The goal of the freshwater component of the Missouri Wildlife Action Plan was to identify and map a set of conservation-opportunity areas (COAs) that holistically represent all riverine ecosystems, habitats, and species in Missouri. Since conservation planning is a geographical exercise, both efforts utilized geographic information systems (GIS). Four principal GIS data sets were used in each planning effort: (1) a hierarchical riverine ecosystem classification, (2) predicted species distributions, (3) public ownership/stewardship, and (4) a human-threat index. Results of the gap analyses are not encouraging. Forty five, mostly rare, threatened, or endangered, species are not represented in lands set aside for conserving biodiversity. Results also illustrate the fragmented nature of conservation lands, which are mainly situated in the uplands and fail to provide connectivity among riverine habitats. Furthermore, many conservation lands are severely threatened by an array of human disturbances. In contrast, results of the WAP provide hope that relatively intact riverine ecosystems still exist. A total of 158 COAs, representing ~6% of the total kilometers of stream in Missouri, were selected for the WAP. This illustrates that a wide spectrum of biodiversity can be represented within a small portion of the total resource base, but the area of conservation concern is often much larger. Identifying priority riverscapes for conservation is an important first step toward effective biodiversity conservation. Yet, achieving the ultimate goal of conserving biodiversity will require vigilance on the part of all responsible parties, with particular attention to addressing and coordinating the many remaining logistical tasks.

Key words: aquatic ecological classification; conservation planning; crayfish; fish; freshwater biodiversity; gap analysis; human-threat index; Missouri (USA) aquatic gap-analysis project; mussels; predicted species distributions; public stewardship mapping; riverine ecosystem protection; wildlife action plan.

Introduction

While only about 0.01% of the total volume of water on Earth occurs in rivers and lakes, anywhere from 25% (Stiassny 1996) to >50% (Abramovitz 1996) of the global vertebrate diversity is concentrated into this tiny fraction of the biosphere, with the vast majority of this diversity occurring within and along riverine ecosystems. Unfortunately, most conservation lands in the United States are situated in the uplands, away from these ribbons of extraordinary biological diversity, since lands adjacent to rivers tend to be the most easily developed, with high economic value for housing, agriculture, or other human uses (Scott et al. 2001).

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Freshwater ecosystems in the United States harbor a large proportion of the world's freshwater species. Ten percent of all the freshwater fish species, 30% of all the freshwater mussels, and 61% of all the freshwater crayfish that have been described worldwide occur in the United States (Page and Burr 1991, Williams et al. 1993, Warren and Burr 1994, Taylor et al. 1996, Master et al. 1998). Even more impressive statistics have been reported for other freshwater taxa (e.g., stoneflies, dragonflies, mayflies; Master et al. 1998). It is apparent that the United States is a global "hot spot" for freshwater biodiversity, especially when comparisons are restricted to temperate regions.

Despite these impressive statistics, North America is facing a freshwater biodiversity crisis. In the last one hundred years 123 freshwater animals have gone extinct in North America (Ricciardi and Rasmussen 1999). In the United States alone, 71% of freshwater mussels, 51%

of freshwater crayfish, and 37% of freshwater fish are currently considered vulnerable to extinction (Williams et al. 1993, Warren and Burr 1994, Taylor et al. 1996, Master et al. 1998). Perhaps even more alarming are predictions by Riccardi and Rasmussen (1999) who, by using extinction records and an exponential decay model, found extinction rates of freshwater fauna in North America to be 5 times higher than those of terrestrial fauna. In addition, assuming imperiled freshwater species would not survive throughout the 21st century, their model projects a future extinction rate of 4% per decade, which is comparable to estimates for tropical rain forests.

While much attention has been focused on global losses of terrestrial biodiversity especially in tropical ecosystems, comparatively little attention has been given to the alarming declines in freshwater biodiversity (Allendorf 1988, Benke 1990, Hughes and Noss 1992, Allan and Flecker 1993, Stiassny 1996, Vreugdenhil et al. 2003). Only within the last decade has more attention been focused on conserving freshwater biodiversity (Blockstein 1992, Allan and Flecker 1993, Stiassny 1996, Ricciardi and Rasmussen 1999, Abell et al. 2000, Revenga et al. 2000, Higgins 2003). Much of this attention has focused on outlining the severity of the problem, likely causes for declines, and providing general recommendations for curbing these losses. Yet, as Moyle and Yoshiyama (1994) noted, a critical first step to slowing these losses involves identifying gaps in existing efforts to conserve freshwater biodiversity across the landscape and prioritizing opportunities to fill these gaps. In this monograph we detail two complementary conservation planning efforts—Gap Analysis and a State Wildlife Action Plan—for Missouri that heed the recommendations of Moyle and Yoshiyama (1994).

Gap analysis

The U.S. Geological Survey's National Gap Analysis Program (GAP) was initiated in 1988 to provide a coarse-filter approach for identifying biodiversity conservation needs. It seeks to identify species, habitats, and ecosystems not adequately represented within biodiversity management areas (i.e., gaps), which may be filled through establishment of new protected areas or changes in land-management practices (Scott et al. 1993). To accomplish this spatially oriented task, GAP utilizes remote sensing and geographic information system (GIS) technologies. Gap analysis is a technically efficient version of the well-established method of identifying gaps in the representation of biodiversity within protected areas (Scott et al. 1987, 1989, 1991, Burley 1988, Davis et al. 1990). This approach to conservation evaluation has been widely used in Australia (Specht 1975, Bolton and Specht 1983, Pressey and Nicholls 1991).

While GAP has made major strides in devising coarse-filter conservation assessments for terrestrial ecosystems, much less has been accomplished for aquatic ecosystems. The program's initial focus on terrestrial vertebrates and vegetation types was a choice based on what was achievable at the time (Jennings 1999). In principle, GAP is committed to developing coarse-filter assessment strategies for all major ecosystem types (Jennings 1999).

GAP initiated development of an aquatic component of the program in 1995 with a pilot project in the upper Allegheny River Basin in Western New York (USA), which was completed in 1999 (Meixler and Bain 1999). In 1997, in cooperation with the Missouri Resource Assessment Partnership (MoRAP) and financial assistance by the USGS National Water Quality Assessment Program, the U.S. Department of Defense, and the Missouri Department of Conservation, GAP initiated a statewide pilot project for Missouri. Both of these projects focused on riverine ecosystems. Since 2000, several other regional and state projects have been initiated across the United States. Information on these various aquatic projects can be obtained online.[2] Many of these projects also focus on riverine ecosystems. However, the program has also been expanded to develop methods for both freshwater and marine coastal ecosystems. The first part of this monograph summarizes the methods, results, and conclusions of the Missouri aquatic GAP pilot project.

State Wildlife Action Plans

In fall 2001, federal legislation established the State Wildlife Grants (SWG) program, which provides funds to state wildlife agencies for conservation (Public Law 107-63).[3]

The objective of the SWG program, which is administered by the U.S. Fish and Wildlife Service, is to develop and implement programs for the benefit of wildlife and their habitat, including species that are not hunted or fished. Agencies responsible for managing fish and wildlife resources in each state and U.S. territory are eligible to receive SWG funds. Annual appropriations for the SWG have averaged $68 million dollars through fiscal year (FY) 2006 (1 October 2005–30 September 2006), with Missouri receiving an average of $1.2 million. In order to continue receiving SWG funds, Congress charged each state and territory with developing statewide Wildlife Action Plans (WAPs). The purpose of these WAPs is to provide a strategic plan for the holistic conservation of all wildlife species and their habitats. The first WAPs were due in October 2005. The second part of this monograph covers those methods and results of the Missouri WAP that pertain to the conservation of freshwater biodiversity. We included this section to illustrate that data developed for an aquatic GAP project are not only useful for identifying gaps in biodiversity conservation efforts, but also for

[2] ⟨http://www.gap.uidaho.edu/projects/aquatic/default.htm⟩

[3] Department of the Interior and Related Agencies Appropriations Act of 2002.

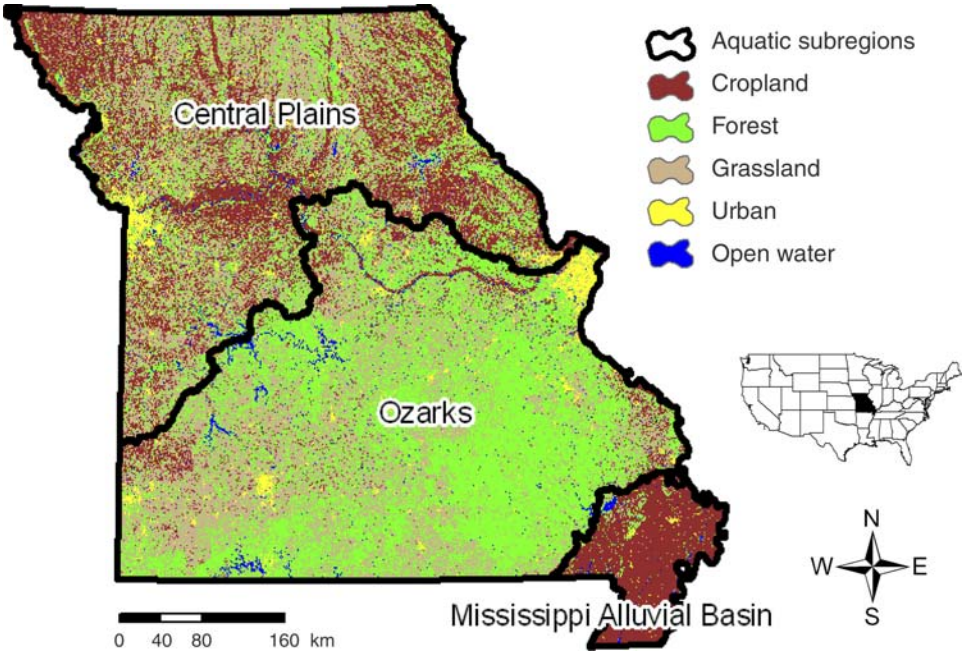

FIG. 1. Map of Missouri (USA) showing current land cover ca. 2003 (MoRAP 2005) and the three aquatic subregions that account for major differences in instream habitat and freshwater assemblages across the state.

developing strategic plans for conserving biodiversity (i.e., filling the gaps).

STUDY AREA

Missouri is a physiographically diverse state situated in the east-central United States. Two great rivers, the Mississippi, forming the eastern border, and the Missouri, forming the northwestern border and cutting an east–west path across the state to meet the Mississippi, give the state a unique identity. The Missouri River roughly follows the southern boundary of Pleistocene glacial advances.

Missouri has a humid continental climate with an average annual temperature of 13°C. Average annual temperatures are lowest in the northwest (11°C) part of the state and highest in the southeast (15°C). Average annual precipitation is 97 cm, of which 71 cm are lost to evaporation (Vandike 1995). Annual precipitation is lowest in the northwest (89 cm) and highest in the southeast (122 cm). Runoff ranges from 13 cm in the northwest to 51 cm in the southeast (Vandike 1995).

A total of 364 native freshwater animal species and subspecies (32 crayfishes, 56 snails, 65 mussels, and 211 fishes) have been collected within Missouri. Only a handful of states in the Southeastern United States contain a higher number of freshwater species. This rich diversity is primarily the result of three factors operating over both contemporary and evolutionary timeframes. First, the physiographic diversity of the state provides the template for an amazing array of stream habitats. Second, all of the state's freshwater ecosystems are part of the Missouri and Mississippi River Basins, which were two principal refugia for freshwater organisms during Pleistocene glaciation (Matthews 1998). Third, the Ozark Highlands, which contains most of the states freshwater biodiversity, is a very old unglaciated landscape with many isolated drainages that have promoted and allowed divergent evolutionary processes to proceed for millions of years (Pflieger 1971, 1996).

Three distinct Aquatic subregions are generally recognized in Missouri: Central Plains, Ozarks, and Mississippi Alluvial Basin (Fig. 1) (Pflieger 1971, 1989, Sowa et al. 2005). Boundaries of these subregions follow major drainage divides that generally correspond with abrupt transitions in geology, landform, soils, land cover, and groundwater influences. The distinct physiographic character of these three subregions is reflected in their relatively distinct stream habitats and freshwater assemblages.

Central Plains

Physiography of the Central Plains is strongly influenced by Pleistocene glaciation. Thick glacial loess and till deposits overlay the Mississippian and Pennsylvanian shales, sandstones, and limestones, of the subregion. Landscapes of the Central Plains are mainly flat to gently sloping with an average land slope of 5% and local relief from 5 to 60 m. Average stream gradients are 10.3 m/km for headwaters, 2.3 m/km for creeks, 0.7 m/km for small rivers, and 0.3 m/km for large rivers. Streams generally occupy broad valleys and grade gradually into uplands (Nigh and Schroeder 2002). Streambeds are generally fine silts and sands and the water is frequently turbid. Historically, headwater

streams tended to have well-defined pools and riffles, while further downstream pools were long and riffles were short or absent (Rabeni 1996).

Few springs exist in the subregion and base flows are generally quite low. Smaller streams are often intermittent or ephemeral. Low dissolved-oxygen concentrations are common throughout the subregion and have helped shape the riverine biota characteristic to this subregion (Smale and Rabeni 1995*a*, *b*). Nearly all native grasslands have been converted to cropland or pastureland and riparian forests have been largely removed (Fig. 1). Many streams have also been channelized. Streams are probably more turbid, tend to have lower dissolved oxygen concentrations, have less predictable base flows, and have wider temperature fluctuations than in pre-European settlement times (Rabeni 1996).

Ozarks

The Ozarks is an uplifted and unglaciated region that is one of the oldest regions of the world. It has been a land surface since the end of the Paleozoic Era (Steyermark 1959). The subregion generally consists of older bedrocks, higher elevations, and greater local relief than the other subregions. A core of igneous rocks is surrounded by Paleozoic Era sedimentary rocks. Topography ranges from very flat to very rugged with an average land slope of 9% and local relief >90 m common. The subregion consists of thin stony and cherty residual soils with little or no loess deposits (Thom and Wilson 1980). Presettlement vegetation generally consisted of deciduous pine–oak and pine forests, with some glades, prairie, and savanna (Nigh and Schroeder 2002). Bottomlands were typically deciduous forest.

Many streams are spring fed and carry little suspended sediment except during periods of high runoff. Smaller streams tend to be relatively high gradient, with an average of 17.3 m/km for headwaters and 4 m/km for creeks. Headwaters are characterized by well-defined riffles and short pools over gravel, cobble, or bedrock substrates, whereas creeks have riffles over gravel or cobble and pools with sand and silt overlying larger substrates (Pflieger 1989). Gradients for streams classified as small river average 1.2 m/km, while those classified as large river average 0.5 m/km. Small rivers are characterized by deep pools with silty substrates and riffles composed of gravel and cobble (Pflieger 1989, Femmer 1997). Large rivers are characterized by long pools and deep chutes along with backwaters and cutoffs (Pflieger 1989, Panfil and Jacobson 2001). Pools tend to have sand and silt bottoms, while swifter areas maintain gravel and cobble substrates. Permeable dolomite and limestone bedrock allow for the formation of karst that supports numerous springs in many parts of the subregion, and these springs account for the relatively stable base flows and spatially heterogeneous thermal conditions of this subregion. In general, Ozark streams are less impacted by gross physical alterations such as agriculture and channelization vs. the other aquatic subregions in Missouri, and land cover is mainly in a semi-natural state (<10% urban plus cropland) (Fig. 1). Yet, some of the poorest water quality in the state can be found in the Ozarks in areas downstream from urban development in the St. Louis area, and stream segments downstream from lead mines sometimes have extensive areas with substrates derived from mine tailings (Cieslewicz 2004).

Mississippi Alluvial Basin

The Mississippi Alluvial Basin (MAB) represents the northern extension of the broad valley of the Mississippi Embayment. The MAB is a nearly flat plain with natural levees and meander scars except for Crowley's ridge, which is a narrow band of hills formed as an erosional remnant. Bedrock is an unimportant feature of MAB landscape except within Crowley's Ridge. The MAB is underlain by Cretaceous and Tertiary deposits of clay, sand, and gravel that range from <1 m to >820 m in thickness (Grohskopf 1955). These older sediments are buried under a layer of alluvium deposited by the St. Francis, Mississippi, and Ohio rivers during Pleistocene and recent times (Pflieger 1971).

Historically the MAB was one of the most heavily timbered regions of Missouri (Pflieger 1971). Site conditions ranged from permanently flooded areas supporting only emergent or floating aquatic vegetation, to cypress swamps, to high-elevation sites supporting complex hardwood forests (Brown et al. 1999). Almost 95% (excluding Crowley's Ridge) of this subregion has been drained and converted to farmland (Nigh and Schroeder 2002; Fig. 1). Average annual runoff ranges from 46 to 51 cm, which is the highest in the state. However, the nearly flat topography results in low runoff rates, and the sand and gravel alluvial deposits that overlie the relatively impermeable clayey subsoils make excellent shallow aquifers (Pflieger 1971). These two factors contribute to the relatively stable hydrographs and high base-flow potential of streams and ditches within the MAB. Springs are relatively scarce except along the toeslope of Crowley's Ridge.

The ditches and few remaining natural streams in the MAB vary substantially in terms of discharge, turbidity, current, substrates, aquatic vegetation, and shading by riparian vegetation (Pflieger 1971). Smaller ditches are most variable in character, but generally have higher water clarity than larger ditches. Some have no perceptible current during base flow with bottoms comprised mainly of silt while others are fairly swift and have bottoms mostly comprised of sand and small gravel (Pflieger 1989). Channels with clear water and little riparian shading are generally choked with submergent vegetation. The largest ditches are extremely wide and shallow with considerable current throughout. Channel gradients are significantly lower than the other two subregions. Despite these low stream gradients headcutting and rill and gully erosion are substantial

problems upstream from channelized sections (Boone 2001).

An Overview of Biodiversity Conservation Planning

In order to adequately assess gaps in biodiversity conservation you must first identify what constitutes a "gap," and the only way to do this is to develop criteria for what constitutes "effective" conservation. These very criteria are established in the conservation planning process. Consequently, before discussing the principal geospatial data layers we developed for the two conservation-planning efforts covered in this monograph, we believe it is necessary to provide an overview of conservation planning. This overview provides the context to more clearly illustrate why we developed each geospatial data layer and provides a common language that allows a more succinct and clear description of the two conservation planning efforts. Margules and Pressey (2000), Groves (2003), and Noss (2004) all provide excellent overviews of conservation planning and we essentially cover the most basic elements discussed by these authors in our review of the topic.

The first step in conservation planning involves establishing an overall goal describing the ultimate purpose of the planning effort. Goals pertaining to biodiversity conservation have been variously described, but most reflect the need to conserve the native species, habitats, and ecological processes of the region of interest (Groves 2003). Once an overall goal has been established, the fundamental principles, theories, and assumptions that must be considered in order to achieve this goal must be identified. These generally pertain to basic ecological or conservation principles and theories that provide the foundation for the conservation strategy that will be used for achieving the overall goal. For example, it is widely recognized that biodiversity can be described and thus should be conserved at multiple levels of organization (e.g., genotypes to ecosystems) (Whittaker 1962, 1972, Franklin 1993, Noss 1994, Angermeier and Schlosser 1995, Jennings 1996, Leslie et al. 1996, Grossman et al. 1998, Olson and Dinerstein 1998, Abell et al. 2000).

Because conservation planning is a geographical exercise, the next step in the process requires selecting a suitable geographic framework. This involves selecting, defining, and mapping planning regions and assessment units. A *planning region* refers to the area for which the conservation plan will be developed and defines the spatial extent of the planning effort(s). *Assessment units* are geographic subunits of the planning region. These units define the spatial grain of analysis and represent those units among which relative comparisons will be made in order to select specific geographic locations as priorities for conservation. Since biodiversity does not follow sociopolitical boundaries or regular grids, planning regions and assessment units should be based on ecologically defined boundaries as these boundaries provide a more appropriate and informative ecological context (Bailey 1995, Omernik 1995, Leslie et al. 1996, Higgins 2003).

Because it is impossible to directly measure or map all facets of biodiversity, surrogate targets for conservation must be identified and mapped (Margules and Pressey 2000, Groves et al. 2002, Brooks et al. 2004, Noss 2004, Pressey 2004). For the terrestrial component of GAP (gap analysis) these surrogates usually include plant communities or vegetation types and vertebrate species (Scott et al. 1991). It is assumed that measures to conserve these surrogates will also conserve unmapped or unmappable elements of biodiversity. Because different targets often lead to different answers on which locations should be a priority for conservation, it is generally more effective to use a variety of targets (Kirpatrick and Brown 1994, Noss 2004, Diamond et al. 2005). Also, because biological survey data are often incomplete, biased, or lacking, abiotic surrogates (e.g., ecosystems, landscapes, or habitats), are often considered as targets (Belbin 1993, Nicholls et al. 1998, Noss et al. 2002, Roux et al. 2002, Chadderton et al. 2004, Higgins et al. 2004, Noss 2004, Pressey 2004, Thieme et al. 2005).

Once planning regions, assessment units, and conservation targets have been identified and mapped, a conservation strategy for selecting priority areas within the planning region must be established. This strategy is built around the fundamental principles, theories, and assumptions that deal with issues such as: How many occurrences of each target should be captured? How much area or length should be captured? Is connectivity essential? Unfortunately, for most of these and other pertinent questions there are no detailed guidelines. Even when there is some guidance (e.g., biogeography theory, population viability analysis, or metapopulation theory) the data needed for these more detailed evaluations are usually lacking (Grumbine 1990, Margules and Pressey 2000, Groves 2003). Expert opinion will therefore often play a major role in developing the conservation plan. In addition to establishing a general conservation strategy, quantitative and/or qualitative assessment criteria that will be used to make relative comparisons among assessment units must also be established. These criteria include measures of relative significance or irreplaceability, condition, future threats, costs, and opportunities, which guide the selection of one particular assessment unit over another (Groves 2003).

After addressing the issues discussed above, the next step involves selecting priority locations within the planning region(s). Since conservation planning is a geographical exercise, it is no surprise that GIS is an invaluable tool to the actual planning process. However, because not all essential data are in a geospatial format and because much of the data that are available often lack important contextual information, expert knowledge must be incorporated into the planning process. The GIS data provide a more objective, spatially

explicit, and comprehensive view of the planning region, while experts provide additional and more detailed information for certain locations. Conservation planning is also a logistical exercise, and once priority areas have been identified, much work remains to be done. The questions of Who? What? How? and When? must all be addressed. Questions such as: Who is responsible for the management of each priority location? What are the principal threats and critical ecosystem processes? How are you going to eliminate or minimize threats? When should conservation actions be taken—immediately or is there time? Not addressing these important questions could lead to failure in efforts to conserve biodiversity (Margules and Pressey 2000). Once these logistical questions have been addressed, then on-the-ground conservation actions can be taken. However, since conservation efforts cannot be initiated immediately within all priority locations, additional priorities must be established among the selected localities in order to develop a schedule of conservation action (Margules and Pressey 2000). Monitoring programs should also be established to ensure conservation efforts are successful and to signal when, and possibly how, management actions should be modified. Because of the complexity and dynamic nature of ecosystems, adaptive management will be a key to long-term conservation of biodiversity (Leslie et al. 1996).

Methods and Rationale for Primary Geospatial Data Sets

Four primary geospatial data sets were used in both the gap analysis (GAP) and the development of the State Wildlife Action Plan (WAP). Methods for developing these data sets, described below, are extremely complex. We provide enough detail to give readers sufficient understanding of how each data set was created. Detailed methods are provided in Sowa et al. (2005).

Hierarchical classification of riverine ecosystems

To be successful in conserving biodiversity it is necessary to demonstrate the extent of the problem and thus the need for new conservation policies and actions (Orians 1993, Angermeier and Schlosser 1995). Demonstrating this need requires a systematic accounting of the various elements of biodiversity, not just species, but also the ecosystems and habitats that sustain these species. As Angermeier and Schlosser (1995) point out, only then will we be able to answer fundamental questions, such as: How many types of ecosystems/habitats exist? How many of each type remain? Where are they? Which ones are most disturbed or threatened? Failure to answer these questions will relegate the conservation of biodiversity to haphazard preservation of fragments of disintegrating systems (Angermeier and Schlosser 1995). Following this logic, a key objective of our project was to classify and map distinct riverine ecosystems (often termed "ecological units") and habitats at multiple levels.

While classifying the natural world into discrete units places somewhat arbitrary boundaries on a continuum of change (Whittaker 1962, Grossman et al. 1998), it is required because it is impossible to generate an inventory for a continuum, since every value is unique (Lotspeich and Platts 1982). However, before distinct riverine ecosystems could be classified and mapped, the question of "What factors make an ecosystem distinct?" had to be answered. Ecosystems can be distinct with regard to their structure, function, or composition (Noss 1990). *Structural features* in riverine ecosystems include factors such as depth, velocity, substrate, or the presence and relative abundance of local habitat types. *Functional properties* include flow regime, thermal regime, sediment budgets, energy sources, and energy budgets. *Composition* can refer to either abiotic (e.g., habitat types) or biotic factors (e.g., species). While both are important, our focus here will be on biological composition, which can be further subdivided into *ecological composition* (e.g., physiological tolerances, reproductive strategies, foraging strategies, etc.) or *taxonomic composition* (e.g., distinct species or phylogenies) (Angermeier and Schlosser 1995). Geographic variation in ecological composition is generally closely associated with geographic variation in ecosystem structure and function. For instance, fish species found in streams draining the Central Plains of northern Missouri generally have greater physiological tolerances for low dissolved-oxygen levels and high temperatures than do species restricted to the Ozarks, which corresponds with the historical and contemporary prevalence of such conditions within the Central Plains (Pflieger 1971, Matthews 1987, Smale and Rabeni 1995*a*, *b*). Differences in taxonomic composition, not related to differences in ecological composition, are typically the result of differences in evolutionary history between locations (Mayr 1963)—for instance, differences among biological assemblages found on adjacent islands despite the physiographic similarity of the islands.

Considering the above, our more specific objective was to identify and map *riverine ecosystems* (i.e., an ecological community together with its environment, functioning as a unit) that are relatively distinct with regard to ecosystem structure, function, and evolutionary history at multiple levels. To accomplish this, an eight-level classification hierarchy was developed in cooperation with personnel from The Nature Conservancy's Freshwater Initiative (Higgins 2003, Higgins et al. 2005) (Appendix A; Fig. 2). Levels within the hierarchy were either empirically delineated using biological data or delineated in a top-down fashion using landscape and stream features (e.g., drainage boundaries, geology, soils, landform, stream size, gradient, etc.) that have consistently been shown to be associated with or ultimately control structural, functional, and compositional variation in riverine ecosystems (Hynes 1975, Dunne and Leopold 1978, Matthews 1998). More specifically, levels 1–3 and 5 primarily

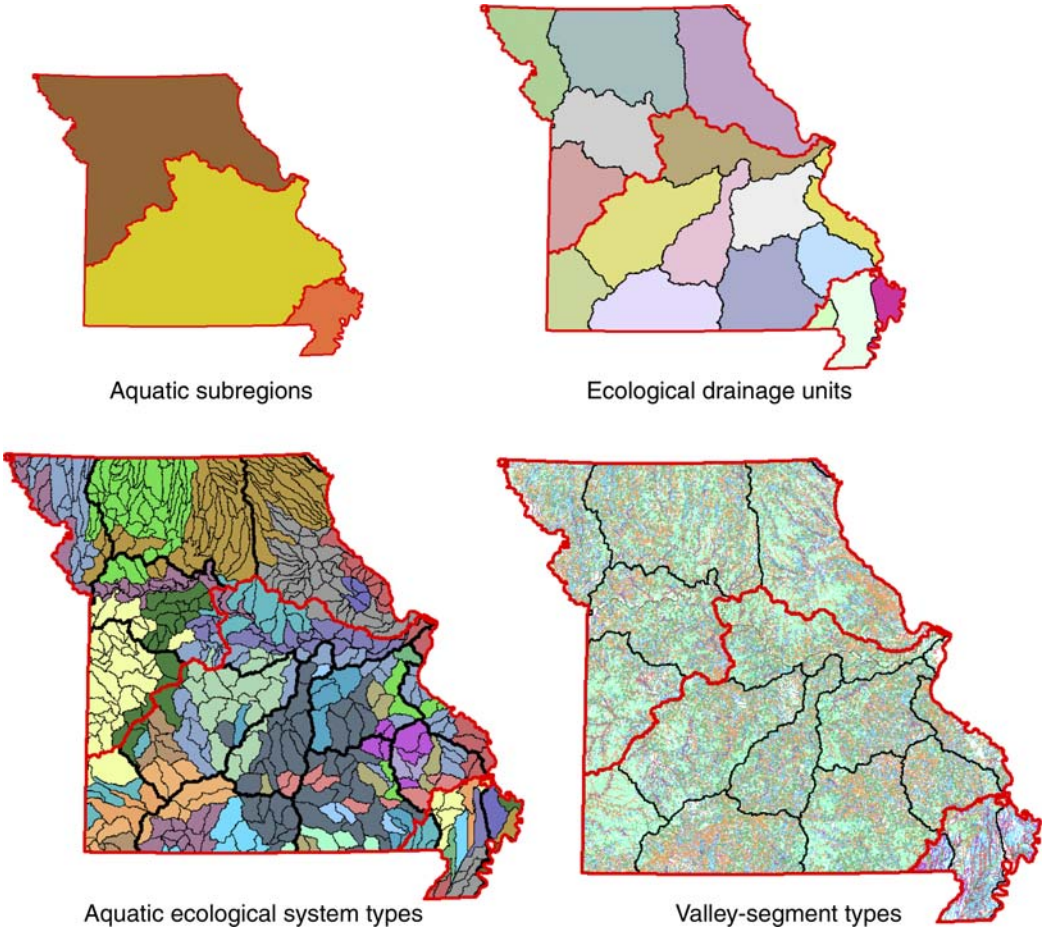

FIG. 2. Maps of Missouri showing levels 4–7 of the MoRAP aquatic ecological classification hierarchy.

account for geographic variation in *taxonomic or genetic-level composition* resulting from distinct evolutionary histories, while levels 4 and 6–8 primarily account for geographic variation in ecosystem structure, function, and *ecological composition* of riverine assemblages. This hierarchy represents a merger between the different approaches taken by biogeographers and physical scientists for tessellating the landscape into distinct geographic units.

Levels 1–3: zones, subzones, and regions.—The upper three levels of the hierarchy are largely zoogeographic strata representing geographic variation in taxonomic (family- and species-level) composition of aquatic assemblages across the landscape resulting from distinct evolutionary histories (e.g., Pacific vs. Atlantic drainages). For these three levels we adopted the ecological units delineated by Maxwell et al. (1995). Maxwell et al. (1995) used existing literature and data, expert opinion, and maps of North American aquatic zoogeography to delineate each of the geographic units. More recent analyses of family-level faunal similarities for fishes provide additional empirical support for the upper levels of the Maxwell et al. (1995) hierarchy (cf. Matthews 1998).

The ecological context provided by these first three levels may seem of little value, however, such global or subcontinental perspectives are critically important for research and conservation. For instance, the physiographic similarities along the boundary of the Mississippi and Atlantic drainages often produce ecologically similar (i.e., in ecological composition) riverine assemblages within the smaller streams draining either side of this boundary, as Angermeier and Winston (1998) and Angermeier et al. (2000) found in Virginia (USA). However, from a taxonomic composition or phylogenetic standpoint, these ecologically similar assemblages are quite different as a result of their distinct evolutionary histories (Angermeier and Winston 1998, Angermeier et al. 2000). Such information is especially important for those states that straddle these two drainages, since simple richness or diversity measures not placed within this broader ecological context would likely fail to identify, separate, and thus conserve highly distinctive components of biodiversity.

Level 4: aquatic subregions.—Aquatic subregions are physiographic or ecoregional substrata of regions and thus account for differences in the ecological composi-

tion of riverine assemblages resulting from geographic variation in ecosystem structure and function. The three aquatic subregions that cover Missouri (i.e., Central Plains, Ozarks, and Mississippi Alluvial Basin) largely correspond with the three major aquatic faunal regions of Missouri described by Pflieger (1989) and closely correspond to the Ecological Provinces of Bailey (1995) and the Level III ecoregions of Omernik (1995). Pflieger (1989) used a distributional-limit analysis and multivariate analyses of fish-community data to empirically define his three major faunal regions. We slightly modified Pflieger's faunal regions to ensure that subregion boundaries followed major drainage divides in order to account for drainage-specific evolutionary histories in succeeding levels of the hierarchy. Subsequent studies examining macroinvertebrate assemblages have provided additional empirical evidence that these subregions are necessary strata to account for biophysical variation in Missouri's riverine ecosystems (Pflieger 1996, Rabeni et al. 1997, Rabeni and Doisy 2000). Each subregion contains streams with relatively distinct structural features and functional processes and with relatively distinct aquatic assemblages in terms of both ecological and taxonomic composition.

Level 5: ecological drainage units.—Isolation is a key component of divergent evolutionary processes and is especially prevalent in freshwater ecosystems (Sheldon 1988, Matthews 1998). For animals lacking a terrestrial life-history phase, drainage boundaries serve as important isolating mechanisms, which is why each one tends to contain a relatively distinct fauna (Gilbert 1980, Pflieger 1989, Brown 1995). Embedded within aquatic subregions are geographic variations in taxonomic composition (at species and genetic level) resulting from the geographically distinct evolutionary histories of the major drainages within each subregion (Pflieger 1971, Mayden 1987, 1988, Crandall 1998, Matthews and Robison 1998). Level 5 of the hierarchy, ecological drainage units (EDUs), accounts for these differences in taxonomic composition. EDUs are analogous to "islands" when viewed within the context of the surrounding aquatic subregion, which is analogous to the "sea" in which the EDUs reside. Within a given aquatic subregion, all of the EDUs have assemblages with relatively similar ecological composition (e.g., physiological tolerances, reproductive and foraging strategies). However, the taxonomic composition (species and phylogenetic composition) of the assemblage within any given EDU is relatively distinct due to evolutionary processes such as adaptive radiation, genetic drift, differences in colonization history, or random genetic mutations.

An initial set of EDUs was empirically defined by grouping USGS 8-digit hydrologic units (HUs) with relatively similar fish assemblages based on the results of multivariate analyses of fish community data (nonmetric multidimensional scaling, principal-components analysis, and cluster analysis) (Sowa et al. 2005). We then used collection records for three other taxa (crayfish, mussels, and snails) to further examine faunal similarities among the major drainages within each subregion and refined the boundaries of this draft set of EDUs when necessary. Spatial biases and the limited amount of sampling data prohibited including these taxa in the multivariate analyses. In total, 17 EDUs were delineated for Missouri (5 EDUs in the Central Plains, 9 EDUs in the Ozarks, and 3 EDUs in the Missouri Alluvial Basin) (Appendix B).

Level 6: aquatic ecological system types.—The three aquatic subregions (level 4 of the hierarchy) of Missouri are relatively distinct in terms of their climatic, geologic, soil, landform, and therefore stream-habitat character. However, they are by no means homogeneous (Pflieger 1989). This finer-resolution variation in physiography also influences spatial variation in stream-habitat conditions and subsequently the ecological composition of local riverine assemblages (Pflieger 1971, Hynes 1975, Richards et al. 1996, Panfil and Jacobson 2001, Wang et al. 2003). To account for this spatial variation in ecological composition we used multivariate cluster analysis of quantitative landscape data to group watersheds/hydrologic units into distinct aquatic ecological system types (AES types). AES types represent hydrologic units that are from ~250 to 1500 km^2, with relatively distinct (local and overall watershed) combinations of geology, soils, landform, and groundwater influence.

Our specific objective for this level of the classification was to identify and map hydrologic units that are relatively similar with regard to nutrient and energy sources/dynamics, physical habitat, water chemistry, hydrologic regimes, and functionally defined biotic assemblages. Lacking sufficient field data for this broad range of factors and processes, we had to rely on a more indirect "top-down" approach that utilized surrogate landscape variables to classify distinct ecological units at this level of the classification. For each AES polygon we quantified local and overall watershed percentages or densities for a suite of 22 landscape variables (geology, soils, landform, and spring/groundwater inputs) that ultimately determine hydrologic and physicochemical conditions within stream ecosystems (Table 1) (Hynes 1970, 1975, Dunne and Leopold 1978, Frissell et al. 1986, Allan 1995, Richards et al. 1996, Matthews 1998). We then performed a cluster analysis on these data to group hydrologic units sharing similar percentages and densities for this suite of variables into AES types (Sowa et al. 2005). The number of distinct types was determined by examining relativized overlay plots of three statistics, (1) cubic clustering criterion, (2) pseudo F statistic, and (3) the overall r^2 as the number of clusters was increased (Calinski and Harabasz 1974, Sarle 1983). Plotting these statistics against the number of clusters and determining where all three are simultaneously maximized provides a good indication of the number of distinct clusters within the overall data set

TABLE 1. Landscape variables and associated classes used in the cluster analyses to classify aquatic ecological system (AES) types.

Landscape factor	Variable classes	Data source
General geology	alluvium, clay, dolomite, igneous, limestone, sandstone	1:500 000 statewide geology (MSDIS 1998)
Hydrologic soil group	groups A–D	1:250 000 STATSGO soils (NRCS 1994)
Surface texture	clays, cherty, loams, sandy, stony	1:250 000 STATSGO soils (NRCS 1994)
Relief (in feet)	0–50, 51–100, 101–200, 210–300, 301–500, 501–700, ≥701	30-m DEM (USGS 1998)

Notes: STATSGO stands for state soil geographic database; DEM indicates the digital elevation model. Conversion to SI units: 1 foot = 0.3084 m.

(Calinski and Harabasz 1974, Sarle 1983, Milligan and Cooper 1985, SAS 2001, Salvador and Chan 2003). Thirty-nine AES types were identified for Missouri using these methods (Appendix C). Each individual AES is a spatially distinct ecological unit, however; all individual AESs that are structurally and functionally similar fall under the same AES type.

The reason biological data were not used to empirically define and map AES types is that the available data were not suitable. At this level of the hierarchy we were interested in differences in the *relative abundance* of various physiological and functional guilds, not the mere presence or absence of species, and existing biological survey data are not suited to this more detailed quantification. We were also interested in defining assemblages in a pluralistic context, essentially identifying ecological neighborhoods (e.g., distinct interacting complexes of headwater, creek, small, and/or large river assemblages; Fausch et al. 2002).

Level 7: valley-segment types.—In level 7 of the hierarchy valley-segment types (VSTs) are defined and mapped to account for longitudinal and other linear variation in ecosystem structure and function that is so prevalent in lotic environments. VSTs represent hydrogeomorphic units defined by local physical factors and their position within the broader stream network. They stratify stream networks into major functional components that define broad similarities in fluvial processes, sediment transport, riparian conditions, and thermal regimes. Outside of the context of the upper levels of the classification hierarchy we expect VSTs to contain functionally similar aquatic assemblages. However, within the context of the upper levels of the classification we assume VSTs will contain aquatic assemblages that are similar in actual taxonomic composition.

Stream segments within the 1:100 000 USGS/EPA National Hydrography Dataset were attributed according to various categories of stream size, flow, gradient, temperature, and geology through which they flow, and also the position of the segment within the larger drainage network (data *available online*).[4] These variables have been consistently shown to be associated with geographic variation in assemblage composition (Moyle and Cech 1988, Pflieger 1989, Osborne and Wiley 1992, Allan 1995, Seelbach et al. 1997, Matthews 1998). The specific details of how these variables were mapped and attributed to each individual stream segment within our VST coverage are described in Sowa et al. (2005). Each distinct combination of variable attributes represents a distinct VST. Stream size classes (i.e., headwater, creek, small river, large river, and great river) are based on those of Pflieger (1989). Each individual valley segment is a spatially distinct habitat, but valley segments of the same size, temperature, flow, gradient, etc., all fall under the same VST (Appendix D).

Level 8: habitat types.—Units in the final level of the hierarchy, habitat types (e.g., high-gradient riffle, lateral scour pool), are too small and temporally dynamic to map within a GIS across broad regions or at a scale of 1:100 000. However, we believe it is important to recognize this level of the hierarchy, since it is a widely recognized component of natural variation in riverine assemblages (Bisson et al. 1981, Frissell et al. 1986, Peterson 1996, Peterson and Rabeni 2001).

Modeling species distributions

Since we cannot directly measure or map the full spectrum of biodiversity, we must rely on surrogate biodiversity-assessment elements, which usually include those species for which sufficient sampling data are available. However, existing sampling data, even for the most intensively studied species, are spatially and temporally incomplete and biased, and therefore inadequate for calculating the total amount and relative percentage of a species distribution that occurs within the existing matrix of public lands (Csuti and Crist 1998). For instance, the nearly 6000 collection records we compiled for fish, mussel, and crayfish in Missouri, cover <1% of the total length of stream in the state. In contrast, predicted-distribution maps provide spatially comprehensive biological data for conservation planning. GAP projects therefore use either qualitative or quantitative modeling techniques to develop spatial-explicit statements on the probability of a species being present within a given mapping unit (Csuti and Scott 1991, Scott et al. 1991, 1993, Butterfield et al. 1994).

A major distinction between the predictive-distributions maps developed for the Missouri Aquatic GAP Project, and those produced in the terrestrial component of GAP, pertains to what the final maps portray. Typically, predictive-distribution maps generated for terrestrial biota reflect the present-day distribution of a species (Scott et al. 2002; however see Oregon Gap Analysis Project [Kagan et al. 1999]), whereas our

[4] ⟨http://nhd.usgs.gov/⟩

predictions reflect a combination of both historic and present distributions. This difference in end products is the result of several confounding factors that inhibit our ability to strictly map present-day distributions for riverine biota. First, the lack of sufficient collection records inhibits our ability to precisely document the present geographic range of a species. Attempts to use only "recent" collections (e.g., collections after 1970) resulted in grossly restricted ranges for many species due to the omission of a high percentage (~50%) of the already-limited number of collection records. A second confounding factor related to our inability to account for the effect of historic and existing human disturbances on the distribution of aquatic biota (Poff 1997, Rose 2000). Because satellite-derived land cover provides a depiction of the current condition of the landscape and because the distribution of many animal species is closely tied to land cover (i.e., vegetative communities), predicted-distribution models for terrestrial animals generally reflect the present-day distribution of a species, except when a species distribution is tied to unmapped or unmappable landscape features (e.g., microclimates). Unfortunately, there are no satellites that provide comparable data on the present instream habitat conditions for every individual stream segment, which is the spatial grain at which our predictions were made. The endpoint of our predictive modeling efforts is therefore distinctly different than what can be accomplished for the terrestrial component of GAP. Due to these and other confounding factors, predictive distributions for most riverine biota must reflect the biological potential (cf. Warren 1979, Frissell et al. 1986) of a given stream segment and not necessarily the present-day assemblage of species.

Methods

Compiling existing sampling data.—To construct our predictive-distribution models we initially compiled nearly 6000 community collection records for fish (3723), mussels (1157), and crayfish (940). Data were obtained from a variety of respected data sources (Sowa et al. 2005). Collection dates ranged from 1900 through 1999. Based on a review of taxonomic references for these three groups in Missouri (Oesch 1995, Pflieger 1996, 1997) a total of 310 species and five subspecies (32 crayfishes, 67 mussels, and 216 fishes) were selected to be included in our project. Collection data were entered into a Microsoft Access relational database consisting of 10 separate, but related, tables that contain three primary elements: (1) information about the collector and collection, (2) information about the location of each collection, and (3) information about the species collected.

Mapping geographic ranges.—After completing the species-occurrence database, each collection in the database was geographically linked to individual stream segments (i.e., between tributary confluences) within our 1:100 000 VST (valley-segment type) coverage and to the appropriate 14-digit HU (hydrologic unit) within the Missouri 14-digit HU coverage using ArcView 3.2 (ESRI 1999). (Note: The 11- and 14-digit HUs have been recently renamed and recoded as 10- and 12-digit HUs. However, during this renaming and recoding process some of the boundaries have changed. For our project, we used the initial release of the 11- and 14-digit HUs, and thus retain these older naming conventions.) The 11-digit HUs ("watersheds") were a further subdivision of the 8-digit HUs ("subbasins") mentioned earlier (see *Hierarchical classification…: Level 5…*, above). Each stream segment within our VST coverage and each 14-digit HU has a unique numeric identifier that can be used to link tabular data, like chemical or biological data, to these data sets within a GIS.

Range maps were created for each species and sent out for professional review. The significantly higher number of collections records available for fish enabled the geographic ranges for this group to be generated and professionally reviewed at the 11-digit HU level. Lack of sufficient data, geographic sampling biases, and a lack of expert knowledge for many of the 11-digit HUs forced us to generate range maps for all crayfish and mussels at the coarser 8-digit HU level. Reviewer's edits were entered into a separate, but related, Microsoft Access database in order to keep the two information sources separate for future reviews and possible revisions.

GIS base layer and predictor variables.—The base layer for our predictive distributional modeling efforts was our 1:100 000 VST coverage, described above. The finest resolution ("linear spatial grain") of our predictions was the stream segment, which in most instances is represented by a section of stream between tributary confluences. Within Missouri there are ~106 000 individual stream segments in the1:100 000 VST coverage with an average length of 1.7 km.

In the study of stream fishes, four factors have proven most effective for predicting patterns of distribution and abundance: measures of stream size, gradient, temperature, and flow regime (Moyle and Cech 1988). We selected seven variables as potential predictors, all of which specifically or generally pertain to these four factors (Table 2). In addition to their reputation as useful predictors, these variables were selected because they either already had been or could be mapped within a GIS at a scale of 1:100 000.

Statistical methods.—For most species we used decision-tree (also known as "classification and regression-tree") analyses to construct the predictive distribution models and corresponding maps. However, due to the limited number of predictor variables that could be mapped within a GIS for the Missouri Alluvial Basin (MAB), we had to rely on general associations with stream size categories to construct predictive-distribution maps within this aquatic subregion. Decision-tree analyses are nonlinear/nonparametric modeling techniques that typically employ a recursive-partitioning algorithm that repeatedly partitions the input data set

into a nested series of mutually exclusive groups, each of which is as homogeneous as possible with respect to the response variable (Olden and Jackson 2002). Specifically, we used the Exhaustive CHAID algorithm within AnswerTree 3.0 to construct all of our decision tree models (Kass 1980, Biggs et al. 1991, SPSS 2001).

Input data sets.—Distributional constraints, like dispersal barriers or time since last disturbance (e.g., glaciation), play a prominent role in determining the distribution of a freshwater species (Hocutt and Wiley 1986, Mandrak 1995). Because these distributional constraints will act to decouple species–environment relations and thus hinder model development (Wiens 1989) we only used collection records within the 8-digit HUs from which a given species had actually been collected to define the input data set (i.e., suite of collection records) for each species. Consequently, an assumption of our modeling efforts was that each species collected within an 8-digit HU has, or at one time had, the ability to populate all stream segments within that HU.

Species often exhibit regional variation in their relation with predictor variables. For instance, Pflieger (1997) noted that the shorthead redhorse (*Moxostoma macrolepidotum*) is the most abundant redhorse in downstream sections of the largest Ozark rivers; however, in the Central Plains it frequents much smaller streams. To account for potential regional variation in species–habitat associations we constructed regionally specific input data sets.

Pruning criteria.—The recursive partitioning algorithms used in decision-tree analyses tend to over-fit the data and produce trees with too many levels and terminal nodes (Breiman et al. 1984). When over fitting occurs it is necessary to "prune" the decision tree by evaluating model performance under different tree structures and then remove nodes that actually increase misclassification rates or otherwise negatively alter other measures of model performance (e.g., sensitivity or specificity) (cf. Olden and Jackson 2002). Although simple in theory, such evaluations are very time consuming and inefficient. With >500 models to evaluate, we had to develop efficient pruning criteria in order to select which nodes from the overfit models would be used in the final model(s) for each species. We decided to use a "relative 50% approach." For each model we first identified the node with the highest occurrence percentage that also contained at least 5% of all the collection records from the overall input data set. We then divided the highest occurrence percentage by 2 and selected all nodes having occurrence percentages greater than or equal to this percentage. For example, if the highest occurrence percentage was 80%, we selected all nodes with occurrence percentages ≥40%, whereas if the highest occurrence percentage was 50% we selected all nodes with occurrence percentages ≥25%. This proved to be an efficient and standardized pruning method that accounted for differences in species prevalence or commonness, which were not accounted for by the other model evaluation tools included in Answer Tree 3.0.

TABLE 2. Predictor variables used to model the distribution of fish, mussel, and crayfish species throughout Missouri (based on the four factors of Moyle and Cech [1988]).

Variable	Predictor variable type	Range of values
Stream size 5 class	stream size measure	1–5
Stream size 10 class	stream size measure	1–10
Stream segment gradient	gradient measure	1–10
Relative stream gradient	gradient measure	1–3
Stream temperature	temperature	1 or 2
Stream flow	permanence of flow	1 or 2
Size discrepancy	size discrepancy	1 or 2

Notes: The "stream size 5 class" consists of five classes of stream size (headwater, creek, small river, large river, and great river); the stream size 10 class consists of 10 classes of stream size (small headwater, big headwater, small creek, big creek, etc.). "Size discrepancy" is based on the stream size 5 class variable that distinguishes between stream segments that flow into another stream of similar size (no discrepancy) or larger size (discrepancy); e.g., headwater into headwater would be attributed with a value of 1, while headwater into any larger size class would get a value of 2.

Mapping predicted distributions.—The number of models generated for any given species ranged from one to four, with most species requiring two regionally-specific models to account for regional variations in habitat associations. Predicted-distribution maps were generated by creating a field for each species in the attribute table of the VST coverage. We then used the individual models to query the VST coverage and select all stream segments that have the combination of attributes that meet the model criteria. From this initial subset of segments we then selected those segments falling within the professionally reviewed range of the species (Fig. 3). All of these segments were then coded with a value of 1 in that species-attribute field. Individual species maps were then merged into a single hyperdistribution, which was related to a Microsoft Access database containing information on the conservation status, ecological guilds, and endemism level of each species (Appendix E). We then calculated a variety of statistics (e.g., species richness) for each stream segment.

Mapping public ownership/stewardship

To fulfill the analytical mission of GAP, it is necessary to assess the representation of mapped elements of biodiversity within existing public land holdings and management status categories (Crist et al. 1995). As will be explained in the gap-analysis section, these assessments do not measure viability, but are a start to assessing existing threats and the likelihood of future threats to biodiversity through habitat conversion, a primary cause of the loss of biodiversity (Scott et al. 1993). The term "stewardship" is used in place of "ownership" in recognition that legal ownership does

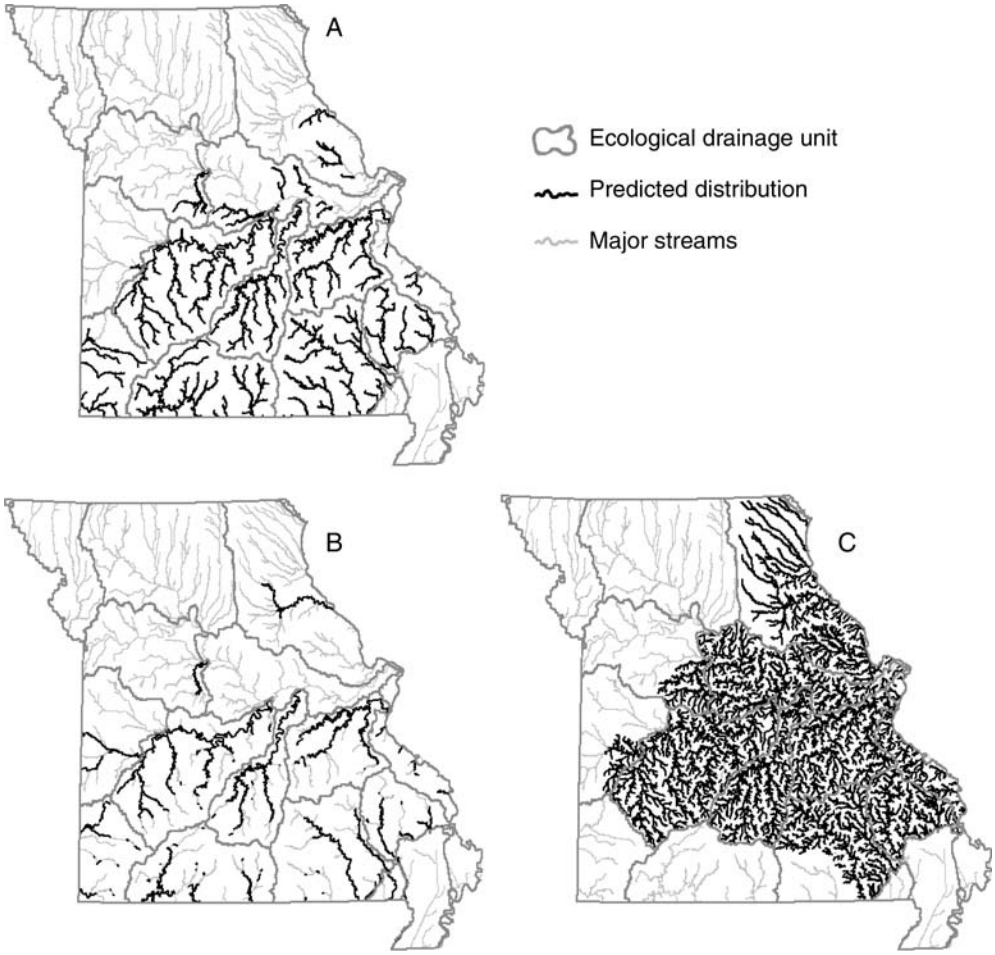

FIG. 3. Predicted-distribution maps for three species: (A) black redhorse (*Moxostoma dusquesnei*), (B) round pigtoe (*Pleurobema sintoxia*), and (C) golden crayfish (*Orconectes luteus*).

not necessarily equate to the entity charged with management of the resource, and that the mix of ownership and managing entities is a complex and rapidly changing condition not suitably mapped by GAP.

GAP currently uses a scale of 1 to 4 to characterize the relative degree of maintenance of biodiversity for each tract. A status of "1" denotes the highest, most permanent level of maintenance, and "4" represents the lowest level of biodiversity management, or unknown status (Crist et al. 1995). This is a highly subjective area and GAP recognizes the limitations of this approach, although certain principles are maintained in assigning the status level (Crist et al. 1995). The first principle is that land ownership is not the primary determinant in assigning status. The second principle is that while data are imperfect, and all land is subject to changes in ownership and management, the intent of a land steward (as evidenced by legal and institutional factors) can be used to assign status. Detailed definitions for the four management status categories can be found in Scott et al. (1993), Edwards et al. (1995), and Crist et al. (1995).

Methods.—An existing GAP stewardship coverage for Missouri was used in conjunction with the VST coverage to first identify and attribute those stream segments flowing through public lands. A customized ArcView tool was used to identify those segments that have the majority of their length (>51%) within public lands (Appendix F). These segments were then further attributed with the responsible management agency and the four GAP management-status categories. Another ARC Macro Language (ESRI 1995) algorithm was used to calculate the percentage of the watershed and upstream drainage network of each segment that occurs within each of the four GAP management-status categories. Since the watersheds of many of the stream segments within Missouri extend beyond the state boundary, the GAP stewardship coverages for the neighboring states of Arkansas, Iowa, and Kansas were merged with that of Missouri in order to calculate these percentages.

TABLE 3. Eleven metrics included in the human-threat index (HTI) and the criteria used to define the four relative ranks for each individual metric.

Metric	Relative ranks			
	1	2	3	4
1) Number of introduced species	1	2	3	4–5
2) Percentage urban	0–5	5–10	11–20	>20
3) Percentage agriculture	0–25	26–50	51–75	>75
4) Density of road–stream crossings (no./km^2)	0–0.09	0.10–0.19	0.2–0.4	>0.4
5) Population change 1990–2000 (no./km^2)	−16–0	0.04–5	6–17	>17
6) Degree of hydrologic modification and/or fragmentation by major impoundments†	1	2 or 3	4 or 5	6
7) Number of Federally licensed dams	0	1–9	10–20	>20
8) Density of coal mines (no./km^2)	0	0.1–2	2.1–8	>8
9) Density of lead mines (no./km^2)	0	0.1–2	2.1–8	>8
10) Density of permitted discharges (no./km^2)	0	0.1–2	2.1–8	>8
11) Density of confined animal feeding operations (no./km^2)	0	0.1–2	2.1–4	>4

† A major impoundment was defined as an impoundment that occurs on streams classified as small, large, or great river. Codes used to categorize the degree of hydrologic modification and/or fragmentation can be interpreted as follows: (1) *no hydrologic alteration or fragmentation*; (2) *externally fragmented* (obligate aquatic biota could reach one or more adjacent watersheds, but not the Missouri or Mississippi Rivers without passing through a major impoundment); (3) *hydrologically modified* (included all inundated aquatic ecological system [AES] polygons and any area downstream of the dam known to have a significantly modified hydrologic regime); (4) both externally fragmented and hydrologically modified (includes those AES polygons that contain stream segments situated in the interceding area between two major impoundments on the same stream); (5) *isolated* (obligate aquatic biota could not reach any adjacent watershed without passing through a major impoundment); and (6) both isolated and hydrologically modified.

Accounting for human threats

Considering the multitude of human disturbances affecting riverine ecosystems, the diffuse and cumulative nature of such disturbances, and that disturbances are often greatly removed from the site of interest, it becomes apparent that any sort or conservation planning effort must attempt to account for human disturbances (Allan and Flecker 1993, Richter et al. 1997). Failure to do so could lead to misleading statistics. For example, in those instances where streams flowing through status 1 or 2 conservation lands are significantly impaired due to hydrologic modification, nonpoint source pollution, or any number of other factors that occur outside the public land holding, it would be incorrect to state that these stream segments and their biota are being adequately conserved within the existing matrix of public lands. In an effort to address this issue we developed a human-threat index (HTI) to provide a measure of the relative degree of human disturbance affecting the freshwater ecosystems across Missouri.

Methods.—A multitude of human activities affect the ecological integrity of riverine ecosystems (Allan and Flecker 1993, Richter et al. 1997). The first step in accounting for anthropogenic stressors is developing a list of candidate causes or threats (U.S. EPA 2000). Working in consultation with a team of aquatic-resource professionals, we generated a list of human activities that can negatively affect the ecological integrity of Missouri streams. We then assembled the best available (i.e., highest resolution and most recent) geospatial data that could either directly or indirectly account for each of these activities (Sowa et al. 2005). Most of these geospatial data sets were acquired from the U.S. EPA, U.S Bureau of Mines, and the Missouri Departments of Conservation and Natural Resources.

Once these data were assembled, we calculated a suite of 65 threat metrics (e.g., percent urban landcover, lead-mine density, degree of fragmentation) for each of the 542 AES polygons in Missouri. Forty-eight of these metrics were generated with the EPA Analytical Tools Interface for Landscape Assessments (ATtILA, Version 3.0), which is an ArcView extension that allows users to easily calculate many common landscape metrics (U.S. EPA 2004). Fourteen metrics were simply generated by summing or calculating point densities for data obtained from EPA BASINS 3.1 (U.S. EPA 2001) or data explicitly developed for Missouri. All of these metrics were calculated for the area contained within each individual AES polygon. Finally, three of the metrics, pertaining to hydrologic modification and network fragmentation, were categorical metrics and were visually determined by overlaying the high-pool reservoir boundaries onto the AES polygon boundaries (see Sowa et al. 2005).

After the 65 metrics were calculated for each AES polygon, we used correlation analysis to reduce this overall set of metrics into a final set of 11, relatively uncorrelated ($r < 0.5$), measures of human disturbance (Table 3). Relative rankings (range: 1 to 4) were then developed for each of these 11 metrics. A rank of 1 is indicative of relatively low disturbance for that particular metric, while a rank of 4 indicates a relatively high level of disturbance. These rankings were based on information contained within the literature, or either quartiles or equal intervals when no empirical evidence on thresholds was available. For instance, rankings for percentage urban; 1: 0–5%; 2: 6–10%; 3: 11–20%; and 4: >20%, were based on the results of various studies that

have examined the effects of urban land cover on the ecological integrity of stream ecosystems (Klein 1979, Osborne and Wiley 1988, Limburg and Schmidt 1990, Booth 1991, Weaver and Garman 1994, Booth and Jackson 1997, Wang et al. 2000). However, we were unable to find any thresholds in the literature dealing with the relations between percentage agriculture in the watershed and measures of ecological integrity. For this measure of threat we used four equal-interval categories: 1, 0–25%; 2, 26–50%; 3, 51–75%; and 4, >75%.

Relative rankings for each of the 11 metrics were then combined into a three-number human-threat index (HTI). The first number reflects the highest ranking across all 11 metrics (range 1 to 4), while the last two numbers reflect the sum of the 11 metrics (range 11 to 44; Appendix G). The numeric structure of this index allows users to evaluate potential individual and cumulative disturbance. For instance, a value of 418, indicates relatively low cumulative disturbance (i.e., last two digits = 18 out of a possible 44), however, the first number is a 4, which indicates that at least one of the metrics is relatively high and potentially acting as a major human disturbance within the ecosystem. This index is an admittedly crude measure of human disturbance, however, it is well suited for a coarse-filter assessment since it does act as a "red flag" for further evaluation. Yet, the general metrics that make up this index are by no means a substitute for a more detailed assessment of ecosystem health.

Gap Analysis (GAP) for Riverine Ecosystems of Missouri

The principal goal of the Missouri aquatic GAP project was to identify riverine ecosystems, habitats, and native species not adequately represented (i.e., gaps) within the existing matrix of conservation lands in Missouri. Addressing this goal is accomplished by intersecting the stream stewardship map with the distribution of the selected biodiversity elements in order to generate tables that summarize the representation of each element in different management status categories. Although GAP seeks to identify habitat types and species not adequately represented in the current network of biodiversity management areas (Scott et al. 1993), it is unrealistic to create a standard definition of "adequate representation" for either habitat or species (Noss et al. 1995). Principles of conservation biology and ecology can offer guidance to address this issue; however our knowledge of the life-history requirements of species and how ecosystems function is too incomplete to provide definitive answers (Groves 2003). A practical solution to this problem is to report both percentages and absolute length of each biodiversity element within each management status category and allow the user to determine which elements are adequately represented based on detailed studies of the ecology and on population viability assessments, as well as on studies of the spatial and temporal dimensions of ecological processes. Clearly, opinions will differ among users, but this disagreement is an issue of policy, not scientific analysis.

Generally, GAP management-status categories 1 and 2 are considered to have reasonably secure conservation provisions that benefit biodiversity (see *Methods and rationale…: Mapping public ownership/stewardship* above), and our gap analyses focus on these categories. Our gap analyses also focus on local management status of individual stream segments vs. percentage of the watershed or upstream network within status 1 or 2 lands. This decision is based on the belief that local public ownership is a necessary first step for the long-term maintenance of riverine biodiversity since even the most ambitious of watershed-management efforts (e.g., 90% of watershed in status 1 or 2 lands) can be thwarted by local human disturbances to those stream segments that are the focus of conservation. Another reason pertains to the lack of empirical data addressing the question of, "How much is enough?" Is 25, 50, or 75% of a watershed in status 1 or 2 lands sufficient to ensure long-term protection? Such thresholds must be identified before they can be incorporated into a gap analysis.

Our gap analyses quantify representation of both abiotic and biotic elements of biodiversity. For the abiotic elements we generated statistics to address two fundamental questions: (1) How well are the various stream types (valley-segment types [VSTs]) represented within status 1 or 2 lands? and (2) How well are the various watershed types (aquatic ecological system [AES] types) represented within status 1 or 2 lands? By addressing these questions we are attempting to assess the representation of the various riverine ecosystems and habitats across the Missouri landscape, which may prove more useful than assessing representation of individual species (Angermeier and Schlosser 1995).

Our analyses for the biotic elements (fish, mussel, and crayfish species) followed those used in previous GAP projects dealing with terrestrial plant communities and vertebrates. However, our statistics are presented in terms of length, not area, since we are dealing with linear and not polygonal data. Furthermore, we also quantified the number of distinct locations in which each species is represented in status 1 or 2 lands, which is further explained in the species-analysis section below.

The conservation-status statistics for each biodiversity element are examined from a statewide perspective and also within the context of our aquatic subregions and ecological drainage units (EDUs; see *Methods and rationale…: Hierarchical classification…: Level 5: ecological drainge units*). These ecological-unit-based assessments provide a more holistic and realistic context for biodiversity conservation than those based on political boundaries.

Results of the analyses performed in this section are based on models and mapping data that are certainly not without error. Results should therefore be interpreted from a general perspective since data used in the

TABLE 4. Stream lengths that are flowing within GAP management-status 1 or 2 lands for each aquatic subregion in Missouri.

Aquatic subregion	Total stream length (km)	Stream in status 1 or 2 lands	
		Length (km)	Percentage of total length
Central Plains	70 243	97	0.14
Ozarks	93 230	1185	1.27
Mississippi Alluvial Basin	8929	60	0.67

analyses are suited to coarse-scale assessments that illustrate general patterns of representation of abiotic and biotic elements of biodiversity within the existing matrix of public lands in Missouri. Readers are encouraged to consult Sowa et al. (2005) which provides metadata for each geospatial data set used in these analyses and a thorough discussion of methods used to create these data and their limitations.

Analysis of abiotic targets: VSTs.—To assess the conservation status of the various stream types within Missouri, we used a five-variable valley-segment type (VST) code that included five fundamental parameters; temperature (two classes), stream size (four classes), flow (two classes), geology (five classes), and relative gradient (three classes). Within our 1:100 000 VST coverage there are 74 distinct VSTs based on these five parameters. The number of VSTs decreases with stream size, with 29 headwater, 23 creek, 14 small-river, and 8 large-river VSTs.

Results.—Approximately 9.4% of Missouri is contained within public lands. Many of these lands are situated in the uplands, away from the larger stream channels. Consequently, just over 5% of the total 174 063 km of stream within Missouri are contained within the existing matrix of public lands. Eighty-five percent of these public streams flow through lands classified as GAP management-status 3. Less than 1% (1342 km) flow through status 1 or 2 lands and 88% of these stream kilometers occur within the Ozarks (Table 4; Appendix H).

Our statewide analyses revealed that 55 of the 74 VSTs are presently represented in status 1 or 2 lands. Fig. 4 further breaks down these statewide statistics according to stream size and six length-based categories of representation. This figure shows that ~25% of the VSTs that occur in each stream size class are not represented in status 1 or 2 lands. This figure also shows that most VSTs have between 1 and 10 km represented. None of the VSTs, classified as "creeks," have more than 50 km represented; however, 7 of the 29 headwater VSTs have >50 km represented (Fig. 4).

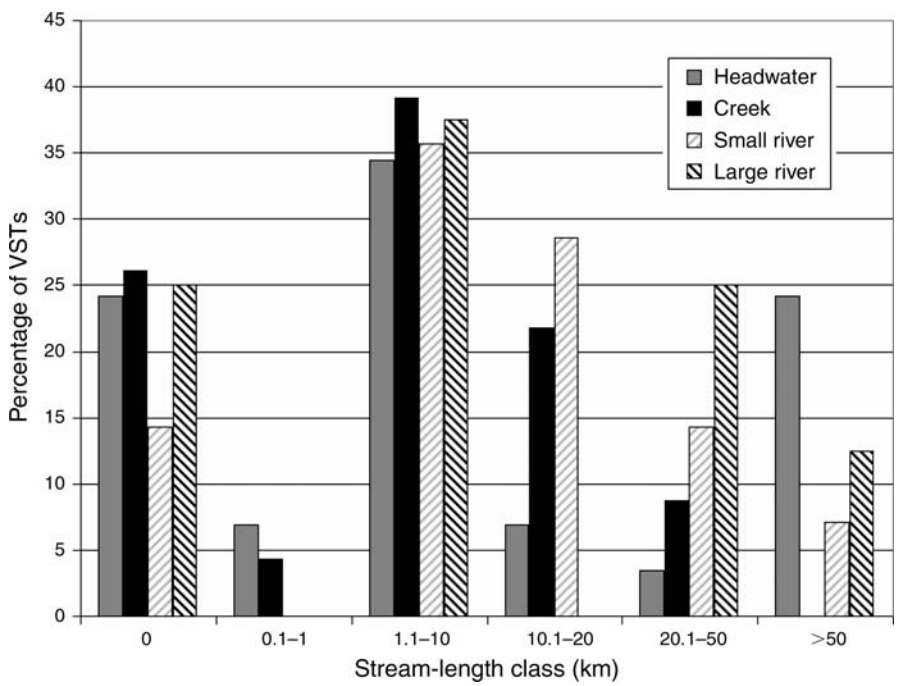

FIG. 4. Bar chart showing the percentage of valley-segment types (VSTs), for each stream size class, that occur in six levels of representation by stream length. For example, of the eight distinct large-river VSTs, two (25%) are not represented in any management-status 1 or 2 lands, none (0.0%) have between 0 and 1 km, three (37.5%) have between 1 and 10 km, none (0.0%) have between 10 and 20 km, two (25%) have between 20 and 50 km, and 1 (12.5%) has >50 km represented.

TABLE 5. Conservation status statistics for the five individual parameters used to classify distinct valley-segment types (VSTs) in Missouri.

Factor	Variable	Total stream length (km)	Stream in management-status 1 or 2 lands	
			Length (km)	Percentage of total length
Temperature	Cold	558	59	10.6
	Warm	171 700	1249	0.7
Stream size	Headwater	128 799	772	0.6
	Creek	27 174	181	0.7
	Small river	11 487	210	1.8
	Large river	3239	145	4.5
Flow	Intermittent	120 089	719	0.6
	Perennial	46 574	581	1.3
Geology	Alluvium	12 404	79	0.6
	Clay	304	0	0.0
	Igneous	664	58	8.8
	Limestone/Dolomite	135 076	871	0.7
	Sandstone	23 623	300	1.3
Gradient	Low	72 260	299	0.4
	Moderate	53 649	345	0.6
	High	37 409	640	1.7

Appendix I provides the conservation-status statistics for all 74 VSTs. While useful for detailed evaluations of the representation of the various stream types in Missouri, a more general but informative evaluation can be made by examining representation of each of the five parameters that comprise the VSTs, which are provided in Table 5. Coldwater streams and streams flowing through igneous geology have a much higher percentage of their total length represented in status 1 or 2 lands. These stream types are certainly distinctive and rare, yet are also some of the least biologically diverse stream types in the state (Pflieger 1989). Furthermore, most of the coldwater streams contain highly managed populations of nonnative rainbow trout (*Oncorhnchus mykiss*) and brown trout (*Salmo trutta*).

We also found a positive association between stream size and percentage representation in status 1 or 2 lands (Table 5). Large rivers have the highest percentage of their total length represented in these lands; however, a closer examination of the more detailed data provided in Appendix I shows that a high percentage (30 km) of the 145 km of large rivers that are flowing through status 1 or 2 lands is classified as coldwater. Consequently, 20% of the total length of large rivers that are flowing within status 1 or 2 lands is coldwater stream. Table 5 also shows that a higher percentage of the high-gradient streams is represented compared to lower gradient streams.

Representation statistics of VSTs by aquatic subregion reveal that the Ozarks has a considerably higher percentage of stream types represented than the other two subregions. Of the 65 VSTs that occur within the Ozarks, 49 VSTs are represented in status 1 or 2 lands. Only 13 of the 30 and 14 of the 45 VSTs that occur within the Missouri Alluvial Basin (MAB) and the Central Plains (CP), respectively, are represented.

When we examined the representation of VSTs by the various EDUs we found a great deal of variation, especially within the Ozarks and the MAB (Table 6, Appendix J). On average, EDUs within the CP had 11% of the VSTs represented in status 1 or 2 lands, compared with an average of 28% in the Ozarks and 21% in the MAB. Within the Ozarks the number and percentage of VSTs represented ranged from a single stream type in the Neosho EDU (4%) to 34 stream types represented in the Black/Current EDU (63%). There was also a high degree of variation among the three EDUs within the MAB. Forty percent of the VSTs within the St. Francis/Little EDU were represented in status 1 or 2 lands, compared with 14.7% in Black/Cache and only 8.3% in the St. John's Bayou.

Analysis of abiotic targets: AES types.—Each individual AES contains three stream size classes: (a) headwater, creek, and small river, (b) headwater, creek, and large river, or (c) headwater, creek, and great river. As Pflieger (1989) and our data show, the biological assemblages that occur within these various stream sizes are dramatically different. In addition, many species collectively utilize the distinct habitats of these different stream size classes in order to successfully meet various life-history requirements (Vannote et al. 1980, Schlosser and Angermeier 1995). Consequently, to assess the representation of these broader-scale habitats we determined that, at an absolute minimum, each of the three size classes within a given AES polygon should be represented in status 1 or 2 lands before it could be considered effectively represented.

Our analyses initially focused on identifying individual AESs that have all three stream size classes represented in status 1 or 2 lands. We then applied more stringent and, we believe, more ecologically meaningful criteria. Specifically, we then identified those individual AES polygons that have all three stream size

TABLE 6. Statistics showing the total number of valley-segment types (VSTs) within each ecological drainage unit (EDU) together with the corresponding number and percentage of these totals that are represented in management-status 1 or 2 lands.

Subregion	EDU name	VSTs in status 1 or 2 lands		
		Total no. VSTs	No.	Percentage of total no.
Central Plains, CP	Blackwater/Lamine	42	3	7.1
	Grand/Chariton	41	5	12.2
	Nishnabotna/Platte	26	3	11.5
	Osage/South Grand	33	3	9.1
	Cuivre/Salt	35	6	17.1
Mean				11.4
Ozarks	Black/Current	54	31	57.4
	Neosho	28	1	3.6
	Gasconade	42	19	45.2
	Apple/Joachim	37	5	13.5
	Meramec	45	9	20.0
	Moreau/Loutre	38	9	23.7
	Osage	40	4	10.0
	Upper St. Francis/Castor	49	13	26.5
	White	43	21	48.8
Mean				27.6
Mississippi Alluvial Basin, MAB	St. Francis/Little	30	12	40.0
	St. Johns Bayou	12	1	8.3
	Black/Cache	7	1	14.3
Mean				20.9

Note: Mean percentages are also provided for each aquatic subregion.

classes represented as an interconnected matrix in status 1 or 2 lands. Finally, using our human-threat index (HTI) and the raw human-threat data, we examined the ecological condition of the AESs meeting the above criteria, in an effort to assess whether or not these units are effectively providing long-term maintenance of freshwater biodiversity.

Results.—Our statewide analysis revealed that 19 of the 542 individual AESs within Missouri have all three stream size classes represented in status 1 or 2 lands (Appendix K). These 19 AESs represent only 6 of the 39 AES types that occur in the state. In most instances, only a single example of a given AES type is represented. However, there are 13 AESs, classified as the Jacks Fork AES type, that have all stream size classes represented in status 1 or 2 lands. The East Locust Creek AES type, which is the most common watershed type in the Central Plains, is the only other type to be represented more than once.

For the subregion-level analyses, 3 of the 13 AES types that occur in the CP are represented using the least stringent criteria, compared with 2 of 25 AESs in the Ozarks, and 1 of 11 AESs in the MAB (Table 7). The EDU-level analyses revealed that no EDU has more than a single AES type represented, despite the fact that some have multiple individual AESs represented (Table 8, Appendix K). For instance, the Black/Current EDU has eight individual AESs with all size classes represented in status 1 or 2 lands. However, all eight of these AESs are classified as the Jacks Fork AES type, which means eight of the nine AES types that occur within this EDU are not represented using the least stringent criteria. This redundancy in representation also occurs in three other EDUs; Grand/Chariton, Gasconade, and White.

When we applied slightly more stringent criteria to assess the representation of AESs we found 12 AESs that have all of the size classes represented in status 1 or 2 lands as an interconnected complex (Appendix K). When we applied even more stringent criteria, and assessed the ecological integrity of the remaining 12 AESs, only 4 AESs could be considered relatively undisturbed or ecologically intact (Appendix L). All four of these occur within the Black/Current EDU and furthermore all four represent the Jacks Fork AES type.

Analysis of biotic targets.—A total of 315 species of fish, mussels and crayfish have been collected within Missouri. Fourteen of these species are not native to Missouri and five of the native species occur in cave habitats (three fish and two crayfish), and were not included in our gap analyses. Consequently our analyses focused on 296 native species. To assess the representation of these fish, mussel, and crayfish species we calculated the length of stream and percentage of total length of stream in which each species was predicted to occur that flows through status 1 or 2 lands. We also calculated the number of AES polygons in which each species was represented in status 1 or 2 lands. The first calculation provides insight into which species have little or no suitable habitat currently represented in lands set aside for the long-term maintenance of biodiversity. The second calculation provides insight into how many distinct occurrences ("population subunits") are represented in status 1 or 2 lands for each species. For this

TABLE 7. Conservation-status statistics for each aquatic ecological system (AES) type within each aquatic subregion.

AES type	Total no. individual AESs	AESs in management-status 1 or 2 lands	
		No.	Percentage of total no.
Central Plains, CP			
Boeuf Creek	8	0	0.0
Clear Creek	18	0	0.0
East Locust Creek	59	2	3.4
Honey Creek	19	0	0.0
Lick Creek	40	0	0.0
Middle River	4	0	0.0
Moniteau Creek	3	0	0.0
Ramsey Creek	10	1	10.0
Rock Creek	23	1	4.4
Sampson Creek	49	0	0.0
South Deepwater Creek	43	0	0.0
Tavern Creek	1	0	0.0
Upper Cuivre River	4	0	0.0
Ozarks			
Beaver Creek	7	0	0.0
Big Creek	2	0	0.0
Boeuf Creek	30	0	0.0
Bull Creek	12	0	0.0
Clear Creek	5	0	0.0
Crowley's Ridge	1	0	0.0
Dry Fork	8	0	0.0
Finley Creek	15	0	0.0
Indian Creek	9	0	0.0
Jacks Fork	40	13	32.5
Lick Creek	1	0	0.0
Little St. Francis River	8	1	12.5
Lower Meramec	1	0	0.0
Middle River	10	0	0.0
Upper Big River	6	0	0.0
Upper Little Sac	8	0	0.0
Moniteau Creek	13	0	0.0
Ramsey Creek	7	0	0.0
Rock Creek	1	0	0.0
South Deepwater Creek	3	0	0.0
Spring Creek	4	0	0.0
Spring River	4	0	0.0
Tavern Creek	19	0	0.0
Upper Big Piney	9	0	0.0
Upper Spring River/Neosho	3	0	0.0
Mississippi Alluvial Basin, MAB			
Cane Creek	4	0	0.0
Chaffee	2	0	0.0
Charleston	2	0	0.0
Gideon	1	0	0.0
Hayti	4	0	0.0
Senath	2	0	0.0
Crowley's Ridge	7	1	14.3
Little River	1	0	0.0
St. Johns Diversion Ditch	1	0	0.0
West Ditch	2	0	0.0
Wilkerson Ditch	1	0	0.0

Note: The table shows the total number of individual AESs of each type that occur in each subregion along with the number and percentage that have all three stream size classes represented in GAP management-status 1 or 2 lands.

second calculation we assume that each individual AES represents a distinct occurrence or population subunit for each species—which is not always a correct assumption, especially for wide-ranging species. However, we believe that these statistics are important and do provide additional insight into how well each species is currently represented in the existing matrix of public lands. The above statistics were generated and reported from a statewide perspective and also within the ecosystem context provided by our aquatic subregions and EDUs.

Results for species analyses based on length.—Most of the 296 native fish, mussel, and crayfish species included

TABLE 8. Conservation-status statistics for each aquatic ecological system (AES) type within each ecological drainage unit (EDU).

		AES types in management-status 1 or 2 lands		
Aquatic subregion	EDU	Total no. AES types	No.	Percentage of total
Central Plains, CP	Blackwater/Lamine	9	0	0.0
	Cuivre/Salt	4	1	25.0
	Grand/Chariton	3	1	33.3
	Nishnabotna/Platte	4	1	25.0
	Osage/South Grand	2	0	0.0
Ozarks	Apple/Joachim	3	0	0.0
	Black/Current	9	1	11.1
	Gasconade	6	1	16.7
	Meramec	7	0	0.0
	Moreau/Loutre	7	0	0.0
	Neosho	5	0	0.0
	Osage	8	0	0.0
	Uppper St.Francis/Castor	7	1	14.3
	White	5	1	20.0
Mississippi Alluvial Basin, MAB	Black/Cache	1	0	0.0
	St. Francis/Little	7	1	14.3
	St. Johns Bayou	3	0	0.0

Note: The table shows the total number of AES types that occur in each EDU along with the number and percentage that have all three stream size classes represented in GAP management-status 1 or 2 conservation lands.

in our analyses have more than 50 km of their predicted distribution within status 1 or 2 lands (Fig. 5). In fact, anywhere from 40% to 70% of the species within each taxonomic group have >50 km of their distribution within status 1 or 2 lands. Appendix M provides the length and percentage length contained within each GAP management-status category for all 296 species.

A total of 45 (15%) native species (32 fish, 5 mussels, and 8 crayfish) are currently not represented in status 1 or 2 lands (Appendix N). The vast majority of these (30 species, 67%) are state listed as rare, threatened, or endangered and 10 are listed as globally rare, threatened, or endangered. Although these 45 species occur all across the state, the richness plot provided in Fig. 6 shows that the highest concentration occurs within the Mississippi River, the MAB, and the Neosho EDU, located in southwestern Missouri. Also, within the MAB and the Neosho EDU, the highest concentration of these species occurs within the larger mainstem streams.

When we examined the representation of species by aquatic subregion, we found that the Ozarks has the highest percentage of species represented in status 1 or 2 lands, followed by the MAB, and with the lowest percentage occurring in the Central Plains. Specifically, there are 278 native fish, mussel, and crayfish species that occur within the Ozarks, of which 52 species (19%) are not represented within the status 1 or 2 lands that occur within this subregion. Within the MAB there are 163 native species and 69 species (42%) that do not occur in the status 1 or 2 lands. Finally, of the 178 native species that occur within the Central Plains aquatic subregion, 90 species (51%) are not currently represented within the status 1 or 2 lands that occur within this subregion.

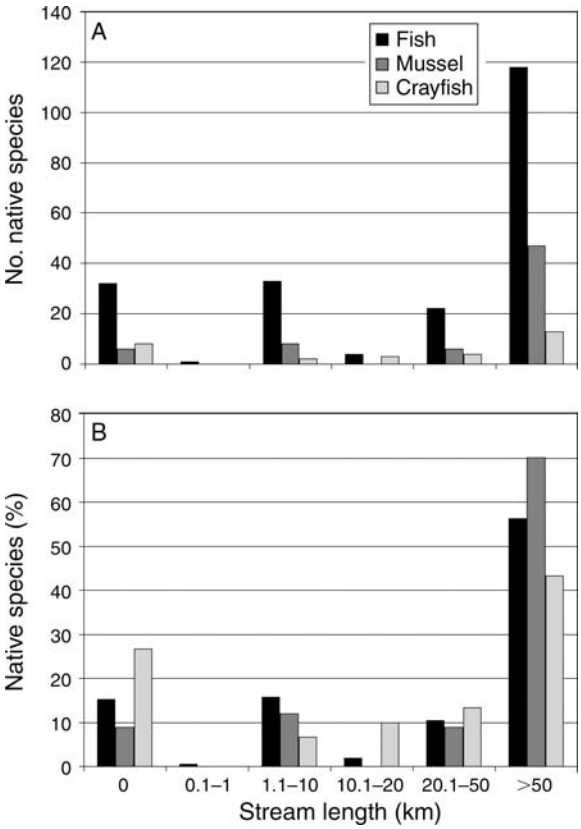

FIG. 5. Bar charts showing (A) the number of native species and (B) the percentage of native species, within each taxon, that occur within six levels of representation (in management-status 1 or 2 lands), by stream length.

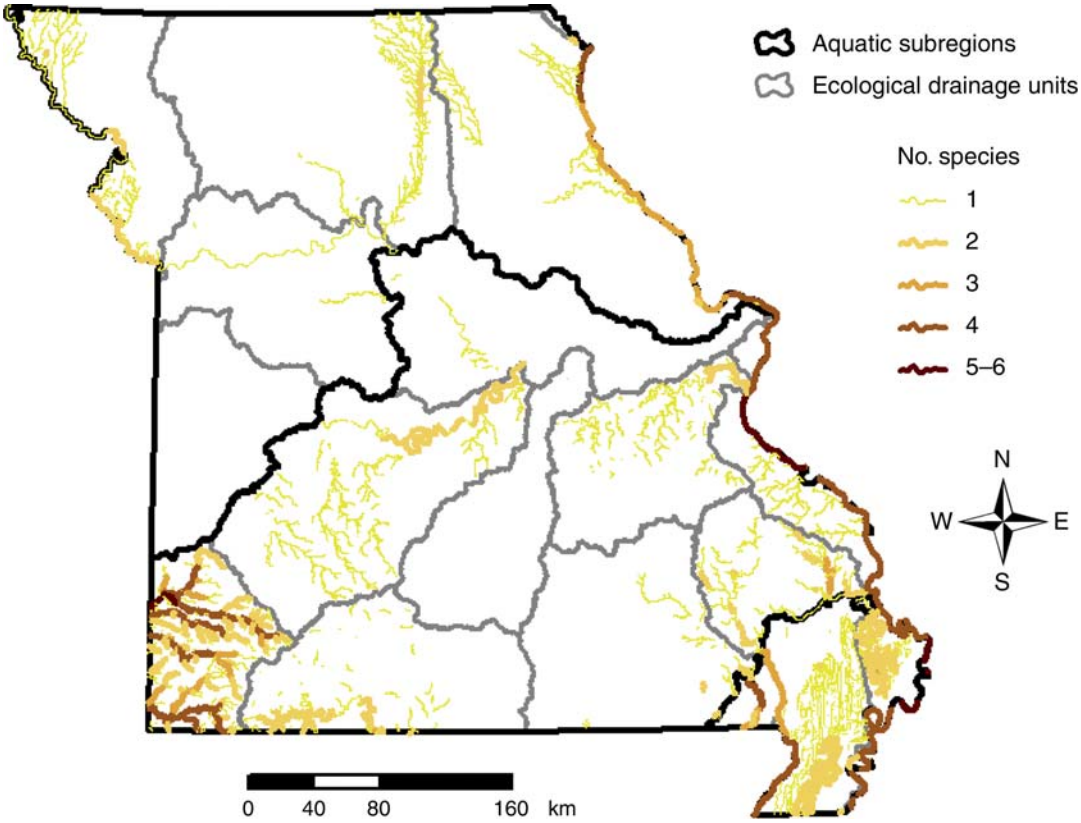

FIG. 6. Map of species richness for the 45 native fish, mussel, and crayfish species that are currently not represented within GAP management-status 1 or 2 conservation lands of Missouri. See Appendix N for a list of the species represented in this map.

TABLE 9. Statistics illustrating how well native fish, mussel, and crayfish species are represented in status 1 or 2 lands within each ecological drainage unit (EDU).

		Native species not in status 1 or 2 lands		Native species with <2 occurrences in status 1 or 2 lands	
Aquatic subregion and EDU	Total no. native species	No. species	Percentage of total	No. species	Percentage of total
Central Plains, CP					
Blackwater/Lamine	122	95	78	102	84
Cuivre/Salt	158	87	55	133	84
Grand/Chariton	92	30	33	35	38
Nishnabotna/Platte	91	60	66	91	100
Osage/South Grand	110	40	36	81	74
Ozarks					
Apple/Joachim	142	118	83	125	88
Black/Current	187	32	17	50	27
Gasconade	150	35	23	50	33
Meramec	172	43	25	102	59
Moreau/Loutre	137	34	25	90	66
Neosho	132	111	125	132	100
Osage	158	125	79	140	89
Upper St. Francis/Castor	181	63	35	84	46
White	139	50	36	56	40
Mississippi Alluvial Basin, MAB					
Black/Cache	109	60	55	109	100
St. Francis/Little	126	31	25	39	31
St. Johns Bayou	135	87	64	135	100

Note: The table shows the total number of native species that occur within each EDU and the number and percentage of these species that have 0 or <2 occurrences within the GAP management-status 1 or 2 conservation lands that occur within each EDU.

Representation of native species within each EDU shows a high degree of variation (Table 9; Appendix O). None of the EDUs have all of the native species occurring within their boundaries currently represented in status 1 or 2 lands. Within the Central Plains 34% of the native species that occur within the Grand/Chariton EDU were not represented within the status 1 or 2 lands that occur within this EDU, compared with 78% within the Blackwater/Lamine EDU. Within the Ozarks four EDUs had 25% or less of the native species not represented in status 1 or 2 lands. However, the Osage (79%), the Apple/Joachim (83%), and the Neosho (84%) EDUs all had <75% of their native species represented in status 1 or 2 lands. Within the MAB aquatic subregion there is fairly good representation within the St. Francis/Little EDU with only 25% of the native species not represented in status 1 or 2 lands. However, the Black/Cache and St. John's Bayou EDUs both have more than 50% of the native species not represented.

Results for species analyses based on distinct occurrences.—From a statewide perspective, most of the 296 native fish, mussel and crayfish species (227 species, 77%) have multiple distinct occurrences or population subunits represented in status 1 or 2 lands (Fig. 7). A high percentage of the species, within each of the three taxonomic groups, have >10 distinct population subunits represented in status 1 or 2 lands (crayfish 23%, fish 35%, and mussels 51%). A total of 69 (23%) native species (50 fish, 8 mussels, and 11 crayfish) have fewer than two distinct occurrences represented in status 1 or 2 lands (Sowa et al. 2005). Most of these (49 species, 71%) are state listed as rare, threatened, or endangered and 21 species (30%) are listed as globally rare, threatened, or endangered.

When examined at the aquatic subregion level we find a drop in the percentage of species that have multiple distinct occurrences represented in status 1 or 2 lands. The Ozarks has the highest percentage followed by the MAB, with the lowest percentage occurring in the Central Plains. There are 278 native fish, mussel, and crayfish species that occur within the Ozarks, of which 81 species (29%) have fewer than two distinct occurrences represented within the status 1 or 2 lands that occur within this subregion. Within the MAB there are 163 native species and 76 species (47%) have fewer than two distinct occurrences represented. Finally, of the 178 native species that occur within the Central Plains aquatic subregion, 109 species (61%) have fewer than two distinct occurrences represented in the status 1 or 2 lands that occur within this subregion.

Similar to what was found for the analyses by length, results of the analyses examining distinct occurrences by EDU revealed a high degree of variation (Table 9; Appendix P). No EDU had all native species that occurred within their boundaries represented more than once within status 1 or 2 lands. Within the Central Plains 62% of the native species that occur within the Grand/Chariton EDU had multiple population subunits represented in the status 1 or 2 lands, however none of the species within the Nishnabotna/Platte EDU were represented more than once. Within the Ozarks 73% of the native species that occur within the Black/Current EDU had multiple population subunits represented in status 1 or 2 lands; however, none of the species within the Neosho EDU were represented more than once. Within the MAB aquatic subregion there is fairly good representation within the St. Francis/Little EDU, with 69% of the native species represented more than once. However, none of the native species within the Black/Cache and St. John's Bayou EDUs were represented more than once.

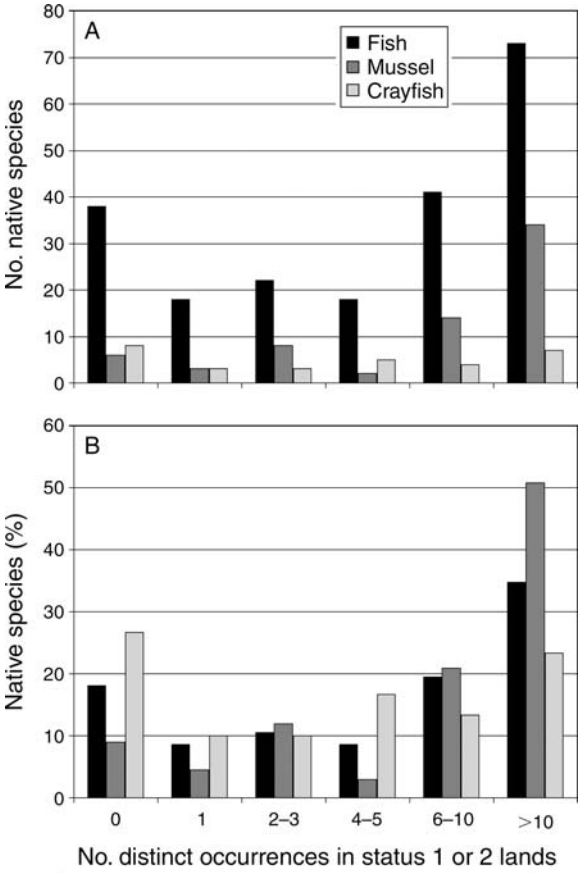

FIG. 7. Bar charts showing (A) the number of species and (B) the percentage of species, within each taxon, that fall within six levels of representation by distinct occurrence.

Discussion

Results of our gap analyses appear somewhat encouraging and also surprising when you consider that only ~5% of the nearly 175 000 km of stream within Missouri is contained within public lands and <1% flow through lands with mandated provisions for the long-term maintenance of biodiversity (i.e., status 1 or 2 lands). Despite these low percentages, a relatively high percentage of the various stream types (77%) and native

species (85%) are represented in status 1 or 2 lands. Furthermore, in many instances these biodiversity elements are represented within a significant length of stream (e.g., >50 km) and most species have multiple distinct occurrences represented. Yet, 45 native species were identified as having none of their predicted distribution contained within status 1 or 2 lands. An additional 24 species were identified as having less than two distinct occurrences represented in status 1 or 2 lands. Furthermore, most of these 69 species are listed as either state or globally rare, threatened or endangered.

The highest concentrations of these underrepresented species occur mainly within three areas of the state: (1) the Mississippi River below the confluence with the Missouri River, (2) the Mississippi Alluvial Basin (MAB) aquatic subregion, and (3) the Neosho Ecological Drainage Unit (EDU), which is located in the southwestern corner of Missouri. These areas contain some very distinct species and unique assemblages (Pflieger 1971, 1989). The extremely limited amount of public land within these areas requires that private-land conservation initiatives play a prominent role in the long-term conservation of these unique assemblages. However, measures to secure at least some of the lands within the Conservation Opportunity Areas identified for these areas (see *Wildlife action plan…: Results: Statewide*, below) should also be a high priority.

The fact that most of the 69 underrepresented species are either large-river species or local endemics presents a significant challenge to stream-resource managers. Conserving large rivers is obviously difficult due to the enormous land area that must be managed, but the diversity and cumulative nature of the human disturbances, particularly fragmentation, also adds to the complexity of the management efforts (Galat and Lipkin 2000, Pringle 2001). For most drainages east of the Rocky Mountains we will likely never secure a significant portion of the watersheds for streams classified as large rivers (Sheldon 1988). If our results for Missouri are any indication, we will likely never achieve greater than 5–10% public ownership within the watersheds of these large rivers. Once again, private lands management will be the key to the long-term maintenance of biodiversity within these large rivers. Local endemics present a management challenge because, as the species-specific literature reviews conducted for this project showed, very little is known about the life-history requirements of these species (Sowa et al. 2005). Our lack of knowledge about these species is not an excuse for inaction, but may signal that a more effective strategy would be to focus on the conservation of habitat and ecosystem processes, since they are generally better understood. Furthermore, in Missouri, these local endemics occur as widely scattered populations across the state, which places a strain on the limited financial and human resources dedicated to freshwater biodiversity conservation.

While the results of the statewide analyses are somewhat encouraging, when examined more closely and from an ecosystem-conservation standpoint, our results clearly reveal the enormity of the challenge we face when it comes to the long-term conservation of freshwater biodiversity in Missouri. We believe that all of the major drainages in Missouri must be viewed as a chain of islands, and, as such, each must be conserved as a holistic unit. Under this philosophy the most meaningful results from our project would be those generated from the analyses examining the representation of the biodiversity elements within each Ecological Drainage Unit (EDU). Perhaps the clearest perspective on how well we are achieving this goal is provided by specifically examining the "best case scenario" in terms of representation of abiotic and biotic elements that occur within the Ozark Black/Current EDU. Twenty of the 54 valley-segment types (VSTs) and 32 of the 187 native species that occur within this EDU are not represented in status 1 or 2 lands. Furthermore, only one of the nine AES types have all stream sizes represented either separately or as an interconnected complex. Again, these statistics represent the best-case scenario, whereas in many other EDUs, like the Neosho or St. John's Bayou, we are essentially starting with a "clean slate" in terms of representation. These results clearly indicate that the existing public lands in Missouri do not even come close to holistically representing the full spectrum of freshwater biodiversity, especially at higher levels of ecological organization. Our failure to examine and attempt to conserve our freshwater resources within these broader contexts has likely contributed to the decline of freshwater biodiversity in Missouri, which has many freshwater species exhibiting significant declines (MDC 2006).

Some of the most illuminating results were revealed by our analyses that assessed representation of aquatic ecological systems (AESs) using a hierarchical set of criteria. Using the least stringent critieria, which simply required that all stream sizes within an AES be represented in status 1 or 2 lands, only 19 of the 542 individual AESs were determined to be "effectively represented" and these 19 only represented six of the 39 distinct AES types. These results illustrate that in most instances different stream size classes are represented in entirely different watersheds. Applying more stringent criteria, which required representation of the various stream sizes as an interconnected matrix, only 12 of the 19 AESs met the criteria. These results show that even in those situations where all stream size classes are represented within the same watershed, they are many times represented in different parts of the watershed. This fragmented nature of public ownership is probably one of the most pressing conservation issues that must be addressed in the future. When you consider that many riverine species require a range of stream sizes to meet all of their life-history requirements (Schlosser 1995), it becomes evident that in Missouri greater

attention must be paid to the spatial arrangement of future conservation lands or private land conservation measures. Finally, using all available human-threats data only four of the remaining 12 AESs were considered to have relatively high ecological integrity. These results illustrate that conservation lands do not ensure effective long-term conservation for riverine ecosystems due to the effects of human disturbances occurring outside of protected areas (Pringle 2001). These results also illustrate the need for gap analyses to include some assessment of human disturbance in order to accurately assess conservation gaps.

Aside from the results of the statewide analyses, results of our gap analyses paint a bleak picture in terms of the representation of Missouri's freshwater biodiversity within status 1 or 2 lands and possibly its long-term conservation. However, these results are to be expected considering the fact that most public lands have been opportunistically established because they lacked commercial value, are difficult to develop, or have high scenic or recreational value (Shands and Healy 1977, Pressey 1994, 1995, Scott et al. 2001). In addition, most status 1 or 2 lands have been set aside for the conservation of terrestrial biota and have largely ignored aquatic biodiversity (Noss and Kranz 2001). Sullivan and Shaffer (1975) predicted that such opportunistic reserve selection and establishment methods would result in a network of reserves that is very inefficient at representing the diversity of ecosystems and their associated processes. Our results pertaining to the representation of Missouri's freshwater ecosystems and component resources are certainly consistent with these predictions.

Since most of Missouri and its stream resources are within private ownership, successful conservation of freshwater biodiversity will require creative partnerships between resource agencies and private landowners. The many federal and state conservation-incentive programs that are currently used as management tools are certainly a step in the right direction. However, we believe the results our gap analyses illustrate the need for a more strategic approach to where these and other conservation measures are applied on the landscape. Randomly applying the conservation measures across the landscape will likely not provide the same level of benefits as would efforts directed at restoring and protecting key locations across the riverscape that represent the diversity of freshwater ecosystems in Missouri. The data we have developed for the Missouri Aquatic GAP Project are perfectly suited to develop such strategies, as will be illustrated in the following section.

Wildlife Action Plan for Conserving Missouri's Freshwater Biodiversity

In Missouri, the Department of Conservation (MDC) was responsible for developing the Wildlife Action Plan (WAP). The MDC contracted with MoRAP, the Missouri Resource Assessment Partnership, to develop customized GIS projects that would assist in the development of the statewide plan for conserving freshwater biodiversity. These customized GIS projects included all of the data compiled or created for the Missouri Aquatic GAP Project as well as other pertinent geospatial data. At the same time, MDC developed customized GIS projects for developing a statewide plan for conserving terrestrial biodiversity. Results of these two separate, but parallel, plans were merged into a single WAP for the state (MDC 2005). This section of our monograph covers the methods and results of the Missouri WAP that pertain to the conservation of freshwater biodiversity.

Methods

After the customized GIS projects were developed, a team of aquatic resource professionals from Missouri was assembled to address each of the basic components of conservation planning discussed above (see *An overview of biodiversity conservation planning*). First, the team formulated an overall goal for the planning effort—"Ensure the long-term persistence of native aquatic plant and animal communities, by conserving the conditions and processes that sustain them, so people may benefit from their values in the future" (MDC 2005:2). A tactical objective for achieving this goal was also established— "Identify and map a set of aquatic conservation-opportunity areas (COAs) that holistically represent the full breadth of distinct riverine ecosystems and habitats in Missouri and multiple populations of all native aquatic species" (MDC 2005:2).

Next, the team put together a list of principles, theories, and assumptions that must be considered in order to achieve the overall goal and to guide the development of the conservation strategy that would be used to meet the tactical objective. Most related to basic principles of stream ecology, landscape ecology, and conservation biology as reflected in the decisions made by the team and presented below. However, some reflected the personal experiences of team members and the challenges they face when conserving natural resources in regions with limited public land holdings. For instance, one of the assumptions identified by the team was—"Success will often hinge upon the participation of local stakeholders, which will often be private landowners" (MDC:3). In fact, the importance of private lands management to aquatic biodiversity conservation was a topic that permeated the initial meetings of the team.

The MoRAP aquatic ecological classification hierarchy was adopted as the geographic framework (i.e., planning regions and asssessment units) for developing the conservation plan. This decision was based on the recognition that biodiversity conservation requires an ecosystem approach (Franklin 1993, Grumbine 1994, Leslie et al. 1996, De Leo and Levin 1997) and that

biodiversity can be described and should be conserved at multiple levels of organization (Whittaker 1962, 1972, Noss 1990, Angermeier and Schlosser 1995, Jennings 1996, Rabeni and Sowa 1996, Grossman et al. 1998, Olson and Dinerstein 1998, Abell et al. 2000).

The team recognized our limited understanding of the life-history requirements of most freshwater species and agreed with the assumption that taking measures to conserve a variety of biotic and abiotic conservation targets is the best and most efficient approach to conservation (Kirpatrick and Brown 1994, Noss et al. 2002, Diamond et al. 2005). From the classification hierarchy, aquatic ecological system (AES) types and valley-segment types (VSTs) were selected as abiotic- or habitat-conservation targets. For biotic targets, a list of target species (fish, mussel, and crayfish) was developed for each ecological drainage unit (EDU). These lists represent species of conservation concern, endemic species, and focal or characteristic species (e.g., top predators, dominant prey species, unique ecological role, etc.; MDC 2005). Recognizing the limitations of existing sampling data it was also agreed that all biological statistics would be based on the predicted distributions developed for the Missouri Aquatic GAP Project, but that actual collection data would also be used when it was deemed necessary during the planning process.

The team then crafted a conservation strategy for meeting the tactical objective and overall goal of the planning effort. First, the team selected the EDU level of the classification hierarchy as the primary planning unit. It was agreed that separate conservation plans should be developed for each EDU in order to conserve the distinct evolutionary histories of these ecological units. This decision was based on the theory that major drainage systems are analogous to islands embedded within the landscape and the assumption that freshwater biodiversity conservation must be similar to the approach taken to conserve biodiversity on a chain of islands (Sheldon 1988).

The team agreed with the contentions of Leslie et al. (1996) and Meffe and Carroll (1997) that populations, not species, should be considered the fundamental unit of biological conservation. The team also agreed with the axiom of conservation biology that redundancy in representation of populations is a safeguard against extinction and that redundancy promotes the generation of biodiversity through processes like adaptive radiation, random genetic mutations, and genetic drift (Noss and Cooperrider 1994, Meffe and Carroll 1997, Shaffer and Stein 2000, Groves 2003). Following this logic it was decided that, whenever possible, conservation-opportunity areas (COAs) should be selected in order to represent at least two spatially distinct occurrences of each target species within each EDU. Since most species occur in more than one EDU this method results in the representation of several distinct populations, occurrences, or phylogenies for many species.

For the abiotic targets it was first determined that the plan should attempt to conserve an individual example of each AES type within each EDU. This decision was based on several realizations including our extremely limited understanding of the metapopulation dynamics of the hundreds of species being addressed in the plan and thus the relative importance the various watershed types or riverscapes to these species. As a safeguard the team agreed it was best to represent the full array of riverscapes within each EDU (cf. Schlosser 1991). The team also realized that ecological systems are constantly changing due to natural and human-induced forces and therefore from a long-term perspective this decision was also made in an effort to account for successional pathways and safeguard against long-term changes in environmental conditions caused by factors like global climate change (Fausch et al. 2002). For instance, climatic or land-use changes may make conditions in one AES type unsuitable for a certain species, but at the same time make conditions in another AES type more favorable.

Because of competing societal demands and the limited human and financial resources dedicated to biodiversity conservation we must recognize that we cannot conserve everything. In many instances we can only conserve a relatively small fraction of the resource base (Scott et al. 1993, Rodrigues et al. 2003). We must therefore strive for efficiency in our conservation efforts (Margules and Pressey 2000). Although most AES types contain an array of stream types, each one is dominated (in terms of total stream length) by only a handful of types. In an effort to be efficient in the design of the conservation plan the team agreed that the boundaries of the COAs should be drawn to represent the dominant VSTs within each selected AES. This method in theory should represent the dominant physicochemical conditions within each AES, which we assume represent the environmental conditions to which most species in the associated assemblage have evolved adaptations for maximizing growth, reproduction, and survival (cf. Southwood 1977).

Connectivity among habitats is often essential for meeting the various life-history requirements of riverine species, as well as providing essential dispersal avenues during periods of disturbance (Schlosser 1987, 1995, Matthews 1998, Pringle 2001, 2003, Fausch et al. 2002, Rabeni and Sowa 2002, Benda et al. 2004). For instance, during periods of severe drought many headwater species may have to seek refuge in larger streams in order to find any form of suitable habitat due to the lack of water or flow in the headwaters (Matthews 1998, Fausch et al. 2002). Recognizing the importance of hydrologic connectivity it was decided that the location and boundary of each COA would be drawn to represent at least 1 km of the dominant VSTs for each stream size class (headwater, creek, small river, large river, or great river) as an interconnected complex. By representing at least 1km of each valley-segment type the

TABLE 10. Assessment criteria used for prioritizing and selecting aquatic ecological system (AES) polygons and valley-segment type (VST) complexes for inclusion in the portfolio of conservation-opportunity areas.

AES-level criteria	VST-level criteria
Select the AES polygon that:	Select an interconnected complex of VSTs that:
1) Has the highest predicted richness of target species	1) Contains known viable populations of species of special concern
2) Has the lowest degree of human disturbance based on human-threat index (HTI) value and qualitative evaluation of threats using the full breadth of available human-threats data	2) Has the lowest degree of human disturbance based on a qualitative evaluation of relative local and watershed conditions using the full breadth of available human-threats data
3) Has the highest percentage of public ownership	3) Is already contained within the existing matrix of public lands
4) Overlaps with existing conservation initiatives or high public support for conservation	4) Overlaps with existing conservation initiatives or high public support for conservation

Note: Criteria were examined in an iterative and simultaneous fashion but are listed in order of importance.

team assumed that each COA would represent a wide spectrum of the diversity of local stream habitat types (e.g., riffles, pools, runs, backwaters, etc.) within each VST, which would possibly account for seasonal and ontogenetic changes in local habitat use or changes in habitat use brought about by disturbance (e.g., floods and droughts). For instance, many species require different habitats for foraging (deep habitats with high amounts of cover), reproduction (high-gradient riffles), over-wintering (extremely deep habitats with flow refugia or thermally stable habitats like spring branches), or disturbance avoidance (deep or shallow habitats with flow refugia). Recognizing the importance of headwater streams as key reproductive and nursery habitats for many species (Meyer et al. 2003) it was also decided that each COA should contain at least three examples of the dominant headwater VST. This last decision was also based on the recognition that many headwater species (e.g., darters and sculpins) have extremely limited home ranges (Hill and Grossman 1987) and the need to represent multiple distinct occurrences or populations for such species.

The team then established quantitative and qualitative assessment criteria for making relative comparisons and establishing priorities among the assessment units. Since the assessment was conducted at two spatial grains (i.e., AES and VST) there exist two different assessment units with criteria for establishing priorities developed separately for each (Table 10). Assessment criteria were examined in an iterative fashion with the objective of simultaneously meeting as many of the criteria as possible at a particular location. For instance, the idealized objective of the AES-level criteria was to identify the AES of each type that had the highest target species richness and lowest human disturbance and highest percentage of public land and contained existing conservation initiatives. The decision to select the least impacted locations was based on the assumption that proactive conservation measures are less costly and more likely to succeed than restoration activities (Scott et al. 1996). Selecting locations within existing public lands recognized that it is easier to implement conservation action on these lands and that they provide a safeguard against future disturbance and permanent conversion (Rodrigues et al. 2003). Finally, in trying to select locations with existing conservation initiatives we recognized that public support is critical to the success of biodiversity conservation efforts.

The conservation strategy and assessment is essentially a five-step process. First the AES selection criteria are used identify one priority AES of each type within the EDU. Next, within each selected AES we used the VST selection criteria to identify a priority complex of the dominant VSTs. Within a GIS we then created a map of the localized subdrainage (termed "conservation-opportunity area," COA) that specifically contained the selected interconnected complex of VSTs. After representing abiotic targets we evaluated the capture of all target species and, if necessary, additional COAs were selected to capture underrepresented species.

Each COA was given a name that generally corresponded with the name of the largest tributary stream. The team also documented other information for each COA to facilitate future conservation action such as those agencies owning land within the COA or watershed and the primary human threats and management options (Sowa et al. 2005). This information was captured within an MS Access database that can be spatially related to the resulting GIS coverage of the COAs. All of this information is critical to the remaining logistical aspects of conservation planning that must be addressed once geographic priorities have been established.

The team used the conservation strategy and assessment process to develop a conservation plan for the Meramec EDU, which served as the initial pilot area. Once the core team finalized the conservation strategy and had completed the conservation plan for the pilot area, the state was partitioned into four regions with each of these regions containing four EDUs. Regional teams of aquatic resource professionals were then established for each region. Each team consisted of six or more resource managers/biologists with detailed and extensive knowledge of the stream resources within the region they were assigned. Three-day conservation planning sessions were held in each region during

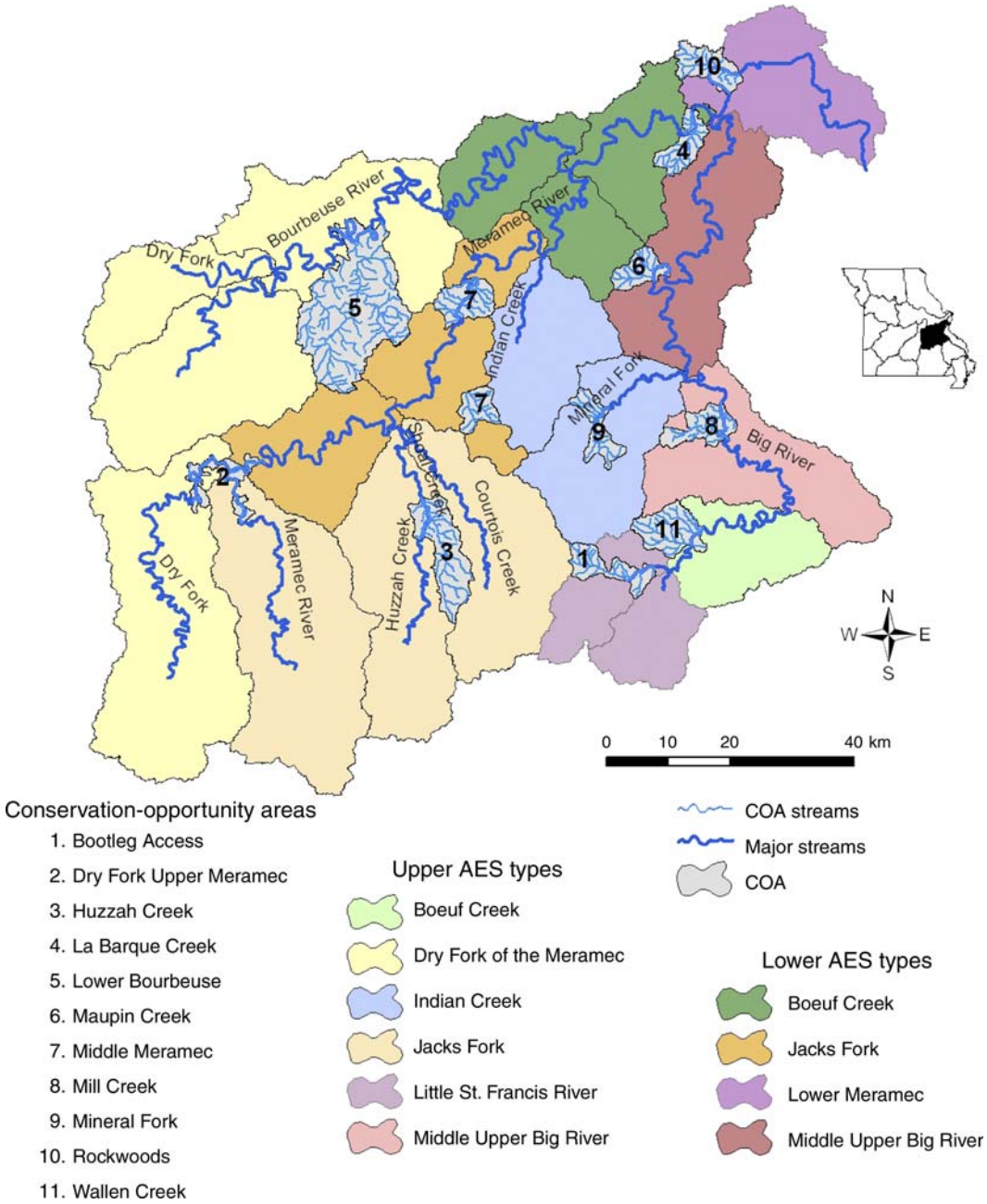

FIG. 8. Map of 11 conservation-opportunity areas (COAs), within the Ozark/Meramec ecological drainage unit (EDU), that were selected to meet all elements of the basic conservation strategy developed for the freshwater biodiversity conservation planning process in Missouri. The figure also shows the aquatic ecological system (AES) types for context. Lower and Upper types differ in terms of their position within the larger drainage network. Specifically, a "Lower AES type" contains streams classified as Large River and associated headwater and creek tributaries, while Upper types contain streams classified as Small River and these smaller tributaries.

summer and early fall of 2004. During these three-day sessions, the regional team used the GIS projects and conservation strategy to develop conservation plans for each of the EDUs within their region.

Results

Pilot area.—Using the above five-step process all components of the conservation strategy were met by selecting 11 COAs within the Meramec EDU (Fig. 8). With the initial assessment process and selection criteria, which focus on abiotic targets (AESs and VSTs), 10 separate COAs were selected. These 10 areas represent the broad diversity of watershed and stream types that occur throughout the Meramec EDU. Within this initial set of 10 COAs, all but five of the 103 target species were captured. We then examined the distribution of these

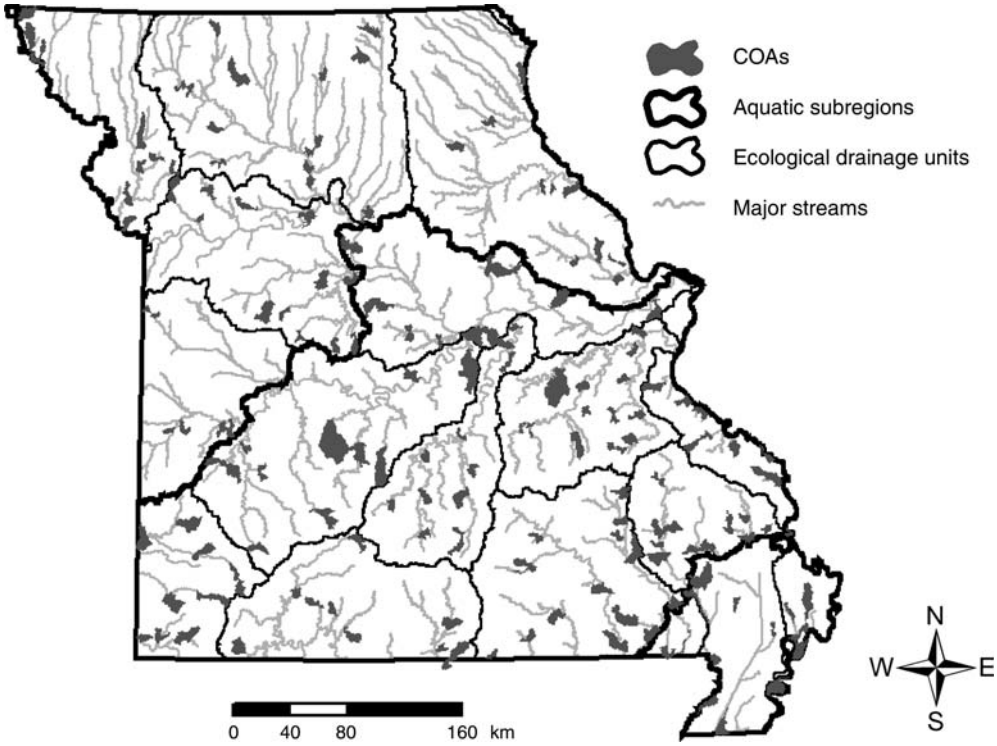

FIG. 9. Map showing all 158 freshwater conservation-opportunity areas (COAs) that were selected for Missouri. Taking measures to conserve all of these locations represents an efficient approach to conserving all of the distinct ecosystems, habitats, and species that occur within each ecological drainage unit (EDU).

five species, within a GIS, and quickly determined that the distribution of all five species overlapped within the same general area of the EDU, near the confluence of the Meramec and Dry Fork Rivers. Consequently, all five of these species were captured by adding a single COA (Dry Fork/Upper Meramec) (see Fig. 8). The final set of priority valley segments, within the 11 COAs, constitutes 299 km of stream. This represents 2.8% of the total length of stream within the Meramec EDU. The COAs themselves represent an overall area of 552 km^2, which is just 5% of the nearly 10 360 km^2 contained within the EDU.

Statewide.—Conservation plans were completed for all 17 EDUs in Missouri. Statewide, a total of 158 COAs were identified through the above assessment and planning process (Fig. 9). These COAs represent the broad diversity of stream ecosystems, riverine assemblages, and populations of all 296 native fish, mussel, and crayfish species within Missouri, yet cover a relatively small percentage of the landscape. Specifically, the COAs contain 10 915 km of stream, which represents 6.3% of the total 174 059 km. In terms of land area, the COAs cover 11 331 km^2 (2.8 million acres), or just 6.6% of the state.

Discussion

The COAs identified during the statewide conservation planning effort encompass ~6.3% of the total length of stream in the state. Currently, 5% of the total length of stream in Missouri is in public ownership. Consequently, there are nearly as many kilometers currently in public ownership as what the conservation planning results suggest is minimally required to represent the "full range" of variation in stream ecosystems, habitats, and multiple populations of all fish, mussel, and crayfish species that occur within the state. However, the results of our gap analyses, presented earlier, clearly illustrated that the existing network of conservation lands does not even come close to effectively representing the full spectrum of riverine ecosystems, habitats, and species that occur in Missouri, especially when more stringent criteria (e.g., connectivity) are used. This irony illustrates the fact that many of the conservation lands in the United States, including Missouri, were established opportunistically with little or no regard for protecting biodiversity (Shands and Healy 1977, Scott et al. 2001). It also illustrates that even in those instances where lands were set aside for conserving biodiversity in Missouri, rarely has freshwater biodiversity been a primary consideration (Leahy 2006). Most importantly, these results illustrate the critical need for geospatial data on various elements of biodiversity and using the conservation-planning process for strategically developing a network of complementary conservation areas that efficiently and

effectively represent biodiversity within a planning region.

The 158 COAs that were identified and mapped across the state provide a blueprint for holistic conservation of the freshwater ecosystems within Missouri, as opposed to the opportunistic approach used in the past. These areas can be, and already are being, used to guide protection efforts such as land acquisitions, restoration efforts, and regulatory activities like the permit-review process administered under the Clean Water Act. These areas also provide an ideal template for research designed to elucidate fundamental ecological processes within riverine ecosystems since they generally represent the least disturbed examples of the various stream ecosystems and habitats that presently exist within Missouri.

During the conservation-planning process we found that the local experts are often humbled by the GIS data. Often, what appear to be the best places to conserve are those places that the local managers know little or nothing about. This exemplifies that the world is a big place, and we cannot expect a handful of experts to know every square inch of an ecological drainage unit (i.e., 10 000+ km^2). At the same time we also found that the GIS data are often insufficient and, if solely relied upon, would often lead to poor decisions. There were several instances where GIS data identified a particular location, while local experts quickly pointed out that, for example, the sewage treatment facility just upstream had one of the worst spill records in the state, and fish kills occur almost on an annual basis. While the GIS data show the location of the sewage treatment facility, they do not contain this more detailed contextual information. Obtaining and capturing this type of information within a GIS must become a priority.

We were pleasantly surprised by the fact that even in the most highly altered and severely degraded landscapes we were able to identify "hidden jewels" that have somehow escaped the massive landscape transformations and other insults in neighboring watersheds. This experience revealed the social aspects of land-use patterns described by Meyer (1995). Yet, in many instances these relatively high-quality locations were quite small and therefore highly susceptible to any future changes in local or watershed conditions. Those COAs facing immediate threats must be identified and the necessary conservation actions must be put into action quickly.

The conservation strategy we developed initially focused on representing all distinct watershed (AES types) and stream types (VSTs) within each EDU. In every instance, this initial strategy of representing abiotic targets successfully represented 95–100% of the biotic targets within the initial set of COAs. This is especially surprising in the Ozark aquatic subregion, which contains numerous local endemics with very restricted and patchy distributions. These results suggest that our classification units do a good job of capturing natural variation in stream habitat and watershed characteristics that are partly responsible for the patchy distribution of these species. These results also illustrate the utility of abiotic targets for freshwater conservation planning, which can prove critical for regions lacking sufficient biological data (e.g., Chadderton et al. 2004, Thieme et al. 2005).

Another surprising result was that we were able to represent all abiotic and biotic targets within a relatively small fraction of the overall resource base (~6%). Unfortunately, the area that must be managed in order to protect or restore the ecological integrity of any given COA is often substantially larger and more daunting than the boundaries we delineated. In some instances, the most important initial conservation action will have to occur outside of a given COA. However, the spatially explicit nature of the COAs provides focus for resource managers, because even when on-the-ground management is far removed from one of these priority locations, the streams and assemblages within each COA are the ultimate focus of conservation action.

When we began our project we recognized the fact that, whenever possible, priorities should be established at a scale that managers can understand and use (e.g., individual stream segments) in order to apply spatially explicit conservation actions. Each team of local experts found the conservation-planning process much more useful than previous planning efforts they were involved in, which identified relatively large areas as priorities for conservation. The managers stated that, because we selected localized complexes of specific stream segments, much of the guesswork on where conservation action should be focused has been taken "out of the equation," which will expedite conservation action.

Since conservation efforts cannot be initiated immediately within all of the COAs, priorities must be established among the COAs in order to develop a schedule of conservation action (Margules and Pressey 2000). For Missouri, this will initially take place within each EDU and then again from a statewide perspective. An important aspect of generating a "comprehensive" plan is that conservation is often driven by opportunity and by identifying a portfolio of priority locations where quick action can be taken when opportunities arise (Noss et al. 2002).

Selecting COAs is the first step toward effective biodiversity conservation, and the Gap Analysis Program is providing data critical to this task. Yet, establishing geographic priorities is only one of the many steps in the overall process of achieving real conservation. Achieving the ultimate goal of conserving biodiversity will require vigilance on the part of all responsible parties, with particular attention to addressing the many remaining logistical exercises such as securing necessary funds, garnering public and political support, coordination among stakeholders, and prioritizing and implementing on-the-ground management efforts.

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APPENDIX A

A table detailing the hierarchical framework with defining physical and biological features used for classifying and mapping riverine ecosystems (*Ecological Archives* M077-010-A1).

APPENDIX B

A map showing the ecological drainage units (EDUs) of Missouri (*Ecological Archives* M077-010-A2).

APPENDIX C

A map of the 39 distinct aquatic ecological system (AES) types for Missouri (*Ecological Archives* M077-010-A3).

APPENDIX D

A map example showing nine distinct valley-segment types (VSTs) that occur within a single 12-digit hydrologic unit (*Ecological Archives* M077-010-A4).

APPENDIX E

Maps of predicted total species richness (fish, mussels, and crayfish) and predicted richness of globally rare, threatened, and endangered species for Missouri (*Ecological Archives* M077-010-A5).

APPENDIX F

A map of stream segments flowing through public land categorized by GAP management status (*Ecological Archives* M077-010-A6).

APPENDIX G

Maps showing the individual component values and overall combined values in the human-threat index (HTI) for each aquatic ecological system (AES) in Missouri (*Ecological Archives* M077-010-A7).

APPENDIX H

A map of stream segments flowing through GAP management status 1 or 2 lands, further broken down by stream size (*Ecological Archives* M077-010-A8).

APPENDIX I

A table providing conservation status statistics for 74 distinct valley-segment types (VSTs) in Missouri (*Ecological Archives* M077-010-A9).

APPENDIX J

A map showing the number and percentage of valley-segment types (VSTs) that are represented in GAP management-status 1 or 2 lands for each ecological drainage unit (EDU) (*Ecological Archives* M077-010-A10).

APPENDIX K

Maps showing aquatic ecological systems (AESs) that have all stream size classes represented in GAP management-status 1 or 2 lands (*Ecological Archives* M077-010-A11).

APPENDIX L

Maps showing the major human disturbances affecting those aquatic ecological systems (AESs) that have all stream sizes represented as an interconnected complex within GAP management-status 1 or 2 lands (*Ecological Archives* M077-010-A12).

APPENDIX M

Statewide management-status statistics for each fish, mussel, and crayfish species in Missouri, by stream length (*Ecological Archives* M077-010-A13).

APPENDIX N

A list of 45 native fish, mussel, and crayfish species that are currently not represented in GAP management-status 1 or 2 lands (*Ecological Archives* M077-010-A14).

APPENDIX O

A map showing the number and percentage of native fish, mussel, and crayfish species that are not represented within the GAP management-status 1 or 2 lands of each ecological drainage unit (EDU) (*Ecological Archives* M077-010-A15).

APPENDIX P

A map showing the number and percentage of native fish, mussel, and crayfish species that have less than two distinct occurrences with the GAP management-status 1 or 2 lands of each ecological drainage unit (EDU) (*Ecological Archives* M077-010-A16).