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A Classification System for Large Reservoirs of the Conterminous U.S

Rebecca Misaye Krogman

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By

Rebecca Misaye Krogman

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By

Rebecca Misaye Krogman

Approved:

____
Leandro E. Miranda
Professor of Wildlife, Fisheries and Aquaculture
(Major Professor)

____
Janice L. DuBien
Associate Professor of Mathematics and Statistics
(Minor Professor)

____
Zhaofei Fan
Assistant Professor of Forestry
(Committee Member)

____
Eric D. Dibble
Professor of Wildlife, Fisheries and Aquaculture
(Graduate Coordinator)

____
Bruce A. Leopold
Head of the Department of Wildlife, Fisheries and Aquaculture

____
George M. Hopper
Dean of the College of Forest Resources

Name: Rebecca Misaye Krogman

Date of Degree: December 15, 2012

Institution: Mississippi State University

Major Field: Wildlife and Fisheries Science

Major Professor: Dr. Leandro E. Miranda

Title of Study: A classification system for large reservoirs of the conterminous U.S.

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Candidate for Degree of Master of Science

Reservoirs represent a relatively young element of the U.S. landscape, with most reservoirs being built within the last century. Despite their recreational, ecological, and socioeconomic importance, reservoirs nationwide are suffering from severe habitat degradation. Habitat impairments related to siltation, eutrophication, poor water quality, water regime, lack of submerged structure, and macrophyte invasions affect reservoirs to differing degrees in different reservoirs. To adequately assess these issues, we needed to develop a classification system within which an assessment mechanism could function. I collected data for large reservoirs across the conterminous U.S. regarding fish habitat impairments and status of the fish community and recreational fishery. Using these data, I developed a fish habitat classification system for large U.S. reservoirs, which can be used to better understand differences among reservoirs, develop habitat management expectations, and prioritize conservation efforts.

DISCLAIMER

The views and conclusions contained in this document are those of the author and should not be interpreted as representing the opinions or policies of the U.S. Government, the Mississippi Cooperative Fish and Wildlife Research Unit, or Mississippi State University. Mention of trade names or commercial products does not constitute their endorsement by said parties.

DEDICATION

This research is dedicated to my husband Kerry, whose unfailing support (and indulgence) kept me going for the past two years, and to my family, who always believed I could be whatever I wanted to be.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Reservoir construction in the U.S.

Reservoirs represent a relatively young element of the U.S. landscape, with most reservoirs being built within the last century (Figure 1.1). About 100 reservoirs with surface areas exceeding 200 hectares (ha) had been constructed by 1900 (Jenkins 1970), and pace of construction increased substantially as new technology became available (Miranda 1996). By 1970, approximately 1,320 reservoirs exceeding 500 ha had been constructed (Jenkins 1970). Construction slowed in the 1970s as optimal building sites dwindled (Miranda 1996). Today, over 83,000 dams or other water control structures are included in the National Inventory of Dams (NID; see criteria for inclusion in USACE 2009). Nearly every major U.S. river has been impounded somewhere along its reaches (Benke 1990), and the number of large reservoirs is dwarfed by the thousands of smaller reservoirs on tributaries (USACE 2009).

Most reservoirs catalogued in the NID were constructed for one or more primary purposes, including flood control, municipal water supplies, navigation, hydropower, and irrigation; rarely were wildlife or fisheries conservation considered during dam licensing (Figure 1.2). In fact, most dams were licensed prior to existence of environmental regulations (e.g., the Clean Water Act or the Endangered Species Act; Ney et al. 1990). However, recreational and ecological values of reservoirs became quickly apparent, and recreational use was cited frequently as a primary purpose on justification documents. As documented by Ney et al. (1990), creation of reservoirs in the southeastern U.S. quickly expanded recreational fishing opportunities and attracted tourism to an area. By 1965, reservoirs attracted approximately 25% of all freshwater fishing in the U.S., and by 1970, approximately 40% (Jenkins 1970). By 1991, 69% of freshwater anglers fished in reservoirs or lakes (USFWS 1991); by 2006, this percentage had increased to 84%, equivalent to approximately 25 million anglers (USFWS 2006). These individuals spent approximately $24.6 billion in direct fishing expenditures. Despite the importance of recreational fisheries and reservoir fish habitat, fishery and habitat management in reservoirs has traditionally been constrained by the requirements of the reservoir's primary purpose (Ney et al. 1990; Kennedy 2005).

1.2 Fish habitat degradation in reservoirs

Due to the nature of their construction, reservoirs are prone to an accelerated rate of ecological succession compared to natural lakes (Wetzel 1990). Completion and closure of a dam results in inundation of formerly terrestrial habitats rich in nutrients and organic matter (Neel 1967). This results in a brief trophic upsurge, a period during which space, food, and habitat are abundantly available, paired with a productive recreational fishery (Ploskey 1981; Miranda and Durocher 1986). However, terrestrially-derived nutrients are depleted within only a few years (Murphy 1962), substrates are filled in with silt and detritus, and reservoir productivity decreases to an equilibrium with watershed inputs (Kimmel and Groeger 1986). At this turning point, the close tie between the reservoir and its watershed becomes the main driver of a series of chemical, physical, structural, and biological changes in the reservoir. Reservoirs tend to have much larger watersheds relative to surface area than natural lakes, and they receive relatively greater allochthonous inputs from incoming tributaries (Thornton 1990). Sediments and nutrients flowing into the reservoir slow and settle, either accumulating in the benthic zone or entering the food web through photosynthetic uptake (Thornton 1990). The reservoir will eutrophy, water quality will decline, and eventually abundant nongame fish species will prevail (Kimmel and Groeger 1986). Whereas these changes can be associated with natural processes (e.g., channel evolution following pool formation in a stream), Kimmel and Groeger (1986) speculated that ecological succession in reservoirs would occur much more slowly without additional anthropogenic disturbances.

Habitat issues such as excessive suspended sediments, excessive nutrient loadings, and lack of submerged structure may emerge in an aging reservoir and worsen over time (Miranda 2008). An early limnological study of several Texas reservoirs observed that relative species abundance of fishes differed among reservoirs of various ages, but no measures of the fish assemblage were taken (Harris and Silvey 1940). Later investigations found that reservoir age was correlated significantly to increased abundance of forage species (e.g., clupeids and catastomids; Jenkins 1967; Gido et al. 2000) and decreased abundance of recreational species (Jenkins 1967). As benthic and littoral habitats deteriorate, pelagic species will tend to increase in abundance, whereas substrate-dependent species will decline (Agostinho et al. 1999). In Texas reservoirs, largemouth bass *Micropterus salmoides* growth rates declined rapidly following impoundment (Miranda and Durocher 1986). Therefore, changes in reservoir fish community structure and fishery quality can be attributed partially to habitat degradation associated with reservoir aging. With mean age of U.S. reservoirs approaching 60 years and demand for recreational fishing opportunities increasing, the issue of aging reservoirs with impaired fish habitat has become a serious concern for fishery managers.

Given the worsening habitat condition of reservoirs and lack of a nationally-applicable method of habitat assessment, the purpose of this study was to develop a classification framework for U.S. reservoirs within which an assessment mechanism could function. This purpose yielded three objectives: 1) to develop a classification system based on fish habitat impairment, 2) to establish support for the classification using external datasets, and 3) to investigate how the classification related to the fish community and recreational fishery.

1.3 Thesis organization

This thesis is organized into four chapters. Chapter I provides a general introduction to reservoirs in the U.S. and the habitat degradation associated with reservoir aging. Chapter II comprises an extensive literature review regarding how reservoirs relate to their surrounding landscapes, their common habitat impairments, and previous efforts to classify reservoirs into logical groups. The issues set forth and the lack of an adequate classification system implied in Chapter II illuminate the reasons for conducting the research herein. Chapter III contains the bulk of my research and is formatted as a manuscript for publication in a fisheries scientific journal. For this reason, some portions of Chapter III (e.g., the Introduction) may appear to be redundant with portions of Chapters I and II. Additionally, the first-person plural tense is used throughout Chapter III, in reference to the co-authoring of the manuscript by my graduate advisor, Dr. Steve Miranda. Chapter IV provides a general synthesis of the project as well as recommendations for future work. Four appendices provide supplementary information that may be useful to the reader to enhance understanding of the project.

1.4 Figures

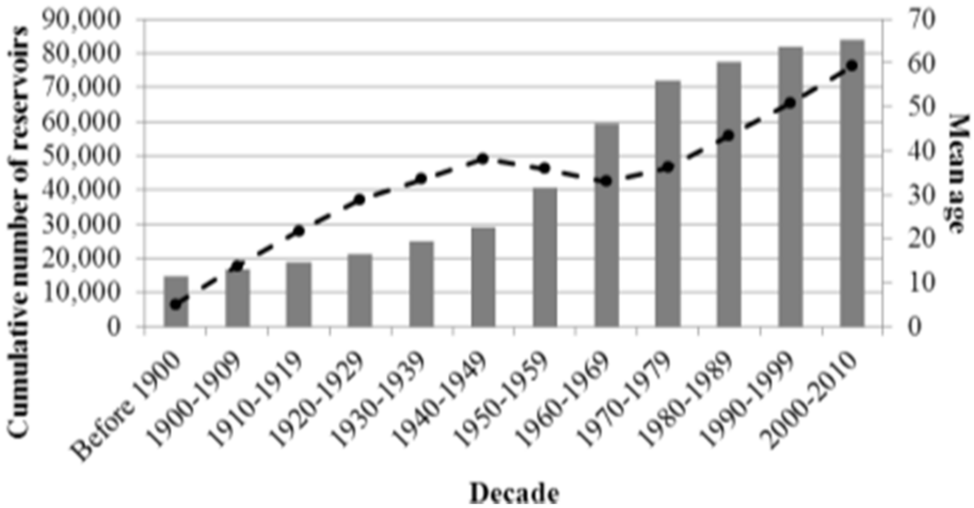

Figure 1.1 Cumulative number of reservoirs constructed in the U.S. (bars) and mean age of reservoirs (dashed line). (Adapted from USACE 2009.)

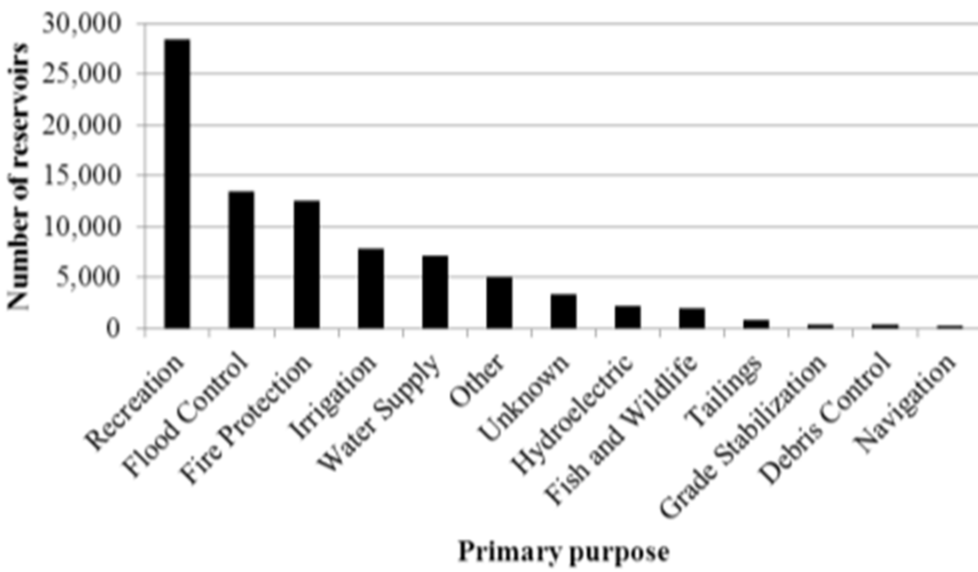

Figure 1.2 Primary purposes of dams catalogued in the U.S. Army Corps of Engineers National Inventory of Dams.

Note that dams may have multiple primary purposes. (Adapted from USACE 2009.)

1.5 References

Agostinho, A. A., L. E. Miranda, L. M. Bini, L. C. Gomes, S. M. Thomaz, and H. I. Suzuki. 1999. Patterns of colonization in neotropical reservoirs, and prognoses on aging. Pages 227-265 *in* J. G. Tundisi and M. Straškraba, editors. Theoretical Reservoir Ecology and its Applications, Brazilian Academy of Sciences, Rio de Janeiro, Brazil.

Benke, A. C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77-88.

Gido, K. B., W. J. Matthews, and W. C. Wolfinbarger. 2000. Long-term changes in a reservoir fish assemblage: stability in an unpredictable environment. Ecological Applications 10:1517-1529.

Harris, B. B., and J. K. G. Silvey. 1940. Limnological investigations of Texas reservoir lakes. Ecological Monographs 10:111-143.

Jenkins, R. M. 1967. The influence of some environmental factors on standing crop and harvest of fishes in U.S. reservoirs. Pages 298-321 *in* Reservoir Fishery Resources Symposium. Southern Division American Fisheries Society, Bethesda, Maryland.

Jenkins, R. M. 1970. Reservoir fish management. Pages 173-182 *in* N. G. Benson, editor. A Century of Fisheries in North America. American Fisheries Society, Special Publication 7, Washington, D.C.

Kennedy, R. H. 2005. Toward integration in reservoir management. Lake and Reservoir Management 21(2):128-138.

Kimmel, B. L., and A. W. Groeger. 1986. Limnological and ecological changes associated with reservoir aging. Pages 103-109 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Miranda, L. E. 1996. Development of reservoir fisheries management paradigms in the twentieth century. Pages 3-11 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional Approaches to Reservoir Fisheries Management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Miranda, L. E. 2008. Extending the scale of reservoir management. Pages 75-102 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Miranda, L. E., and P. P. Durocher. 1986. Effects of environmental factors on growth of largemouth bass in Texas reservoirs. Pages 115-121 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Murphy, X. 1962. Effect of mixing depth and turbidity on the productivity of freshwater impoundments. Transactions of the American Fisheries Society 91:69-76.

Neel, J. K. 1967. Reservoir eutrophication and dystrophication following impoundment. Pages 322-332 in Reservoir Fishery Resources Symposium. Southern Division, American Fisheries Society, Bethesda, Maryland.

Ney, J. J., C. M. Moore, M. S. Tisa, J. J. Yurk, and R. J. Neves. 1990. Factors affecting the sport fishery in a multiple-use Virginia reservoir. Lake and Reservoir Management 6:21-32.

Ploskey, G. R. 1981. Factors affecting fish production and fishing quality in new reservoirs, with guidance on timber clearing, basin preparation, and filling. Technical Report E-81-11, prepared by Fish and Wildlife Service, National Reservoir Research Program, U.S. Department of Interior, for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Thornton, K. W. 1990. Sedimentary processes. Pages 43-70 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

USACE (U.S. Army Corps of Engineers). 2009. National Inventory of Dams (NID). Available: http://geo.usace.army.mil/pgis/f?p=397:1:3514628094309333. (December 2010).

USFWS (U.S. Fish and Wildlife Service). 1991. National survey of fishing, hunting, and wildlife-associated recreation. U.S. Government Printing Office, Washington, D.C.

USFWS. 2006. National survey of fishing, hunting, and wildlife-associated recreation. U.S. Government Printing Office, Washington, D.C.

Wetzel, R. G. 1990. Reservoir ecosystems: conclusions and speculations. Pages 227-238 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

CHAPTER II

LITERATURE REVIEW

2.1 A new outlook on reservoirs

The traditional paradigm of reservoir fisheries management views reservoirs as independent entities on the landscape, artificial environments with little connection to their watersheds (Miranda 1996). Management approaches guided by this paradigm focused on in-reservoir practices that had proven successful in natural lakes, such as fish stocking and installing habitat structures. However, reservoirs are dependent entities. Their entire lifespan evolution—from initial trophic surge to eutrophication to eventual filling in—points to their origin as inundated rivers and to their intrinsically close ties to the surrounding landscape (Hynes 1970; Wetzel 1990).

In contrast to natural lakes, reservoirs typically have larger, dendritic-shaped watersheds that encompass the watersheds of all incoming tributaries (Thornton 1990). They receive proportionally less inflow from adjacent lands and more inflow from upstream. Furthermore, reservoirs are typically built farther downstream, where their function of capturing water is more efficient, whereas lakes are often located in the upper portion of a drainage basin. Subsequently, reservoirs receive greater amounts of allochthonous inputs than natural lakes. Because they do constantly capture large quantities of water from upstream and release some of it downstream, reservoirs also have more brief hydraulic residence times than natural lakes.

Incoming water from tributaries follows a predictable process related to the construction of the reservoir before eventually flowing into the tailwater. First, water enters the riverine zone, the upstream zone characterized by more rapid flow velocity, shallower depths, and higher dissolved oxygen (Kimmel et al. 1990). As the reservoir deepens and widens toward the dam, water enters the transition zone between the riverine and lacustrine zones. At this point, flow velocities decrease, and suspended matter drops out of the water column and deposits on the bottom substrate. This is the zone of greatest sediment accumulation and may develop a deltaic formation similar to the mouth of a river over time (Vanoni 1975). Some nutrients like phosphorus bond to suspended sediments and drop out of the water column at the same time (Holtan et al. 1988). Other nutrients remain dissolved and suspended in the water column, floating downstream into the lacustrine zone of the reservoir. The lacustrine zone is the deepest part of the reservoir and features slower flow velocities, higher water clarity, and greater potential for stratification. In this zone, incoming nutrients like nitrogen combine with lake-like conditions to boost autochthonous production by phytoplankton, leading to eutrophication if nutrient loading is too high. Finally, water is expelled from the reservoir to the tailwater through a release mechanism. In short, the reservoir acts as a sink for sediments, nutrients, and other allochthonous inputs from the entire upstream watershed. Understanding the linkage between a reservoir and its watershed has been repeatedly emphasized more recently by reservoir fisheries scientists (Kennedy 2005; Miranda 2008).

2.2 Common reservoir habitat issues

2.2.1 Siltation

Siltation is one of the primary habitat concerns in reservoirs because it increases turbidity, homogenizes substrate, and reduces storage volume. Dendy et al. (1973) estimated mean annual rate of storage capacity loss to be 2.7% per year in small temperate reservoirs and 0.16% per year in large temperate reservoirs. Many reservoirs that had been built before 1953 in the U.S. Midwest, Great Plains, Southeast, and Southwest had already lost between one-quarter to three-quarters of their original volume by 1975 (Vanoni 1975). Ten percent of study reservoirs had lost all usable storage volume, meaning the reservoir could not even support its primary use. Sedimentation has not only resulted in significant losses in storage volume nationwide, but also in formation of silt levees that isolate reservoirs from their backwaters (Patton and Lyday 2008) and deltas that isolate reservoirs from their incoming tributaries (Vanoni 1975). In Lake Texoma, a large reservoir spanning the Texas and Oklahoma border, extensive levees have formed at the mouth of the incoming Washita River that are high enough to emerge from the water, allowing terrestrial vegetation to grow and further accelerate levee growth (Figure 2.1; Patton and Lyday 2008). Several coves have been isolated from the rest of the reservoir and are connected only during high water events. In California, Matilija Lake has trapped over 4.5 million m^3 of sediment since its construction in 1947 (Figure 2.2; Bureau of Reclamation 2010). Finer silt and clay particles that remain suspended in the water column can increase turbidity, reduce depth of the photic zone, and inhibit submerged macrophyte growth (Vanoni 1975); this problem is exacerbated in shallow areas where wind can cause resuspension (Van Duin et al. 1992).

Siltation affects fish in a myriad of ways. Settling of fine sediments homogenizes rocky substrates by filling in topography with silt and clay particles and can reduce fish spawning habitat and inhibit spawning success, resulting in the decline of lithophilic fish species, benthic invertebrates, and periphyton (Berkman and Rabeni 1987; Miranda and Bettoli 2010). If spawning does occur, further sedimentation may suffocate fish eggs and increase nest mortality. Furthermore, high turbidity that inhibits macrophyte growth can reduce amount of high quality littoral habitat, leading to a loss of littoral-dependent species. Highly-turbid water decreases predatory effectiveness of visual predators such as largemouth bass *Micropterus salmoides* and northern pike *Esox niger*, while allowing nonvisual species such as common carp *Cyprinus carpio* and buffalos *Ictiobus* spp. to thrive (Miranda and Bettoli 2010). Decreased vulnerability of prey species also may allow increases in population. Generally, sedimentation leads eventually to a fish assemblage lacking in piscivorous fishes. If sedimentation continues to the point of levee formation, substantial portions of backwater, wetland, and cove habitats may become disconnected from the main reservoir. These areas often provide spawning habitat, nursery habitat, or full-time habitat for numerous reservoir species. White crappie *Pomoxis annularis* and black crappie *P. nigromaculatus* in flood-control reservoirs of Mississippi typically recruit at higher rates in backwaters and wetlands than in coves (Dagel and Miranda 2012), despite the fact that backwaters do not flood until later in the spawning season.

2.2.2 Eutrophication and water quality

Most reservoirs receive high amounts of allochthonous inputs, including phosphorus and nitrogen. In freshwater ecosystems, phosphorus is most often the limiting factor for photosynthesis, and high phosphorus loading generally results in high primary production by phytoplankton and aquatic macrophytes (Schindler 1971b). For a variety of reasons discussed below, phytoplankton production is favored over macrophyte production, further increasing organic turbidity and shading submerged macrophytes. Increased primary production can boost secondary production, which boosts tertiary production, and so on in a trophic cascade. However, at a certain point, increased production leads to water quality and habitat problems. Very high algal production can inhibit submerged macrophyte growth to the point of reducing littoral habitat for fish (Ozimek et al. 1991), reduce dissolved oxygen levels in the metalimnion during senescence (Bachmann et al. 1996), and cause a hypoxic or anoxic layer to form on the benthos when senescent material sinks (Mallin et al. 2006). When the reservoir stratifies, which is typical in the lacustrine zone, hypoxia may render the entire bottom layer unsuitable for aquatic life (Cole and Hannan 1990). If nitrogen becomes a limiting factor in photosynthesis, blue green algae *Cyanobacteria* may outcompete true algae and proliferate (Schindler 1977). Blue green algae provide a less nutritious, even toxic food source for zooplankton and planktivorous fish and can cause anoxic or hypoxic conditions as algal masses senesce (Bachmann et al. 1996).

Intermediate trophic conditions can provide high quality water and recreational fisheries (Maceina et al. 1996). For example, crappies, spotted bass *M. punctulatus*, and largemouth bass size structure and growth rates were correlated positively with increasing trophic levels in Alabama reservoirs (Bunnell et al. 2006; DiCenzo et al. 1995; Allen et al. 1999). Maximum biomass and optimal densities of game species in Florida lakes occurred in mesotrophic conditions (Bachmann et al. 1996), and maximum largemouth bass growth in Texas reservoirs occurred at intermediate values of the morphoedaphic index (Miranda and Durocher 1986). Jenkins (1967) found a positive correlation between total dissolved solids and sport fish harvest per unit area in southeastern reservoirs, likely due to the high correlation between total dissolved solids and phosphorus. However, as eutrophication progresses, benefits decline invariably as the fish community shifts to a less desirable state. With increases in algal production and decreases in littoral habitat, representation of littoral-dependent species may decline whereas representation of pelagic, planktivorous species may increase. Planktivores such as gizzard shad *Dorosoma cepedianum*, buffaloes, and carpsuckers *Carpiodes* spp. benefit from increases in nutrient loading because they can directly exploit the resulting increase in primary production (Miranda 2008). A prime example is gizzard shad, a planktivorous forage fish found abundantly in high eutrophic systems. Vanni et al. (2006) found that gizzard shad not only consumed plankton and detritus, but also cycled nutrients and made them available for further primary production. Thus, gizzard shad biomass increased disproportionately with increased amounts of agriculture in the watershed. Benthic fish and invertebrate species will also decline as hypoxic regions grow, and fish habitat will be reduced to the region between the hypoxic bottom and the warm surface (Matthews et al. 1985). Fish kills related to anoxia or toxic algal blooms may also occur.

Alternatively, oligotrophication may be an issue in other reservoirs. Reduced external and internal nutrient loading may result in decreasing trophic status; reductions may stem from decreased runoff upstream, improved wastewater treatment, or nutrient trapping by upstream reservoirs (Ney 1996). This is typically of greater concern in reservoirs that do not receive as much nutrient loading from their watersheds, such as the southern and western U.S. (Miranda and Bettoli 2010). Oligotrophication may result in decreased fish production and fishery decline (Ney 1996).

2.2.3 Water regime

Water regime refers to the regular pattern of water inflow into and outflow from the reservoir, a pattern that is linked to and controlled by the reservoir's primary purpose (Kennedy 1999). Depending on the primary purpose, the target water level may look very different. In a navigation reservoir, where river traffic is required nearly year round, target water levels are always above a certain depth to allow barge and other boat traffic to pass upstream unhindered to the next lock. In a flood-control reservoir, where water is held back annually to reduce spring flooding downstream, water levels fluctuate dramatically during the year. In an irrigation or water supply reservoir, where water is retained as long as possible for use, water levels fluctuate slowly throughout multiple years, rising during wet years and dropping during drought. Because of the diversity of water regimes, reservoirs with different primary uses tend to have different sets of habitat issues.

Water regime-related habitat issues are typically caused by regularly-occurring changes in water level, rather than stability. During the initial stream impoundment, the ecotone between land and water moves continuously and dramatically (Duncan and Kubečka 1995), and may never stabilize depending on water regime control (Ploskey 1981). Stability of the land/water ecotone determines the ability of littoral vegetation to establish and influences bank erosion and deposition rates. In some reservoirs, such as flood-control reservoirs, annual changes are spatially extensive, ranging from very full in spring to nearly empty in winter. Extreme drawdowns during winter enable the reservoir to capture more water during spring, thereby mitigating floods. During drawdown, littoral habitats are exposed to the air, resulting in loss of that habitat. When water resubmerges the area, the littoral habitat may not reestablish itself due to the lack of a seed bank and insufficient time before the next drawdown. Colonization by terrestrial riparian plants is also hindered by repeated saturation and draining due to water level fluctuations, and highly erodible mudflats will replace littoral habitats in the drawdown zone. In the upper Tennessee River basin, carbon retention by plant biomass along reservoir shorelines decreased by a factor of 12 following impoundment (Amundsen 1994). Drawdowns may also reduce connectivity to backwaters and wetlands, isolating fish communities until water levels rise again. In other reservoirs, water level fluctuations may be less dramatic, but do not match the seasonal fluctuations a natural aquatic ecosystem might have, such as spring flooding.

Water level fluctuations can affect the fish community in several ways, particularly by altering the littoral zone. Littoral habitat serves as a feeding area, with plants and submerged structure acting as substrate for epiphytes and invertebrates (Hunt and Jones 1972). Herbivores and invertivores find food and cover in the littoral zone, and piscivores find hunting opportunities (Savino and Stein 1982; Valley and Bremigan 2002). The littoral zone may also be used for spawning and nursery habitat by phytophilic or structure-oriented fish species, and complete loss of littoral habitat could substantially affect amount of usable spawning habitat. Therefore, loss of littoral habitat leads to a decline in littoral-dependent species and an increase in pelagic species. Exposure of intact littoral habitat during the spawning season can reduce reproductive success through disruption of spawning or courting behaviors, abandonment of guarded nests, and egg desiccation and mortality (Ploskey 1981). In addition, water level fluctuations may be out of sync with instinctive seasonal fish behavior, resulting in mistimed or absent cues for spawning and migration and even loss of migratory fishes (Bunn and Arthington 2002). Given importance of seasonal cues to native riverine fish communities, a highly stable, "lake-like" water regime may not provide optimal fish habitat either (Bunn and Arthington 2002). If water level management can adequately simulate the natural flow regime, it is possible to mitigate water regime-related spawning issues; water level changes were used successfully in Kansas to improve spawning success of walleye *Sander vitreus*, white crappie, white bass *Morone chrysops*, and largemouth bass (Willis 1986). Extremely low drawdowns can also concentrate fish into a small volume, altering predator-prey interactions (Jenkins 1970; Ploskey 1986).

In addition to water level fluctuations, the primary purpose of a reservoir may alter the temperature regime. For instance, reservoirs used for industrial cooling have altered temperature regimes, often in the form of a lateral thermal gradient (Olmsted and Clugston 1986). Species with different temperature preferences may segregate spatially (Olmsted and Clugston 1986), and the growing season may even be extended by artificially high water temperatures (Jenkins 1967). Fish that congregate near effluent outflows may grow faster but may also become more vulnerable to fishing (Olmsted and Clugston 1986).

2.2.4 Structural habitat

Availability of structural habitat is closely related to water regime, as indicated by the multiple effects of water regime on littoral habitat. Complex physical structure, including aquatic macrophytes, large woody debris, and coarse substrates, is reduced in reservoirs compared to natural lakes. As aforementioned, high turbidity can inhibit photosynthesis in the water column, limiting the maximum depth where macrophytes will grow, and sedimentation can blanket coarse substrates with fine particles (Vanoni 1975). Water level fluctuations can further inhibit growth of aquatic macrophytes through desiccation (e.g., Moore et al. 2010) or freezing during low water levels (Cooke 1980). Other organic physical structure present, including large woody debris, evergreen trees, and stump fields, will decompose rapidly if repeatedly exposed to the air and then resubmerged (Bolding et al. 2004).

Complex physical structure in the littoral zone is correlated with increased fish species richness and fish abundance (Barwick 2004; Barwick et al. 2004). Large woody debris was associated with greater largemouth bass abundance in North Carolina and South Carolina reservoirs, whereas riprap was associated with greater redbreast sunfish *Lepomis auritus* abundance (Barwick 2004). In Bull Shoals Reservoir, Arkansas, spotted bass consistently preferred habitat provided by artificial brush structures than habitat without, and largemouth bass used the brush structures for nesting (Vogele and Rainwater 1975). In two Tennessee River impoundments, largemouth bass tournament catch rates were greater with greater macrophyte coverage, except for memorable-sized fish (Maceina and Reeves 1996). Large-scale removal of aquatic macrophytes in Lake Conroe, Texas, was followed by reduced abundance of phytophilic *Lepomis* spp., cyprinodontids, brook silversides *Labidesthes sicculus*, and crappies, reduced density of adult largemouth bass and longear sunfish *Lepomis megalotis*, and increased abundance or biomass of various cyprinids, channel catfish *Ictalurus punctatus*, and shads

Dorosoma spp. (Bettoli et al. 1993). Widespread community changes led to a recreational fishery shift from largemouth bass dominance to channel catfish dominance, although overall quality of the fishery was not evaluated. Following large-scale removal of woody debris in Little Rock Lake, Wisconsin, largemouth bass switched to a more terrestrially-based diet and grew more slowly, and yellow perch *Perca flavescens* declined to very low densities due to predation and failed recruitment (Sass et al. 2006).

2.2.5 Aquatic plants

In contrast to reservoirs where structural habitat is lacking, some reservoirs suffer from an excess of aquatic plants, oftentimes due to nonnative plant invasions. Nonnative species have characteristics that enable them to colonize the reservoir environment, even when native species do not thrive. For example, tenner-grass *Urochloa subquadripara* was capable of recovering quickly from water level drawdowns in subtropical reservoirs (Thomaz et al. 2009), and yellow lotus *Nelumbo lutea* was able to outcompete native water celery *Vallisneria americana* in an upper Mississippi River navigation pool, reducing water celery standing crop biomass by 56% (Tazik et al. 1993). Hydrilla *Hydrilla verticillata* is capable of photosynthesizing in lower light conditions than other submerged macrophyte species, enabling it to establish in new areas without much competition (Van et al. 1976), and Eurasian watermilfoil *Myriophyllum spicatum* grows so densely that it can suppress native plant species below its canopy (Madsen et al. 1991; Madsen 1994). Canopy-forming macrophytes like Eurasian watermilfoil and hydrilla tend to grow in monoculture, producing dense macrophyte beds with low architectural diversity (Valley and Bremigan 2002). In a New York lake, number of plant species per unit area decreased significantly in Eurasian watermilfoil beds during three years

(Madsen et al. 1991). A dense enough canopy inhibits photosynthesis in the water column, causing low dissolved oxygen concentrations inimical to fish (Chick and McIvor 1994; Miranda and Hodges 2000). Reservoirs have been cited for facilitating nonnative invasions because of inherent characteristics such as greater connectivity and levels of disturbance (Havel et al. 2005; Johnson et al. 2008). Water quality that may inhibit native species may be tolerable by nonnative species, allowing them to establish successfully in a highly variable reservoir environment (e.g., tolerance of low light conditions by hydrilla, Van et al. 1976). In the Laurentian Great Lakes region, reservoirs were 2.4 to 300 times more likely than natural lakes to harbor one or more nonnative species (Johnson et al. 2008).

Whereas moderate plant densities may benefit the fish community, greater densities or areal coverage can alter the fish community in undesirable ways (Dibble et al. 1996). Age-0 largemouth bass were shown experimentally to have greater foraging success in moderate plant densities and diverse, complex plant architecture (Valley and Bremigan 2002), and juvenile largemouth bass were found in greater abundance and at greater lengths in reservoir coves with 10-25% vegetative coverage (Miranda and Pugh 1997). Similarly, adult largemouth bass had greater foraging success in low to moderate plant densities than in high plant densities (Savino and Stein 1982), and largemouth bass standing stock increased linearly with submerged plant cover up to 20% in Texas reservoirs (Durocher et al. 1984). Largemouth bass production was modeled to be greatest in intermediate plant standing crops in Illinois ponds, reaching a maximum at approximately 52 g dry weight/m^3 (Wiley et al. 1984). Greater plant densities reduced foraging efficiency by creating visual and swimming barriers to piscivorous species like largemouth bass, while simultaneously expanding refuge for forage fish (Savino and Stein 1982).

Diverse plant architecture provides more varied habitats than a monospecific plant bed, including foraging, spawning, and nesting habitats for fish (Valley and Bremigan 2002). Invasion by a monospecific canopy-forming macrophyte such as hydrilla or Eurasian watermilfoil would therefore result in reduced foraging success, with potential for reduced growth rates, body condition, spawning success, and fishery quality (Colle and Shireman 1980; Savino and Stein 1982; Dibble et al. 1996; Brown and Maceina 2002; Valley and Bremigan 2002). For example, largemouth bass condition decreased when hydrilla coverage exceeded 30% in two Florida lakes, and smallmouth bass *Micropterus dolomieu* condition decreased when coverage exceeded 50% (Colle and Shireman 1980). Bluegill *L. macrochirus* and redear sunfish *L. microlophus* conditions were not affected until hydrilla occupied most of the water column. In contrast to this study, *Lepomis* spp. had lesser relative abundance in extensive vegetation mats of a eutrophic reservoir (i.e., Aliceville Lake, Alabama-Mississippi) than areas of low vegetation, likely due to hypoxic conditions created by canopy shading (Miranda and Hodges 2000). Declines in the fish community may also be associated with a decline in the recreational fishery, as has been observed for largemouth bass (Slipke et al. 1998).

Large-scale removal of submerged vegetation in Lake Conroe, Texas, was associated with earlier onset of piscivory in largemouth bass, resulting in faster growth rates (Bettoli et al. 1992), and with faster growth rates and earlier recruitment to the fishery in black and white crappies (Maceina et al. 1991). Reduction of hydrilla from 50% areal coverage to less than 10% in Lake Marion, South Carolina, increased catch of numerous littoral species including bowfin *Amia calva*, golden shiner *Notemigonus crysoleucas*, lake chubsucker *Erimyzon sucetta*, bluegill, redear sunfish, largemouth bass, and yellow perch (Killgore et al. 1998). Following reduction of hydrilla and re-establishment by native macrophytes in an arm of Lake Seminole, Georgia, largemouth bass growth rates, length-at-age, condition, and egg production increased (Sammons et al. 2005). Increased growth was related to increased food consumption by largemouth bass, as declining vegetative coverage allowed higher foraging efficiency (Sammons and Maceina 2006). Eradication of hydrilla that had covered up to 79% of Lake Baldwin, Florida, increased black crappie growth rates, allowing fish to recruit to the recreational fishery one to two years earlier (Maceina and Shireman 1982).

2.3 How reservoirs relate to the landscape

The habitat issues aforementioned stem from the close tie between the reservoir and its surrounding landscape (Miranda 2008) and to its inherent characteristics as a manmade tool (Kennedy 2005). It is important to recognize broader-scale factors affecting a reservoir that derive beyond the edge of the water. A useful hierarchy of spatial levels was discussed in depth by Miranda (2008) and includes the reservoir itself, tributaries, riparian habitat, individual watersheds, and the larger river basin within which many reservoirs may reside.

Fish communities in reservoirs have been independently linked to characteristics at the reservoir scale (e.g., predator-prey ratio, Miranda and Durocher 1986), riparian scale (e.g., riparian development), watershed scale (e.g., land-use, Richards et al. 1996), and basin scale (e.g., latitude as surrogate for temperature, Marsh-Matthews and Matthews 2000; elevation, Miranda and Durocher 1986). For instance, an analysis of fish assemblage structure in Midwestern drainage basins ranging from Iowa to Texas revealed significant effects of variables ranging from very broad scale (e.g., latitude) to within-stream scale (e.g., woody structure; Marsh-Matthews and Matthews 2000). An investigation of fish biomass in Ohio reservoirs revealed that 84% of variation could be explained by a combination of factors at different scales (i.e., watershed area, reservoir area and volume, and trophic state; Hale et al. 2008). A short review of each of these spatial scales follows.

2.3.1 In-reservoir

In-reservoir variables, such as submerged structure, habitat diversity, water quality, and water regime, are essential in structuring the fish community, as emphasized in the previous section. In Lake Texoma, fish species were segregated among major habitat types defined by flow and turbidity (Gido et al. 2002). Introduced striped bass *Morone saxatilis* and smallmouth bass were located typically in the pelagic and downlake portions of Lake Texoma, whereas riverine species such as orangespotted sunfish *L. humilis* and white crappie were located typically near the inflows from tributaries. Largemouth bass recruitment in Tennessee River reservoirs was correlated more closely with reservoir discharge than either macrophyte coverage or water level fluctuations (Maceina and Bettoli 1998). Total fish biomass was correlated positively with mean depth, total alkalinity, and predator-prey ratio, but correlated negatively with the morphoedaphic index (Miranda and Durocher 1986). A wide diversity of habitats may increase species richness, whereas habitat impairment and homogenization may lead to a degraded fish community and dissatisfactory fishery (e.g., Barwick 2004). Reservoir morphology can also influence available habitat and space. Surface area of reservoirs delimited weights of record-size fish in Texas reservoirs (Wilde and Pope 2004). Shoreline development can influence extent of a littoral zone, and reservoir shape can affect proportion of riverine, transitional, and lentic areas. It is not surprising, then, that shoreline development was correlated positively with sport fish harvest per unit area in southeastern reservoirs (Jenkins 1967).

Fisheries management activities typically occur at the reservoir scale (Miranda 2008). A common reservoir management strategy is stocking, because the reservoir environment may have limnological characteristics that allow nonnative species or native lentic species to thrive. For example, industrial cooling reservoirs provide adequate thermal conditions to support hybrid striped bass (striped bass × white bass *M. saxatilis* × *M. chrysops*; Prosser 1986). These nonnative species may outcompete native species for food or habitat. In Claytor Lake, Virginia, declining walleye spawning success was attributed to introduction of alewife *Alosa pseudoharengus*, which competed for food from the littoral zone as well as predated directly upon walleye larvae (Kohler et al. 1986). In Georgia, introduced walleye and striped bass competed with native black basses for the forage base of gizzard shad and alewife (Ney et al. 1990). In concert with other variables, this competition contributed to decline of the recreational fishery. In Lake Texoma, stocking of striped bass was attributed for subsequent declines in abundance of goldeye *Hiodon alosoides* (Gido et al. 2000). As indicated by Kohler et al. (1986), the most substantial risk of introducing species to fill "empty" pelagic niches is that the potential consequences are unknown. Biological interactions, such as competition, occur at the reservoir scale.

2.3.2 Tributaries

Tributaries influence reservoir fish assemblages by supporting riverine fish species, providing refuge from adverse reservoir conditions, and adding allochthonous inputs from upstream watersheds. Backwaters and wetlands associated with large incoming tributaries also provide spawning and nursery habitat for many species (e.g., crappies and sunfishes, Meals and Miranda 1991; curimba *Prochilodus lineatus*, Agostinho and Zalewski 1995). Connectivity to tributaries allows persistence of riverine species in a reservoir, including potamodromous fish that migrate upstream to spawn (e.g., walleye, Hubert and O'Shea 1992; paddlefish *Polyodon spathula*, Paukert and Fisher 2001). Bonneville cutthroat trout *Oncorhynchus clarki utah* stocked into Strawberry Reservoir, Utah, spawned successfully in tributaries, where young remained up to two years before migrating back to the reservoir (Knight et al. 1999). Access to upstream floodplain lagoons in the upper Paraná River was so important to numerous fishes that fisheries scientists advocated creation of a national park upstream of the uppermost reservoir to ensure continued access to habitats (Agostinho and Zalewski 1995). Tributaries also allow sensitive species to thrive despite unfavorable environmental conditions in the reservoir. For example, brown trout *Salmo trutta* moved out of Box Canyon Reservoir, Washington, into colder tributaries when reservoir water temperatures rose to 19-20 °C, returning only when water temperatures decreased in autumn (Garrett and Bennett 1995).

2.3.3 Riparian zone

The riparian zone provides thermal regulation, shading, and allochthonous inputs in the form of leaf litter and woody debris in streams, directly influencing reservoir tributaries (Pusey and Arthington 2003). It also intercepts runoff, processes nutrients, and provides habitat in the form of root masses and undercut banks. Therefore, the state of the riparian zone along tributaries of a reservoir can influence amount of allochthonous inputs transported into the reservoir. The role of riparian zones in reservoirs, however, is somewhat altered (Miranda 2008). When a river is impounded, the original riparian vegetation is inundated; the "riparian zone" of reservoirs is thus primarily composed of upland vegetation, barren land, or developed land. Although this zone may still mitigate surface runoff and block wind, it primarily serves to stabilize the bank from erosion.

2.3.4 Watershed

The watershed is defined as the area draining into a specific reservoir and includes all tributary subwatersheds as well as the watershed draining directly into the reservoir. Because reservoirs are part of a stream network, they typically have greater watershed area:surface area ratios. This fact is highly influential because the watershed is the primary source of inputs into the reservoir, including nutrients, sediments, chemicals, and pollutants (Kimmel and Groeger 1986; Kennedy and Walker 1990; Thornton 1990). Effects of geology on water quality have been recognized since 1927 when E. Naumann suggested using watershed geology to group lakes, rather than nutrients (Carlson 1979). Natural features of the watershed, such as soil, bedrock type, or vegetation type, and anthropogenic features, such as agriculture or urban development, can affect surface and subsurface runoff water quality.

Various land-uses differentially destabilize runoff, so land-use and land cover composition of the watershed are important factors (Miranda and Bettoli 2010). For example, proportion of agricultural land was correlated closely with sedimentation in

Missouri reservoirs (Jones and Knowlton 2005) and with total nitrogen, total phosphorus, and chlorophyll-*a* in Ohio reservoirs (Bremigan et al. 2008). Watershed area:surface area ratio and mean depth also were significant indicators of total nitrogen, total phosphorus, and chlorophyll-*a* (Bremigan et al. 2008). In developed areas, the increase in impervious surfaces (e.g., roads, buildings, and sidewalks) enhanced surface runoff, resulting in higher nutrient loading from the watershed (Beaulac and Reckhow 1982). Other land-uses that affect runoff quality or quantity include deforestation, construction, and mining (Miranda and Bettoli 2010). Nutrient values for nitrogen and phosphorus were least in forested and pasture land (Beaulac and Reckhow 1982).

Nutrient and sediment loads regulate primary productivity in reservoirs (Kimmel et al. 1990). Particulate organic matter, including allochthonous inputs and autochthonous production, is passed to the reservoir fish community via planktivores (e.g., clupeids; Vanni et al. 2006) and detritivores (e.g., snails). Fish production has been linked to phosphorus (Hanson and Leggett 1982) and chlorophyll-*a* (Jones and Hoyer 1982). Planktivores (e.g., gizzard shad, buffaloes, and carpsuckers) benefit from increases in nutrient loading because they can directly exploit the resulting primary production (Miranda 2008). Provided planktivores are available to predators, this production is passed on to the recreational fishery, linking trophic state to the fishery. As discussed above, gizzard shad thrive in eutrophic systems, and their biomass increases disproportionately with increased amounts of agriculture in the watershed (Vanni et al. 2006). However, rapid growth rates quickly make these forage fish unavailable to most piscivores.

Morphological characteristics, such as watershed slope, also require consideration. Hill (1984) found significant correlations between total and quality-size crappie biomass and a combination of slope and siltation rate. Watershed area, in combination with reservoir volume, explained 56% of variation in total phosphorus levels in Ohio reservoirs (Knoll et al. 2003). Watershed land cover, be it natural or not, has significant implications for the receiving reservoir, setting limitations to water quality parameters and subsequent aquatic community structure (Bulley et al. 2007).

2.3.5 River basin

The river basin is defined as the entire area draining a major river network; this is the broadest spatial scale and is equivalent to the regional scale referred to by landscape ecologists (*sensu* Soranno et al. 2009). Variables considered at this scale include but are not limited to latitude, longitude, elevation, temperature, precipitation, and geomorphology. If these variables have a spatial pattern in the basin, one might predict probable conditions at different locations in the basin (Miranda et al. 2008; Miranda and Bettoli 2010). For example, in a detrended correspondence analysis (DCA) of fish assemblages in the midwestern U.S., latitude explained 71% of variation of the first DCA axis (Marsh-Matthews and Matthews 2009). In Texas reservoirs, natural gradients affecting fish assemblages included elevation and total alkalinity which changed from east to west (Miranda and Durocher 1986).

Because more than one reservoir may exist within the river basin, basin position also can affect reservoir condition (Miranda and Bettoli 2010). In the Tennessee River basin, upstream reservoirs differed substantially from downstream reservoirs (Miranda et al. 2008). Mean depth and relative size of the limnetic zone were greater in upstream reservoirs, whereas downstream reservoirs were shallower with more littoral habitat. Upstream reservoirs had greater retention times and thus a greater proportion of lentic species, whereas downstream reservoirs had more riverine and floodplain habitat with greater species diversity. Also, multiple impoundments on one stream can influence one another, such as by altering stratification (Barbosa et al. 1999) or trapping nutrients and sediments (Ney 1996). Some reservoirs with another reservoir immediately upstream experience oligotrophication, in which a decrease in nutrient loading results in reduced productivity (e.g., Lake Mead, Nevada-Arizona: Vaux et al. 1995; Tietê River reservoir cascade, São Paulo, Brazil: Barbosa et al. 1999).

As discussed above, reservoirs relate to their landscapes via complex pathways, making a landscape-conscious approach necessary to any classification regarding reservoir habitat. Reservoir fish habitat is not only affected by factors within the reservoir, but also by tributaries, riparian zones adjacent to and upstream of the reservoir, the upstream watershed, and river basin influences.

2.4 Need for a reservoir classification system

Lack of an adequate classification system for fish habitat hampers effective watershed planning and interdisciplinary coordination in aquatic resource management (Platts 1980; Orians 1993). Failure to develop an adequate classification system may stem from a lack of consensus on precisely what fisheries scientists need to allow for effective fisheries management and integration with terrestrial land use planning (Platts 1980). Although the current study was not intended to apply to all fish habitats nationwide, it did represent a step in the direction of a unified, national classification system for reservoir fish habitat.

Classification provides a method of nationwide standardization. According to the Nature Conservancy (Grossman et al. 1998), classification of ecological communities provides “a consistent basis for the characterization of the biological components of different ecosystem units across the physical and administrative landscape…It also allows for the comparison of units that are defined and managed by different land management agencies within and among regions.” This holds true for reservoirs, which frequently border multiple states and counties and fall under the jurisdiction of multiple agencies, including the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Fish and Wildlife Service, state water and natural resource agencies, and townships. For knowledge regarding reservoirs to be integrated, these agencies must be working in the same classification system (Platts 1980). Classes can then be described and generalized, facilitating conceptual understanding of how reservoirs differ amongst each other (Bailey et al. 1978).

In addition to improved integration of information regarding reservoir fish habitat, classification provides a framework for assessment of condition. If each class represents a unique set of characteristics, assessment within the classification framework would acknowledge inherent differences among classes. Variation in characteristics within classes would represent different conditions, which could be assessed and compared, allowing for prioritization of management activities. For example, classification of mountain meadows in central Nevada yielded six unique ecological types characterized by differing landform, soil, and vegetation (Weixelman et al. 1997). Within one ecological type, three levels of range degradation were identified, wherein a grass-dominated state provided high forage production and a grass/forb/shrub state provided the least forage production. Bulley et al. (2007) classified Nebraska reservoirs based on environmental variables from a wide range of scales (i.e., climate, watershed area, watershed slope and relief, and various soil characteristics). Classes were then assigned water quality expectations unique to their intrinsic landscape characteristics. The study by Bulley et al. (2007) demonstrated one method of establishing optimal reservoir condition without "pristine" conditions to reference. Similarly, classification of reservoirs based on fish habitat will yield unique groups characterized by differing fish habitat impairments, and fish habitat expectations may be adjusted according to intrinsic reservoir characteristics. Assessment within each class will allow comparison of fish habitat across all reservoirs. Those in worst condition may be targeted for rehabilitation, whereas those in best condition may be targeted for conservation and maintenance of their current state. Therefore, a classification system based on fish habitat enhances large-scale conservation planning in reservoirs.

Past classification systems for aquatic systems have been developed for a multitude of purposes. Most often, the purpose is to define levels of water quality or trophic state based on chemical characteristics (e.g., Vollenweider 1968; Carlson 1977). Other purposes may be to define unique ecosystems (e.g., Abell et al. 2008) or aquatic communities (e.g., Tonn et al. 1983; Dolman 1990; Godinho et al. 1998; Miranda 1999). I am not aware of any past classification systems that focused explicitly on fish habitat in reservoirs. Given the extensive habitat issues to which reservoirs are prone, the need for a fish habitat-focused approach to reservoir classification is clear.

2.4.1 Early descriptions of lentic waters

Many early classification systems for lakes and reservoirs focused on defining water quality in natural lakes (e.g., Vollenweider 1968; Schindler 1971a; Carlson 1977). Vollenweider (1968) classified lakes using total phosphorus loading and mean depth, yielding the trophic states “oligotrophic,” “mesotrophic,” and “eutrophic.” The classification was soon thereafter amended to include water residence time (Vollenweider and Dillon 1974). Schindler (1971a) hypothesized that nutrient loading was directly proportional to the watershed area and inversely proportional to water volume, and that excesses above this estimate were indicative of anthropogenic eutrophication. Carlson (1977) developed a series of equations to calculate a trophic state index using Secchi disk depth, surface chlorophyll, and surface phosphorus. Although none of these classification systems was developed with fish community parameters in mind, primary production in an aquatic system does generally yield higher fish production. Primary productivity has been linked to fish production in Indian and African tropical lakes (Melack 1976), temperate lakes (Oglesby 1977; Liang et al. 1981; Downing et al. 1990), and experimental ponds (Hrbáček 1969; McConnell et al. 1977). Oglesby (1977) and Jones and Hoyer (1982) related chlorophyll-*a* concentrations to fish catch. Hanson and Leggett (1982) linked total phosphorus to commercial and sport fish catch, and Hrbáček (1969) linked total nitrogen to fish growth. Downing et al. (1990) summarized multiple studies worldwide to demonstrate that fish production was more closely related to annual phytoplankton production, mean total phosphorus concentration, and annual average fish standing stock than to the morphoedaphic index (MEI).

In contrast, some models sought to predict fish yield or production using morphometric characteristics. Rounsefell (1946) predicted potential reservoir fish yields using estimates of surface area and fish production from existing water bodies, and Rawson (1952) used mean depth to predict long-term average commercial catch. Hayes and Anthony (1964) then combined the two ideas with alkalinity to predict commercial and sport fish catch. A year later, the well-known MEI, a simple ratio of total dissolved solids over mean depth, was published by Ryder (1965) and taken up immediately by the reservoir management community (Jenkins 1982). Jenkins (1982) demonstrated that sport fish yields could be maximized in reservoirs within a central range of MEI values. Lara et al. (2009) successfully predicted fish density, biomass, and production in Spanish Mediterranean reservoirs using a trophometric index, which synthesized form index, volume with sufficient oxygen to sustain fish life, conductivity, chlorophyll-*a* concentration, and perimeter.

However, neither the MEI nor any other predictive model had yet been used to classify, rather than simply describe, lakes or reservoirs for management purposes. Furthermore, few of these models explicitly differentiated between natural lakes and reservoirs, which have numerous distinct properties as discussed above.

2.4.2 Recent efforts at classification

More recently, a variety of classification approaches have been taken. Some are specific to reservoirs, whereas others continue to focus on natural lakes. Most have combined water quality parameters with lake morphometry (e.g., surface area, lake volume, surface area:shoreline ratio, maximum depth, Schupp 1992; mean depth, Bachmann et al. 1994; surface area, shoreline development, and depth, MNDNR 2012;

but see Ground and Groeger 1994) and watershed characteristics (e.g., basin slope and watershed area:lake surface area ratio, Hill 1986; climate, watershed area, basin slope and relief, and soil characteristics, Bulley et al. 2007). Others have also included measures of potential effectiveness of restoration efforts and benefit to the public (Bachmann et al. 1980; Bachmann et al. 1994; Downing et al. 2005). Biological measures such as macrophyte cover and percent coverage of littoral habitat have also been considered (Edmiston and Myers 1984; Schupp 1992). These classification systems used environmental variables to define classes, and some subsequently related classes to the fish community or fishery (e.g., Hill 1986; Schupp 1992).

In an alternative approach, some classification systems used the fish community to define classes, then related those classes to environmental variables. Tonn et al. (1983) distinguished three groups of natural lakes based on fish community composition, one dominated by mudminnow *Umbra* spp., one by black bass, and one by pike. Groups were predicted by morphometric variables (i.e., lake area and maximum depth), watershed area, and water quality (i.e, pH and conductivity); the authors also indicated that maximum depth was likely a surrogate for another important water quality variable (i.e., winter dissolved oxygen concentration). Dolman (1990) developed a classification scheme for Texas reservoirs based on fish community composition, then used environmental variables to predict reservoir class. Environmental variables included measures of water chemistry (i.e., hardness, pH, total alkalinity, conductivity, turbidity), reservoir morphometry (i.e., surface elevation, depth), and local climate (i.e, water temperature, growing season) and reflected distinct east-west and north-south patterns. The classification scheme facilitated more precise sampling of bluegill and largemouth bass, reducing catch per effort variance for both species (Dolman 1990). The approaches of Tonn et al. (1983) and Dolman (1990) were useful for identifying typical fish communities given broad- and local-scale environmental variables. Similarly, Godinho et al. (1998) and Miranda (1999) identified reservoir groups based on fish communities and subsequently typified environmental conditions for each group. Again, this approach was useful for identifying reservoirs that provided different fisheries, but it did not address how the fishery or fish community was affected by habitat impairment.

2.4.3 A fish habitat-based approach to classification

In light of the worsening habitat condition of reservoirs (as discussed in Sections 1.2 and 2.2) and the lack of a nationally-applicable method of habitat assessment (as discussed in Section 2.4.2), I sought to develop a fish habitat-based classification framework for U.S. reservoirs within which an assessment mechanism could function. Classification based on fish habitat impairment assists in the identification of common habitat impairment patterns, illuminates inherent differences among reservoir groups, and assists in the development of a collection of class-specific management strategies. Subsequent assessment within the classification framework would enable better prioritization of rehabilitation and protection efforts and more efficient use of limited resources at a national level. These are top priorities of the Reservoir Fisheries Habitat Partnership.

2.5 Figures

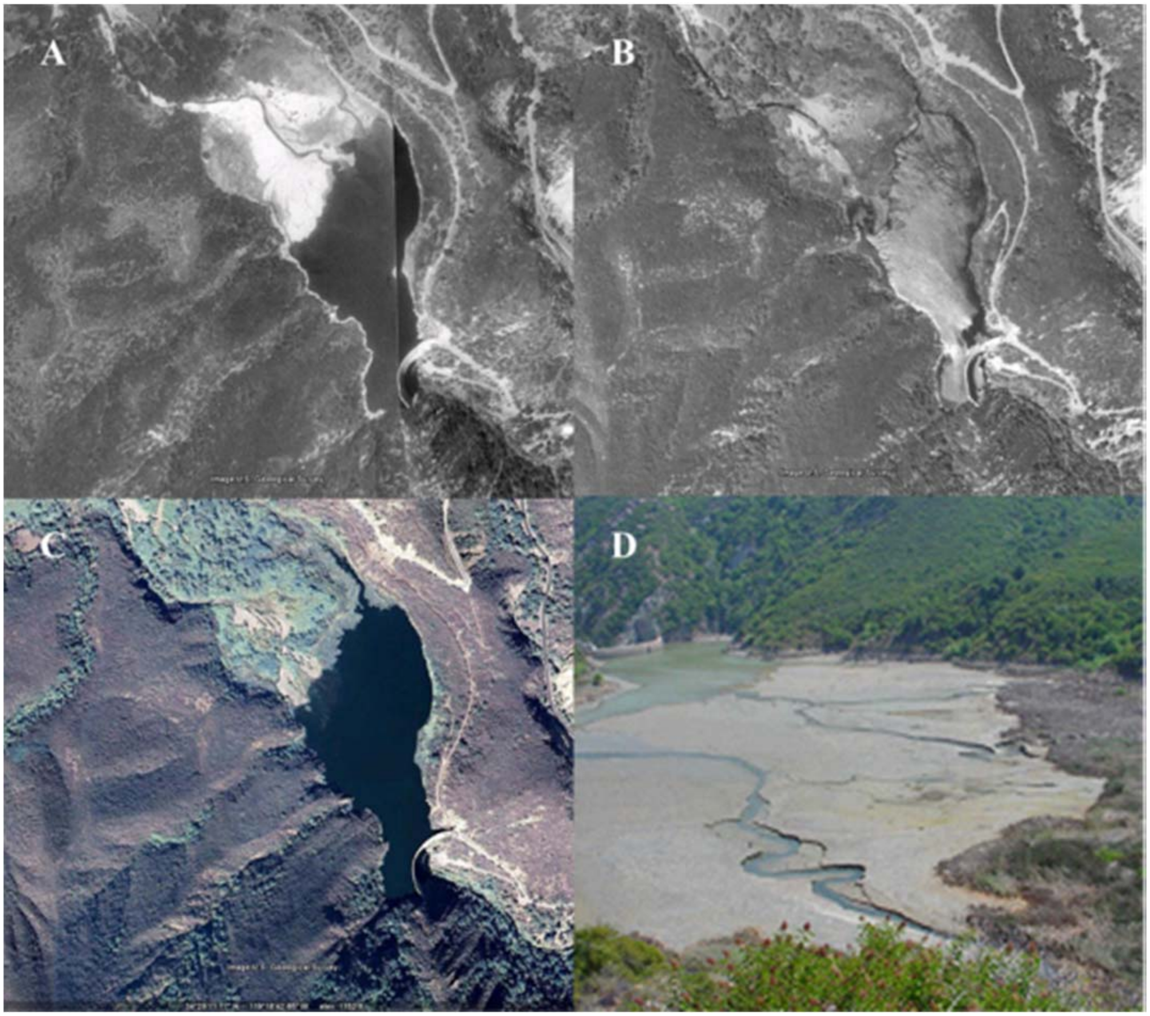

Figure 2.1 Matilija Lake, California, on (A) June 4, 2002, (B) June 11, 2002, and (C) September 1, 2007.

Sedimentation has resulted in a substantial decrease in storage volume in this reservoir (D). (Photo credit: Paul Jenkin)

Figure 2.2 Satellite image of the Washita River arm of Lake Texoma, Texas-Oklahoma, showing extensive sediment deposition and channel formation.

2.6 References

Abell, R., M. L. Thieme, C. Revenga, M. Bryer, M. Kottelat, N. Bogutskaya, B. Coad, N. Mandrak, S. C. Balderas, W. Bussing, M. L. J. Stiassny, P. Skelton, G. R. Allen, P. Unmack, A. Naseka, R. Ng, N. Sindorf, J. Robertson, E. Armijo, J. V. Higgins, T. J. Heibel, E. Wikramanayake, D. Olson, H. L. López, R. E. Reis, J. G. Lundberg, M. H. S. Pérez, and P. Petry. 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. Bioscience 58(5):403-414.

Agostinho, A. A., and M. Zalewski. 1995. The dependence of fish community structure and dynamics on floodplain and riparian ecotone zone in Paraná River, Brazil. Hydrobiologia 303:141-148.

Allen, M. S., J. C. Green, F. J. Snow, M. J. Maceina, and D. R. DeVries. 1999. Recruitment of largemouth bass in Alabama reservoirs: relations to trophic state and larval shad occurrence. North American Journal of Fisheries Management 19:67-77.

Amundsen, C. C. 1994. Reservoir riparian zone characteristics in the upper Tennessee river valley. Water, Air, and Soil Pollution 77(3-4):469-493.

Bachmann, R. E., T. A. Hoyman, L. K. Hatch, and B. P. Hutchins. 1994. A classification of Iowa's lakes for restoration. Department of Animal Ecology, Iowa State University: Ames, Iowa.

Bachmann, R. E., M. R. Johnson, M. V. Moore, and T. A. Noonan. 1980. Clean lakes classification study of Iowa's lakes for restoration: final report. Iowa Cooperative Fisheries Research Unit and Department of Animal Ecology, Iowa State University: Ames, Iowa.

Bachmann, R. W., B. L. Jones, D. D. Fox, M. Hoyer, L. A. Bull, and D. E. Canfield, Jr. 1996. Relations between trophic state indicators and fish in Florida (U.S.A.) lakes. Canadian Journal of Fisheries and Aquatic Sciences 53:842-855.

Bailey, R. G., R. D. Pfister, and J. A. Henderson. 1978. Nature of land and resource classification – a review. Journal of Forestry 76(10):650-655.

Barbosa, F. A. R., J. Padisák, E. L. G. Espíndola, G. Borics, and O. Rocha. 1999. The cascading reservoir continuum concept (CRCC) and its application to the river Tietê-basin, São Paulo State, Brazil. Pages 425-437 *in* J. G. Tundisi and M. Straškraba, editors. Theoretical Reservoir Ecology and its Applications, Brazilian Academy of Sciences, Rio de Janeiro, Brazil.

Barwick, D. H. 2004. Species richness and centrarchid abundance in littoral habitats of three southern U.S. reservoirs. North American Journal of Fisheries Management 24:76-81.

Barwick, R. D., T. J. Kwak, R. L. Noble, and D. H. Barwick. 2004. Fish populations associated with habitat-modified piers and natural woody debris in Piedmont Carolina reservoirs. North American Journal of Fisheries Management 24(4):1120-1133.

Beaulac, M. N., and K. H. Reckhow. 1982. An examination of land use - nutrient export relationships. Journal of the American Water Resources Association 18:1013-1024.

Berkman, H. E., and C. F. Rabeni. 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes 18(4):285-294.

Bettoli, P. W., M. J. Maceina, R. L. Noble, and R. K. Betsill. 1992. Piscivory in largemouth bass as a function of aquatic vegetation abundance. North American Journal of Fisheries Management 12:509-516.

Bettoli, P. W., M. J. Maceina, R. L. Noble, and R. K. Betsill. 1993. Response of a reservoir fish community to aquatic vegetation removal. North American Journal of Fisheries Management 13(1):110-124.

Bolding, B., S. Bonar, and M. Divens. 2004. Use of artificial structures to enhance angler benefits in lakes, ponds, and reservoirs: a literature review. Reviews in Fisheries Science 12:75-96.

Bremigan, M. T., P. A. Soranno, M. J. Gonzalez, D. B. Bunnell, K. K. Arend, W. H. Renwick, R. A. Stein, and M. J. Vanni. 2008. Hydrogeomorphic features mediate the effects of land us/cover on reservoir productivity and food webs. Limnology and Oceanography 53:1420-1433.

Brown, S. J., and M. J. Maceina. 2002. The influence of disparate levels of submersed aquatic vegetation on largemouth bass population characteristics in a Georgia reservoir. Journal of Aquatic Plant Management 40:28-35.

Bulley, H. N. N., J. W. Merchant, D. B. Marx, J. C. Holz, and A. A. Holz. 2007. A GIS-based approach to watershed classification for Nebraska reservoirs. Journal of the American Water Resources Association 43:605-621.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492-507.

Bunnell, D. B., R. S. Hale, M. J. Vanni, and R. A. Stein. 2006. Predicting crappie recruitment in Ohio reservoirs with spawning stock size, larval density, and chlorophyll concentrations. North American Journal of Fisheries Management 26:1-12.

Bureau of Reclamation. 2010. Matilija Dam Ecosystem Restoration Project, California. Available: http://www.usbr.gov/pmts/sediment/projects/Matilija/MatilijaDam.html. (November 2010).

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22(2):361-369.

Carlson, R. E. 1979. A review of the philosophy and construction of trophic state indices. Pages 1-52 *in* T. E. Maloney, editor. Lake and Reservoir Classification Systems, EPA-600/3-79-074. Corvallis Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, Oregon.

Chick, J. H. and C.C. Mclvor. 1994. Patterns in the abundance and composition of fishes among beds of different macrophytes: viewing a littoral zone as a landscape. Canadian Journal of Fisheries and Aquatic Sciences 51:2873-2883.

Cole, T. M., and H. H. Hannan. 1990. Dissolved oxygen dynamics. Pages 71-108 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Colle, D. E., and J. V. Shireman. 1980. Coefficients of condition for largemouth bass, bluegill, and redear sunfish in hydrilla-infested lakes. Transactions of the American Fisheries Society 109(5):521-531.

Cooke, G. D. 1980. Lake level drawdown as a macrophyte control technique. Journal of the American Water Resources Association 16(2):317-322.

Dagel, J. D., and L. E. Miranda. 2012. Backwaters in the upper reaches of reservoirs produce high densities of age-0 crappies. North American Journal of Fisheries Management 32(4):626-634.

Dendy, F. E., W. A. Champion, and R. B. Wilson. 1973. Reservoir sedimentation surveys in the United States. Pages 349–357 *in* W. C. Ackermann, G. F. White, E. B. Worthington, editors. Man-Made Lakes: Their Problems and Environmental Effects. Geophysical Monograph 17, American Geophysical Union, Washington, D.C.

Dibble, E. D., K. J. Killgore, and S. L. Harrel. 1996. Assessment of fish-plant interactions. American Fisheries Society Symposium 16:357-372.

DiCenzo, V. J., M. J. Maceina, and W. C. Reeves. 1995. Factors related to growth and condition of the Alabama subspecies of spotted bass in reservoirs. North American Journal of Fisheries Management 15:794-798.

Dolman, W. B. 1990. Classification of Texas reservoirs in relation to limnology and fish community associations. Transactions of the American Fisheries Society 119(3):511-520.

Downing, J. A., J. Li, G. Antoniou, D. Kendall, C. Kling, J. Herriges, R. Castro, P. Van Meter, D. Woolnough, K. Egan, Y. Jeon, R. Andrews, S. Conrad, and L. Boatwright. 2005. Iowa Lakes Classification for Restoration. Iowa Department of Natural Resources, Des Moines.

Downing, J. A., C. Plante, and S. Lalonde. 1990. Fish production correlated with primary productivity, not the morphoedaphic index. Canadian Journal of Fisheries and Aquatic Sciences 47:1929-1936.

Duncan, A., and J. Kubečka. 1995. Land/water ecotone effects in reservoirs on the fish fauna. Hydrobiologia 303:11-30.

Durocher, P. P., W. C. Provine, and J. E. Kraai. 1984. Relationship between abundance of largemouth bass and submerged vegetation in Texas reservoirs. North American Journal of Fisheries Management 4:84-88.

Edmiston, H. L., and V. B. Myers. 1984. Florida lakes assessment: combining macrophyte, chlorophyll, nutrient, and public benefit parameters into a meaningful lake management scheme. Lake and Reservoir Management 1(1):25-31.

Garrett, J. W., and D. H. Bennett. 1995. Seasonal movements of adult brown trout relative to temperature in a coolwater reservoir. North American Journal of Fisheries Management 15(2):480-487.

Gido, K. B., C. W. Hargrave, W. J. Matthews, G. D. Schnell, D. W. Pogue, and G. W. Sewell. 2002. Structure of littoral-zone fish communities in relation to habitat, physical, and chemical gradients in a southern reservoir. Environmental Biology of Fishes 63:253-263.

Gido, K. B., W. J. Matthews, and W. C. Wolfinbarger. 2000. Long-term changes in a reservoir fish assemblage: stability in an unpredictable environment. Ecological Applications 10:1517-1529.

Godinho, F. N., M. T. Ferreira, and M. I. Portugal e Castro. 1998. Fish assemblage composition in relation to environmental gradients in Portuguese reservoirs. Aquatic Living Resources 11(5):325-334.

Grossman, D. H., D. Faber-Langendoen, A. S. Weakley, M. Anderson, P. Bourgeron, R. Crawford, K. Goodin, S. Landaal, K. Metzler, K. D. Patterson, M. Pyne, M. Reid, and L. Sneddon. 1998. International classification of ecological communities: terrestrial vegetation of the United States. Volume I. The National Vegetation Classification System: development, status, and applications. The Nature Conservancy, Arlington, Virginia.

Ground, T. A., and A. W. Groeger. 1994. Chemical classification and trophic characteristics of Texas reservoirs. Lake and Reservoir Management 10(2):189-201.

Hale, R. S., D. J. Degan, W. H. Renwick, M. J. Vanni, and R. A. Stein. 2008. Assessing fish biomass and prey availability in Ohio reservoirs. Pages 517-541 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Hanson, J. M., and W. C. Leggett. 1982. Empirical prediction of fish biomass and yield. Canadian Journal of Fisheries and Aquatic Sciences 39:257-263.

Havel, J. E., C. E. Lee, M. J. Vander Zanden. 2005. Do reservoirs facilitate invasions into landscapes? BioScience 55(6):518-525.

Hayes, F. R., and E. H. Anthony. 1964. Productive capacity of North American lakes as related to the quantity and the trophic level of fish, the lake dimensions, and the water chemistry. Transactions of the American Fisheries Society 93:53-57.

Hill, K. R. 1984. Correlation of total and "angler-acceptable" crappie standing stocks with lake basin slopes and a siltation index. North American Journal of Fisheries Management 4:350-354.

Hill, K. R. 1986. Classification of Iowa lakes and their fish standing stock. Lake and Reservoir Management 2(1):105-109.

Holtan, H., L. Kamp-Nielsen, and A. O. Stuanes. 1988. Phosphorus in soil, water and sediment: an overview. Hydrobiologia 170(1):19-34.

Hrbáček, J. 1969. Relations between some environmental parameters and the fish yield as a basis for a predictive model.

Hubert, W. A., and D. T. O'Shea. 1992. Use of spatial resources by fishes in Grayrocks Reservoir, Wyoming. Journal of Freshwater Ecology 7:219-225.

Hunt, P. C., and J. W. Jones. 1972. The effect of water level fluctuations on a littoral fauna. Journal of Fish Biology 4:385-394.

Hynes, H. B. N. 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, Canada.

Jenkins, R. M. 1967. The influence of some environmental factors on standing crop and harvest of fishes in U.S. reservoirs. Pages 298-321 *in* Reservoir Fishery Resources Symposium. Southern Division American Fisheries Society, Bethesda, Maryland.

Jenkins, R. M. 1970. Reservoir fish management. Pages 173-182 *in* N. G. Benson, editor. A Century of Fisheries in North America. American Fisheries Society, Special Publication 7, Washington, D.C.

Jenkins, R. M. 1982. The morphoedaphic index and reservoir fish production. Transactions of the American Fisheries Society 111:133-140.

Johnson, P. T. J., J.D. Olden, and M. J. Vander Zanden. 2008. Dam invaders: impoundments facilitate biological invasions into freshwaters. Frontiers in Ecology and the Environment 6:357-363.

Jones, J. R., and M. V. Hoyer. 1982. Sportfish harvest predicted by summer chlorophyll-*a* concentration in Midwestern lakes and reservoirs. Transactions of the American Fisheries Society 111:176-179.

Jones, J. R., and M. F. Knowlton. 2005. Suspended solids in Missouri reservoirs in relation to catchment features and internal processes. Water Research 39:3629-3635.

Kennedy, R. H. 2005. Toward integration in reservoir management. Lake and Reservoir Management 21(2):128-138.

Kennedy, R. H. 1999. Reservoir design and operation: limnological implications and management opportunities. Pages 1-28 *in* J. G. Tundisi and M. Straškraba, editors. Theoretical Reservoir Ecology and its Applications, Brazilian Academy of Sciences, Rio de Janeiro, Brazil.

Kennedy, R. H., and W. W. Walker. 1990. Reservoir nutrient dynamics. Pages 109-132 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Killgore, K. J., J. P. Kirk, and J. W. Foltz. 1998. Response of littoral fishes in upper Lake Marion, South Carolina following hydrilla control by triploid grass carp. Journal of Aquatic Plant Management 36:82-87.

Kimmel, B. L., and A. W. Groeger. 1986. Limnological and ecological changes associated with reservoir aging. Pages 103-109 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Kimmel, B. L., O. T. Lind, and L. J. Paulson. 1990. Reservoir primary production. Pages 133-194 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Knight, C. A., R. W. Orme, and D. A. Beauchamp. 1999. Growth, survival, and migration patterns of juvenile adfluvial Bonneville cutthroat trout in tributaries of Strawberry Reservoir, Utah. Transactions of the American Fisheries Society 128(4):553-563.

Knoll, L. B., M. J. Vanni, and W. H. Renwick. 2003. Phytoplankton primary production and photosynthetic parameters in reservoirs along a gradient of watershed land use. Limnology and Oceanography 48:608-617.

Kohler, C. C., J. J. Ney, and W. E. Kelso. 1986. Filling the void: development of a pelagic fishery and its consequences to littoral fishes in a Virginia mainstream reservoir. Pages 166-177 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Lara, G., L. Encina, and A. Rodríguez-Ruiz. 2009. Trophometric index: a predictor for fish density, biomass and production in Mediterranean reservoirs in Spain. Fisheries Management and Ecology 16:341-351.

Liang, Y., J. M. Melack, and J. Wang. 1981. Primary production and fish yields in Chinese ponds and lakes. Transactions of the American Fisheries Society 110:346-350.

Maceina, M. J., D. R. Bayne, A. S. Hendricks, W. C. Reeves, W. P. Black, and V. J. DiCenzo. 1996. Compatibility between water clarity and quality black bass and crappie fisheries in Alabama. Pages 296-305 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional Approaches to Reservoir Fisheries Management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Maceina, M. J., and P. W. Bettoli. 1998. Variation in largemouth bass recruitment in four mainstream impoundments of the Tennessee River. North American Journal of Fisheries Management 18:998-1003.

Maceina, M. J., P. W. Bettoli, W. G. Klussmann, R. K. Betsill, and R. L. Noble. 1991. Effect of aquatic macrophyte removal on recruitment and growth of black crappies and white crappies in Lake Conroe, Texas. North American Journal of Fisheries Management 11(4):556-563.

Maceina, M. J., and W. C. Reeves. 1996. Relations between submersed macrophyte abundance and largemouth bass tournament success on two Tennessee River impoundments. Journal of Aquatic Plant Management 34:33-38.

Maceina, M. J., and J. V. Shireman. 1982. Influence of dense hydrilla infestation on black crappie growth. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 36(1982):394-402.

Madsen, J. D. 1994. Invasions and declines of submersed macrophytes in Lake George and other Adirondack lakes. Lake and Reservoir Management 10(1):19-23.

Madsen, J. D., J. W. Sutherland, J. A. Bloomfield, L. W. Eichler, and C. W. Boylen. 1991. The decline of native vegetation under dense Eurasian watermilfoil canopies. Journal of Aquatic Plant Management 29:94-99.

Mallin, M. A., V. L. Johnson, S. H. Ensign, and T. A. MacPherson. 2006. Factors contributing to hypoxia in rivers, lakes, and streams. Limnology and Oceanography 51(1):690-701.

Marsh-Matthews, E., and W. J. Matthews. 2000. Geographic, terrestrial and aquatic factors: which most influence the structure of stream fish assemblages in the Midwestern United States? Ecology of Freshwater Fish 9:9-21.

Matthews, W. J., L. G. Hill, and S. M. Schellhaass. 1985. Depth distribution of striped bass and other fish in Lake Texoma (Oklahoma-Texas) during summer stratification. Transactions of the American Fisheries Society 114(1):84-91.

McConnell, W. J., S. Lewis, and J. E. Olson. 1977. Gross photosynthesis as an estimator of potential fish production. Transactions of American Fisheries Society 106:417-423.

Meals, K. O., and L. E. Miranda. 1991. Abundance of age-0 centrarchids among littoral habitats of flood control reservoirs in Mississippi. North American Journal of Fisheries Management 11:298-304.

Melack, J. M. 1976. Primary productivity and fish yields in tropical lakes. Transactions of the American Fisheries Society 105:575-580.

Miranda, L. E. 1996. Development of reservoir fisheries management paradigms in the twentieth century. Pages 3-11 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional Approaches to Reservoir Fisheries Management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Miranda, L. E. 1999. A typology of fisheries in large reservoirs of the United States. North American Journal of Fisheries Management 19:536-550.

Miranda, L. E. 2008. Extending the scale of reservoir management. Pages 75-102 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Miranda, L. E., and P. W. Bettoli. 2010. Large reservoirs. Chapter 17 *in* W. A. Hubert and M. C. Quist, editors. Inland Fisheries Management in North America, 3rd edition. American Fisheries Society, Bethesda, Maryland.

Miranda, L. E., and P. P. Durocher. 1986. Effects of environmental factors on growth of largemouth bass in Texas reservoirs. Pages 115-121 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Miranda, L. E, M. D. Habrat, and S. Miyazono. 2008. Longitudinal gradients along a reservoir cascade. Transactions of the American Fisheries Society 137:1851-1865.

Miranda, L. E., and K. B. Hodges. 2000. Role of aquatic vegetation coverage on hypoxia and sunfish abundance in bays of a eutrophic reservoir. Hydrobiologia 427(1):51-57.

Miranda, L. E., and L. L. Pugh. 1997. Relationship between vegetation coverage and abundance, size, and diet of juvenile largemouth bass during winter. North American Journal of Fisheries Management 17(3):601-610.

MNDNR (Minnesota Department of Natural Resources). 2012. Shoreland management lake classifications. Available: http://www.dnr.state.mn.us/waters/watermgmt_section/shoreland/lake_shoreland_classifications.html. (May 2012).

Moore, M., S. P. Romano, and T. Cook. 2010. Synthesis of upper Mississippi river system submersed and emergent aquatic vegetation: past, present, and future. Hydrobiologia 640(1):103-114.

Ney, J. J. 1996. Oligotrophication and its discontents: effects of reduced nutrient loading on reservoir fisheries. Pages 285-295 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional Approaches to Reservoir Fisheries Management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Ney, J. J., C. M. Moore, M. S. Tisa, J. J. Yurk, and R. J. Neves. 1990. Factors affecting the sport fishery in a multiple-use Virginia reservoir. Lake and Reservoir Management 6:21-32.

Oglesby, R. T. 1977. Relationships of fish yield to lake phytoplankton standing crop, production, and morphoedaphic factors. Journal of the Fisheries Resource Board of Canada 34:2271-2279.

Olmsted, L. L, and J. P. Clugston. 1986. Fishery management in cooling impoundments. Pages 227-237 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Orians, G. H. 1993. Endangered at what level? Ecological Applications 3:206-208.

Ozimek, T., E. Pieczynska, and A. Hankiewicz. 1991. Effects of filamentous algae on submerged macrophyte growth: a laboratory experiment. Aquatic Botany 41(4):309-315.

Patton, T., and C. Lyday. 2008. Ecological succession and fragmentation in a reservoir: effects of sedimentation on habitats and fish communities. Pages 147-167 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Paukert, C. P., and W. L. Fisher. 2001. Characteristics of paddlefish in a southwestern U.S. reservoir, comparisons of lentic and lotic populations. Transactions of the American Fisheries Society 130:634-643.

Platts, W. S. 1980. A plea for fishery habitat classification. Fisheries 5(1):2-6.

Ploskey, G. R. 1981. Factors affecting fish production and fishing quality in new reservoirs, with guidance on timber clearing, basin preparation, and filling. Technical Report E-81-11, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Ploskey, G. R. 1986. Management of the physical and chemical environment: effects of water-level changes on reservoir ecosystems, with implications for fisheries management. Pages 86-97 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Prosser, N. S. 1986. Overview of reservoir fisheries problems and opportunities resulting from hydropower. Pages 238-246 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Pusey, B. J., and A. H. Arthington. 2003. Importance of the riparian zone to the conservation and management of freshwater fish: a review. Marine and Freshwater Research 54:1-16.

Rawson, D. S. 1952. Mean depth and the fish production of large lakes. Ecology 33:513-521.

Richards, C., L. B. Johnson, and G. E. Host. 1996. Landscape-scale influences on stream habitats and biota. Canadian Journal of Fisheries and Aquatic Sciences 53(Supplement 1):295-311.

Rounsefell, G. A. 1946. Fish production in lakes as a guide for estimating production in proposed reservoirs. Copeia 1946(1):29-40.

Ryder, R. A. 1965. A method for estimating the potential fish production of north-temperate lakes. Transactions of the American Fisheries Society 94:214-218.

Sammons, S. M., and M. J. Maceina. 2006. Changes in diet and food consumption of largemouth bass following large-scale hydrilla reduction in Lake Seminole, Georgia. Hydrobiologia 560:109-120.

Sammons, S. M., M. J. Maceina, and D. G. Partridge. 2005. Population characteristics of largemouth bass associated with changes in abundance of submersed aquatic vegetation in Lake Seminole, Georgia. Journal of Aquatic Plant Management 43:9-16.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, M. G. Turner. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31(7):321-330.

Savino, J. F., and R. A. Stein. 1982. Predator-prey interaction between largemouth bass and bluegills as influenced by simulated, submersed vegetation. Transactions of the American Fisheries Society 111(3):255-266.

Schindler, D. W. 1971a. A hypothesis to explain the differences and similarities among lakes in experimental lakes area, northwestern Ontario. Journal of the Fisheries Research Board of Canada 28:295-301.

Schindler, D. W. 1971b. Carbon, nitrogen, and phosphorus and the eutrophication of freshwater lakes. Journal of Phycology 7:321-329.

Schindler, D. W. 1977. Evolution of phosphorus limitation in lakes: natural mechanisms compensate for deficiencies of nitrogen and carbon in eutrophied lakes. Science 195:260-262.

Schupp, D. H. 1992. An ecological classification of Minnesota lakes with associated fish communities. Investigational Report 417, Minnesota Department of Natural Resources, St. Paul.

Slipke, J. W., M. J. Maceina, and J. M. Grizzle. 1998. Analysis of the recreational fishery and angler attitudes toward aquatic hydrilla in Lake Seminole, a southeastern reservoir. Journal of Aquatic Plant Management 36:101-107.

Soranno, P. A., K. E. Webster, K. S. Cheruvelil, and M. T. Bremigan. 2009. The lake landscape-context framework: linking aquatic connections, terrestrial features and human effects at multiple spatial scales. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 30(5):695-700.

Tazik, P. P., R. V. Anderson, and D. M. Day. 1993. The development of an aquatic vegetation community in Pool 19, upper Mississippi river. Journal of Freshwater Ecology 8(1):19-26.

Thomaz, S. M., P. Carvalho, R. P. Mormul, F.A. Ferreira, M. J. Silveira, and T. S. Michelan. 2009. Temporal trends and effects of diversity on occurrence of exotic macrophytes in a large reservoir. Acta Oecologica 35(5):614-620.

Thornton, K. W. 1990. Sedimentary processes. Pages 43-70 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Tonn, W. M., J. J. Magnuson, and A. M. Forbes. 1983. Community analysis in fishery management: an application with northern Wisconsin lakes. Transactions of the American Fisheries Society 112:368-377.

Valley, R. D., and M. T. Bremigan. 2002. Effects of macrophyte bed architecture on largemouth bass foraging: implications of exotic macrophyte invasions. Transactions of the American Fisheries Society 131(2):234-244.

Van, T. K., W. T. Haller, and G. Bowes. 1976. Comparison of the photosynthetic characteristics of three submersed aquatic plants. Plant Physiology 58:761-768.

Van Duin, E. H. S., G. Blom, L. Lijklema, and M. J. M. Scholten. 1992. Aspects of modeling sediment transport and light conditions in Lake Marken. Hydrobiologia 235/236:167-176.

Vanni, M. J., A. M. Bowling, E. M. Dickman, R. S. Hale, K. A. Higgins, M. J. Horgan, L. B. Knoll, W. H. Renwick, and R. A. Stein. 2006. Nutrient cycling by fish supports relatively more primary production as lake productivity increases. Ecology 87:1696-1709.

Vanoni, V. A. 1975. Sedimentation Engineering. Task Committee for the Preparation of the Manual on Sedimentation, Final Report. American Society of Civil Engineers, New York.

Vaux, P. D., L. J. Paulson, R. P. Axler, and S. Leavitt. 1995. The water quality implications of artificially fertilizing a large desert reservoir for fisheries enhancement. Water Environment Research 67:189-200.

Vogele, L. E., and W. C. Rainwater. 1975. Use of brush shelters as cover by spawning black basses (Micropterus) in Bull Shoals Reservoir. Transactions of the American Fisheries Society 104(2):264-269.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Technical Report DAS/SCI/68.27, Organisation for Economic Cooperation and Development, Directorate for Scientific Affairs, Paris, France.

Vollenweider, R. A., and P. J. Dillon. 1974. The application of the phosphorus loading concept to eutrophication research. Publication Number NRCC 13690 of the Environmental Secretariat. Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario.

Weixelman, D. A., D. C. Zamudio, K. A. Zamudio, and R. J. Tausch. 1997. Classifying ecological types and evaluating site degradation. Journal of Range Management 50(3):315-321.

Wetzel, R. G. 1990. Reservoir ecosystems: conclusions and speculations. Pages 227-238 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Wilde, G. R., and K. L Pope. 2004. Relationship between lake-record weights of fishes and reservoir area and growing season. North American Journal of Fisheries Management 24:1025-1030.

Wiley, M. J., R. W. Gorden, S. W. Waite, and T. Powless. 1984. The relationship between aquatic macrophytes and sport fish production in Illinois ponds: a simple model. North American Journal of Fisheries Management 4(1):111-119.

Willis, D. W. 1986. Review of water level management on Kansas reservoirs. Pages 110-114 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

CHAPTER III

A CLASSIFICATION SYSTEM FOR LARGE RESERVOIRS OF THE CONTERMINOUS U. S.

3.1 Introduction

Reservoirs are an invaluable resource in the U.S., providing flood control, hydroelectric power, municipal and industrial water supplies, recreational opportunities, and countless other commodities (USACE 2009). In terms of fishing, reservoirs and lakes are targeted by approximately 84% of freshwater anglers in the U.S. (USFWS 2006). Nearly every major U.S. river is impounded somewhere along its reaches, but the number of large reservoirs is dwarfed by the thousands of smaller reservoirs on tributaries; together they number in the tens of thousands nationwide (USACE 2009). These reservoirs provide recreational fisheries for over 25 million people and draw approximately $24.6 billion in direct fishing expenditures (USFWS 2006).

In light of the high recreational and socioeconomic value of reservoirs, degradation of reservoir fish habitat has become a serious concern. Reservoirs experience ecological succession at an accelerated rate compared to natural lakes (Wetzel 1990), and aging can result in chemical, physical, structural, and biological changes that may be undesirable (Kimmel and Groeger 1986). Habitat issues—such as excessive suspended sediments, excessive nutrient loadings, and lack of submerged structure—may emerge and worsen over time (Miranda 2008), accompanied by undesirable shifts in the fish community and fishery (Agostinho et al. 1999). To prioritize habitat rehabilitation efforts in reservoirs, a quantitative approach to assessment is needed.

Assessment of fish habitat requires two working components: a classification system that acknowledges inherent differences among reservoirs and a scoring system that functions within the classification framework. A scoring system was developed recently by Miranda and Hunt (2010) and requires minimal adjustment to be applicable nationwide. Previous classification systems for lakes and reservoirs generally focused on in-reservoir water quality parameters indicative of trophic state (e.g., Vollenweider 1968; Schindler 1971; Carlson 1977; Bachmann et al. 1980; Ground and Groeger 1994; Burns et al. 1999; Downing et al. 2005). Others have also used lake morphometry (e.g., basin slope and watershed area:lake surface area ratio, Hill 1986; mean depth, Bachmann et al. 1994; surface area, shoreline development, and depth, MNDNR 2012), macrophyte cover (Edmiston and Myers 1984), potential effectiveness of restoration (Bachmann et al. 1980; Bachmann et al. 1994; Downing et al. 2005), and potential benefit to the public (Bachmann et al. 1980; Bachmann et al. 1994; Downing et al. 2005) as metrics of their classification systems. Development of all of the aforementioned classification systems was stimulated by a need to rank water bodies by water quality, with a general disregard for fish habitat. In addition, each classification system focused on natural lakes, with no explicit differentiation between lakes and reservoirs.

More recently, Dolman (1990), Godinho et al. (1998), and Miranda (1999) identified reservoir groups based on fish communities and fisheries, and subsequently linked each group to environmental conditions. Although this approach was useful for identifying reservoirs with different fish communities, it did not address if the fishery or fish community was affected by habitat impairment. Lara et al. (2009) integrated several commonly used parameters—conductivity, chlorophyll-*a* concentration, reservoir perimeter, and form index—with percentage of water volume with adequate dissolved oxygen to sustain fish life, an explicitly fish-focused metric. The parameters were combined to create a trophometric index capable of predicting total fish biomass and production in Spanish Mediterranean reservoirs (Lara et al. 2009). Again, this approach was useful for identifying reservoirs with greater fish production, but it did not address the state of fish habitat or the nature of the fish community. Bulley et al. (2007) classified Nebraska reservoirs based on variables from a wide range of spatial scales (e.g., climate, watershed area, watershed slope and relief, and various soil characteristics). Cluster analysis and use of a classification tree resulted in nine reservoir classes, which were then assigned water quality expectations unique to their intrinsic landscape characteristics. This approach identified common patterns at a landscape level and adjusted expectations accordingly. A similar approach at the national level could be used to identify common patterns in reservoir fish habitat.

Recognizing the need for a nationally-applicable method of reservoir classification, we sought to develop a classification system for large reservoirs in the conterminous U.S. To this end, we used a four-step classification approach. First, to account for the broad geographic heterogeneity in climate and landscape, reservoirs were assigned to a pre-existing spatial framework relevant to aquatic resources. Second, to account for differences among reservoirs within geographical regions, we used statistical procedures to let reservoirs organize themselves into groups with similar characteristics. Third, classes were compared regarding habitat impairment, the fish community, the recreational fishery, and other variables from an external dataset. Lastly, a method for classifying new reservoirs not included in this study was developed.

3.2 Methods

3.2.1 Study Scope

Large reservoirs within the conterminous U.S. were defined by the Reservoir Fisheries Habitat Partnership (RFHP) as any river impoundment equaling or exceeding 100 ha in surface area. With this simple definition, a sampling frame was identified using the National Inventory of Dams (NID) database administered by the U.S. Army Corps of Engineers. However, the NID did not discern between dams constructed to impound rivers and those constructed to control natural lakes. Thus, our sampling frame included over 4,300 water bodies ≥100 ha, but not all were reservoirs as defined by the RFHP. We relied on local knowledge to help us discard natural lakes controlled by a dam.

3.3 Data Collection

3.3.1 Survey instrument

We surveyed reservoir biologists about fish habitat in reservoirs under their jurisdiction. The survey included 83 habitat and fish-related variables (Appendix A). Habitat impairment questions (N = 52) were expanded from those included in an earlier survey (Miranda et al. 2010) and were divided into sections on habitat availability (N = 20), water quality (N = 16), water regime (N = 9), and degradation processes (N = 7). In addition, questions regarding the fish community (N = 11) and recreational fishery (N = 20) were included. Complete definitions of habitat impairment and fish variables may be found in Appendix B. A six-point Likert-type scale was used for habitat impairment questions with ratings from zero to five: 0 = no impairment, 1 = low impairment, 2 = low to moderate impairment, 3 = moderate impairment, 4 = moderate to high impairment, and 5 = high impairment. A five-point Likert-type scale was used for fish community and fishery questions with ratings from one to five: 1 = low, 2 = below average, 3 = average, 4 = above average, and 5 = high.

3.3.2 Survey implementation

The survey was completed by fishery biologists identified to have knowledge about the survey reservoirs and contacted by the RFHP. After an introductory page outlining the purpose of the survey, as well as the voluntary and confidential nature of responses, each respondent was asked about habitat impairment, the fish community, and the recreational fishery for reservoirs under their jurisdiction. Reservoirs with which biologists were unfamiliar, including privately owned and small reservoirs not considered in regular monitoring, were excluded to reduce guessing on the survey.

The survey was conducted online via the host SurveyMonkey (http://www.surveymonkey.com) between June and December 2010, including a follow-up period during which non-respondents were contacted to encourage participation. Responses were sought for as many reservoirs as possible. The survey was concluded when no further responses were expected.

3.3.3 Data Analysis

3.3.3.1 Initial processing

All survey responses were examined for completeness and duplication (i.e., one entry per reservoir). Highly incomplete (i.e., missing responses for >30% of items) or duplicated cases were identified and removed from analyses. Remaining missing values were estimated using multiple imputation (MI procedure, SAS Corporation 2011), a method typically applied to normally-distributed continuous data. However, multiple imputation may perform as well as or better than other methods for estimating missing multinomial values (Schafer et al. 1993; Schafer 1997; Finch and Margraf 2008; Finch 2010). Multiple imputation is robust to violation of the normality and continuity assumptions, as demonstrated by Leite and Beretvas (2010). This step enabled use of the complete dataset during analysis.

3.3.3.2 Patterns in habitat impairment

After data were prepared for analysis, we followed a four-step approach to elucidate and describe patterns in habitat impairment (Figure 3.1). First, broad-scale patterns among regions were examined based on five spatial frameworks selected because of their ecological and managerial relevance, with the aim of choosing the framework that reflected the greatest differences in reservoir habitat impairment among geographical regions. Second, habitat impairment patterns within regions were investigated using cluster analysis, and reservoir classes were identified. Third, classes were compared descriptively and statistically regarding habitat impairments, the fish community, the recreational fishery, and environmental variables from an external dataset. Support for the classification system was sought by testing if classes differed relative to variables not included in development of the classification. Lastly, a method for classifying new reservoirs not included in this study was developed.

3.3.3.3 Patterns among regions

We assumed *a priori* that habitat patterns in reservoirs would be linked to broad-scale climatic, physiographic, and ecological characteristics that vary latitudinally and longitudinally across the U.S. We examined five spatial frameworks, selected because they encompassed the broad-scale characteristics aforementioned and were already in use for aquatic resource management. These frameworks included Omernik's Level I and II ecological regions (ecoregions; Omernik 1987; Omernik 1995), U.S. Environmental Protection Agency's Wadeable Streams Assessment regions (WSAs; USEPA 2006), U.S. Department of the Interior's Landscape Conservation Cooperatives (LCCs; USFWS 2010), and Hydrologic Unit Code 2 regions (HUC2s; Seaber et al.1987). For individual maps of each framework, refer to Appendix C.

Boundaries for ecoregions were established by Omernik (1987) to provide a geographic framework within which resource managers could compare and assess data. Boundaries were based on regional landscape patterns including land use and land cover, land surface form, potential natural vegetation, and soil types. Hierarchical levels of ecoregions include a continually increasing level of detail (Omernik 1995). Level I ecoregions represent the most general level, followed by Level II and Level III. There are 15 Level I ecoregions delineated in the North American continent, 10 of which encompass areas in the conterminous U.S. There are 50 Level II ecoregions delineated in the North American continent, 18 of which encompass areas in the conterminous U.S.

Boundaries for WSAs were established by the U.S. Environmental Protection Agency (USEPA) to enhance reporting of stream condition at a regional scale (USEPA 2006). Each WSA region is an aggregation of Omernik's Level III ecoregions (Omernik 1995; Wiken et al. 2011), often but not necessarily contiguous to one another. Omernik's system of ecoregion delineation was used as a basis by USEPA because it was based entirely upon environmental similarities. The nine WSA regions are the Northern Appalachians (NAP), Southern Appalachians (SAP), Coastal Plains (CPL), Upper Midwest (UMW), Temperate Plains (TPL), Southern Plains (SPL), Northern Plains (NPL), Western Mountains (WMT), and Xeric (XER).

Boundaries for LCCs were established by the U.S. Department of the Interior (USDOI) based on the National Geographic Framework, with the goal of encouraging regional partnerships and collaborative conservation efforts (USFWS 2010). Decision criteria for boundaries hinged upon three factors, listed in descending order of priority: fidelity to Bird Conservation Regions and terrestrial homogeneity, fidelity to aquatic homogeneity, and fidelity to national partnerships. Aquatic homogeneity was based on freshwater ecoregions as established by Abell et al. (2008). Because boundaries were chosen using the named criteria, LCCs did not necessarily reflect optimal ecological boundaries (Aycrigg et al. 2010). However, they did represent the spatial framework favored by the USDOI for nationally-relevant natural resource science and conservation. There are 16 LCCs in the conterminous U.S.

Boundaries for HUC2s were established by the U.S. Geological Survey with the goal of providing a standard spatial reference for hydrologic research and water resource management (Seaber et al. 1987). The HUC system includes all watersheds arranged hierarchically within their respective basins. Based only upon hydrology, HUC regions reflect the major river basins of the U.S. There are 21 HUC2 regions delineated in the U.S., 18 of which encompass areas within the conterminous U.S.

For each framework, reservoirs were assigned to their respective regions, and a between-reservoir similarity matrix was derived based on scores assigned by respondents to the habitat impairment variables. Similarity was calculated using Gower's general coefficient of similarity (Gower 1971). Gower's resemblance coefficient was chosen because it is appropriate for ordinal data and can be used with datasets containing multiple data types (Romesburg 2004). It averages the difference among samples (i.e., reservoirs) across all variables, each normalized for the range of its values.

We then applied a permutational multivariate analysis of variance (MANOVA) to test if habitat impairment differed among regions, and if differences were identified in the main test, pairwise comparisons established where differences occurred ($\alpha = 0.10$; PRIMER with PERMANOVA+, PRIMER-E 2008). Although the permutational MANOVA method used was not purely nonparametric, it avoided making assumptions regarding the distribution of data through use of permutation techniques (Anderson et al. 2008). These procedures were repeated for each framework. We selected the framework that identified significant differences among regions and minimized pairwise regional similarities.

Habitat variables from the survey were summarized descriptively at the regional level. For each region, the proportion of reservoirs characterized by greater than moderate impairment was calculated for each habitat impairment variable. Fish community and recreational fishery variables were examined to determine if the regional median score differed significantly from the nationwide median. For most fish-related variables, a Wilcoxon signed rank test was used; for a few variables that were not distributed symmetrically, a sign test was used.

3.3.3.4 Patterns within regions

Within each region of the chosen spatial framework, we derived new among-reservoirs similarity matrices using habitat impairment variables, where distance was calculated using Gower's coefficient. For each region, we conducted separate cluster analyses to identify groups of reservoirs with similar habitat impairment characteristics (Ward's algorithm, CLUSTER procedure in SAS). Ward's clustering algorithm was chosen to minimize within-group variance and maximize between-group variance, regardless of group size. Number of clusters in each region was determined as the minimum number, less one, at which there was a peak in the Pseudo T^2 statistic. Each reservoir was assigned to its respective cluster accordingly (TREE procedure in SAS). Clusters within a region that reflected similar habitat issues, but were separated by the procedure due to differences in impairment intensity, were combined to uphold parsimony. Each cluster or cluster combination was designated as a unique reservoir class within a region.

Habitat, fish community, and recreational fishery variables were summarized at the reservoir class level using the same methods used at the region level. In addition, the recreational fishery was characterized by its most popular species as:

$$\text{Relative popularity}_j = \frac{\sum_{r=1}^{3} \frac{n_{rj}}{r}}{\sum_{i=1}^{k} \sum_{r=1}^{3} \frac{n_{ri}}{r}} \tag{3.1}$$

where:

$i =$ species in the recreational fishery, numbered from 1 to k

$j =$ focal species for which score is being calculated

$k =$ number of fish species considered

$r =$ rank of species j in the reservoir's recreational fishery

$n_{ri} =$ number of reservoirs with rank r for species i

3.3.3.5 Support for the classification system

We expected that if reservoir classes differed based on habitat, they would also differ based on 1) major environmental characteristics that might affect habitat, and 2) fish community and fishery characteristics affected by habitat. Therefore, we assessed differences among classes using various sets of environmental variables from the Reservoir Fisheries Habitat Partnership database (Rodgers and Green 2011; Appendix D) and fish community and recreational fishery variables collected during the survey. Sets of environmental variables included reservoir morphology (e.g., shoreline development index, surface area of the reservoir, drainage area of the watershed, and mean depth) and watershed characteristics (e.g., percentages of land use/land cover classes). Within each region, we applied a permutational MANOVA to test if reservoir classes differed based on each set of variables ($\alpha = 0.10$). If significant differences were identified, pairwise comparisons were made to establish where differences occurred.

3.3.3.6 Development of the classification tree for inclusion of new reservoirs

After establishing a working classification system, we developed a classification tree for integrating new reservoirs (rpart function in Program R, R Foundation for

Statistical Computing 2011). Within each region, a tree was grown and pruned using habitat impairment variables, and error rate assessed with cross-validation. Regional trees were then combined, and an overall error rate was calculated.

3.4 Results

We received 1,599 total responses. Of those, 1,302 responses matched our study scope (i.e., surface area ≥ 100 ha and not a natural lake) and were complete enough for habitat impairment analysis (i.e., no duplication and ≤ 30% of data missing). A total of 1,010 responses had no missing data (78%); an additional 274 responses (21%) were missing no more than five habitat impairment variables.

3.4.1 Patterns among Regions

According to permutational MANOVA tests for each spatial framework, all spatial frameworks had regions that differed significantly from each other (all main test $\text{P-values} \le 0.001$). Subsequent pairwise comparisons with region as a factor indicated all WSA regions differed from each other (all $\text{P-values} \le 0.07$). Nine of 120 LCC region pairs did not differ (7.5% of pairs), and 9 of 153 HUC2 region pairs did not differ (5.9%). Fifteen of 153 Level II ecoregion pairs did not differ (9.8% of pairs), and 2 of 28 Level I ecoregion pairs did not differ (7.1%; for all main and pairwise test results for each spatial framework, refer to Appendix C). Because the WSA framework was the only spatial framework within which all pairs of regions differed significantly, further analyses were based on the WSA spatial framework (Figure 3.2).

Each WSA region had a unique set of habitat impairment issues (Table 3.1). However, certain impairments were widespread, affecting all or nearly all reservoirs nationwide (e.g., non-point source pollution, sedimentation, excessive nutrients, lack of submerged structure, and disturbance of the riparian zone) to some degree. Other impairments were specific to regions with similar geographic characteristics. For example, the three mountainous regions NAP, SAP, and WMT were all afflicted to a greater degree than other regions by a lack of sufficient nutrient inputs. Conversely, they were less affected than other regions by habitat homogenization related to siltation.

Certain habitat impairments were more common in specific regions. Reservoirs in the CPL region were typified by excessive macrophyte coverage and nonnative plant invasions, harmful levels of forestry in reservoir watersheds, and a lack of connectivity to adjoining habitats. Reservoirs in the SAP and NAP regions were prone to relatively fewer regionwide issues, most commonly a lack of macrophytes or other submerged structure and limitation of habitat due to stratification. The SPL, TPL, NPL, and UMW regions were prone to relatively more regionwide issues, commonly including harmful levels of agriculture and livestock in the watershed, nonnative animal invasions, disturbed riparian zones, harmful algae blooms, and various water regime issues. Notably, the TPL region was the only region in which a variable affected >50% of all reservoirs (i.e., sedimentation). Reservoirs in the two western regions WMT and XER were commonly affected by water regime issues, contaminants, harmful algae blooms, and nonnative animal invasions. Reservoirs in the WMT region were more frequently affected by impairments associated with greater depth, whereas reservoirs in the XER region were more frequently affected by impairments associated with lesser depths.

Each region also varied in terms of fish community and fishery characteristics (Table 3.2). Prey standing stock was significantly greater than the national average in the

CPL, SAP, and TPL regions and significantly less in the XER region; predator standing stock was greater in the SAP, UMW, and WMT regions and less in the SPL region. Stocking activities differed markedly among regions, with some regions focusing on stocking native fish and other on stocking non-native fish. Undesirable species introductions were more frequent in reservoirs of the TPL region, and the standing stock of exotic fish was greater. Fishing tournaments were more common in the CPL, SAP, and TPL regions and less common in the SPL, WMT, and XER regions. Fishing was very important relative to other recreation in all regions.

3.4.2 Patterns within Regions

We identified 25 clusters within the WSA spatial framework. Within individual regions, number of clusters ranged from one to four. Because they displayed similar habitat impairments but to differing degrees of intensity, two clusters in the SAP region were combined. Thus, we identified 24 reservoir classes divided among nine WSA regions (Figure 3.3).

Each reservoir class had a unique set of habitat impairment issues (Table 3.3); general and pairwise permutational MANOVAs showed that all classes differed (all P-values < 0.01). Several classes were characterized by widespread habitat impairments, including CPL2, SPL4, and TPL2. Some common habitat impairments shared by SPL4 and TPL2 included detrimental levels of agriculture in the watershed, excessive nutrient inputs, excessive inorganic turbidity, sedimentation, shoreline homogenization, low retention time, unfavorable hydrographs, and seasonally mistimed water fluctuations. CPL2 was also characterized by sedimentation and shoreline homogenization, along with numerous impairments related to siltation and extreme shallowness. Other classes were characterized by relatively few widespread habitat impairments, including CPL1, NPL1, SAP1, WMT1, XER1, and XER2. Several classes, including NPL1, SPL4, TPL2, and XER3, were characterized by more water regime-related issues than other classes.

Classes also varied in terms of fish community and recreational fishery characteristics (Table 3.4). Standing stock was greater than the national average in reservoirs of the CPL1, NAP2, SAP3, TPL1, UMW1, and WMT2 classes, but less than the national average in reservoirs of the SPL1 class. The pattern in standing stock was often reflective of prey standing stock, but not always (e.g., UMW1 reservoirs had above-average predator standing stock). Within regions, certain classes were characterized by more nonnative fish invasions than others (e.g., CPL1 and CPL2 versus CPL4; NPL1 versus NPL2); those same classes also tended to have lower species evenness. Classes with fishing pressure greater than the national average also tended to have above-average catch rates, large fish, and angler satisfaction. Classes with fishing pressure less than the national average did not have any uniformly distinguishing fishery characteristics.

The most popular species targeted in the recreational fishery nationwide was largemouth bass *Micropterus salmoides*, followed by channel catfish *Ictalurus punctatus*, white crappie *Pomoxis annularis*, walleye *Sander vitreus*, and black crappie *P. nigromaculatus* (Table 3.5). Each reservoir class had a unique recreational fishery comprising different sets of species with varying levels of popularity. Largemouth bass was typically the most popular species in the eastern and midwestern U.S., whereas rainbow trout *Oncorhynchus mykiss* was typically the most popular species in the western U.S. Channel catfish was the most popular species in SPL4 and TPL1, and walleye was the most popular species in NPL1, SPL3, and UMW1. Black crappie was the most popular species in NAP2. Although less popular overall, additional species were more useful in differentiating among fisheries of each reservoir class. Blue catfish *I. furcatus*, hybrid striped bass *Morone chrysops* × *M. saxatilis*, and spotted bass *Micropterus punctulatus* were more popular in the southern U.S., whereas yellow perch *Perca flavescens* and northern pike *Esox niger* were more popular in the northern U.S. Within WSA regions, where environmental conditions were more likely to be similar, reservoir classes were still distinct amongst each other relative to their recreational fisheries, with no classes sharing the same ranking of fish species in their recreational fisheries.

3.4.3 Support for the Classification System

A total of 779 and 664 reservoirs in the RFHP database were complete enough to test whether classes differed relative to reservoir morphology and watershed characteristics, respectively. A total of 1,274 and 1,217 reservoir surveys were complete enough to test whether classes differed relative to their fish communities and fisheries, respectively.

All reservoir classes were unique in terms of at least one variable group, if not more (Table 3.6). In most regions, classes differed in three of the four groups; in the TPL region, classes differed for all four groups. Our analyses did not find significant differences in reservoir morphology, watershed characteristics, or the recreational fishery among classes in both western regions.

3.4.4 Development of the Classification Tree for Inclusion of New Reservoirs

The classification tree yielded overall accuracy of 75% (Figure 3.4). The greatest regional accuracy was in the NPL region (92%), and the least regional accuracy was in the SPL region (58%). Other regions varied between 75% and 90% accuracy.

3.5 Discussion

The 24 reservoir classes described here represent fish habitat-oriented categories for enhancing management efforts. The WSA spatial framework incorporated broad-scale landscape factors not necessarily accounted for in the habitat survey, and classes developed within each region emphasized different suites of habitat impairments. This type of tiered approach to classification ensures stratification of reservoirs by known landscape features, and further refines results at the local scale (Hawkins et al. 2000). In addition, it is based on Level III ecoregions from a terrestrially-derived framework, enhancing the potential for integration with terrestrial assessments (Platts 1980).

Certain impairments were widespread, affecting all or nearly all reservoir classes, and were often associated with inputs from upstream watersheds (e.g., sedimentation and non-point source pollution). Reservoirs receive relatively greater inputs from their watersheds than natural lakes, and many reservoirs have much larger ratios of watershed area to surface area due to their location and construction purpose (Wetzel 1990). Accordingly, nutrient and sediment loading into reservoirs contribute directly to siltation, eutrophication, high turbidity, and loss of habitat diversity due to sediment deposition. In addition, high turbidity related to suspended sediments and phytoplankton production inhibits photosynthesis of submerged macrophytes, resulting in a lack of macrophyte structure (Westlake 1965; Blom et al. 1994; Engel and Nichols 1994; Duarte 1995).

Also, many reservoir classes were characterized by disturbance of riparian buffers. Natural riparian zones contribute large woody debris to the aquatic environment, representing an important structural component to fish habitat in natural rivers (Angermeier and Karr 1984) and lentic waters (Barwick 2004; Sass et al. 2006). Loss of the riparian buffer and its structural contributions may further contribute to the nationwide lack of submerged structure in reservoirs.

Classification of reservoirs assists in the identification of common patterns and expectations, as well as the development of a collection of class-specific management strategies. A similar classification approach was used to classify Nebraska reservoirs by water quality expectations, but was based solely upon watershed characteristics (Bulley et al. 2007). The study revealed nine watershed-based reservoir classes, whereas our study revealed six unique habitat impairment classes in Nebraska. Although our study encompassed a broader range of habitat-focused variables in addition to watershed characteristics, there were several parallels between the two classification systems. Reservoirs in the southeastern portion of Nebraska were in a single class corresponding to TPL2, whereas reservoirs just to the west were in another class corresponding to SPL3. In the northwestern corner of the state, a separate watershed-based class in the Niobrara shrublands coincided with a reservoir class in the NPL region characterized by high watershed inputs related to agriculture and livestock (i.e., NPL2). In contrast, we classified central Nebraska reservoirs into a single habitat impairment class, but they fell into several watershed classes in Bulley et al. (2007) classification. Differences between classification systems may be related to the larger spatial scale, alternate purpose of development, and wider scope of variables used in our habitat impairment classification system. Additionally, the watershed-based classification system included more smaller reservoirs (<100 ha), and several classes were typified by smaller surface areas. These classes would not have appeared in our habitat impairment classification system because only large reservoirs (≥100 ha) were considered.

Our study design was based on previous work by Miranda et al. (2010), who conducted a similar but shorter survey that briefly covered common habitat impairments in large U.S. reservoirs ≥200 ha. Their analysis revealed five major factors contributing to reservoir habitat impairment: siltation, structural habitat, eutrophication, water regime, and aquatic plants. These factors reflected regional patterns indicative of landscape differences. We expanded the survey based on the five major factors and increased the scope of possible impairments to include potential problems not identified by Miranda et al. (2010). Additionally, we attempted to account for regional spatial variation by adding a spatial framework to the classification.

As discussed by Tonn et al. (1983) and Dolman (1990), accuracy of any classification system may diminish when adding new water bodies with characteristics outside of the range considered during classification system development. Reservoir classes may have differed had we received more surveys from the western U.S. or the northernmost areas of the midwestern and northeastern U.S. However, our goal was to develop an initial classification system for reservoirs that could be applied nationwide, and future reservoir additions to the classification could warrant minor revisions to the system if needed.

Further investigation at the local level of the typical habitat, fish community, and fishery characteristics of each reservoir class is required to establish precise management expectations. For example, blue catfish fisheries in the southeastern U.S. were typically found in reservoirs of the CPL2, SAP2, and SPL1 classes. Blue catfish thrive in reservoirs with open water habitat and can tolerate high turbidity and silt substrates (Graham 1999), impairments common to the CPL2 and SAP2 classes. Cutthroat trout fisheries in the western U.S. were typically found in deep reservoirs connected to incoming tributaries, including reservoirs in the NPL1, WMT1, WMT2, and XER2 classes. Cutthroat trout *O. clarki* require colder water, remaining between the warm epilimnion and the hypoxic hypolimnion during the warm season (Baldwin et al. 2002), and require access to flowing water to spawn (Gresswell 1995); both of these conditions were less common in other western reservoir classes.

Our approach to reservoir classification used survey data provided by biologists involved in local fisheries management, enabling us to obtain information regarding habitat impairment quickly and without expensive onsite surveys. Many variables included in our survey measured factors that are not typically measured during onsite surveys, providing new perspective on reservoir fish habitat. However, variables were measured on a Likert-type ordinal scale, thereby limiting direct comparison to other fish habitat studies. Support for the classification system using quantitative characteristics, such as reservoir morphology and watershed characteristics, upheld our conclusion that classes truly differed from each other. Such quantitative measures, which have been used to establish lake and reservoir classifications in the past (e.g., Hill 1986; Downing et al. 2005; Bulley et al. 2007; MNDNR 2012), adequately demonstrated inherent differences among our reservoir classes. Greater differentiation among classes may have been possible with a more complete RFHP database; for example, classes in the western regions did not reflect significantly different reservoir morphology or watershed characteristics, but classes may have been differentiated by, for instance, elevation or basin slope. Unfortunately, these metrics were not available for enough reservoirs to conduct analyses.

Although some efforts at reservoir classification have been made in the past, our classification system is the first to directly address fish habitat impairments for the purpose of enhancing large-scale conservation planning. It is applicable to large reservoirs ≥100 ha of the conterminous U.S. It should be used early in the conservation planning process to facilitate assessment of project reservoirs. Membership in a reservoir class can help pinpoint major habitat impairments, indicate potential for additional impairments, and identify management strategies that target impairments directly. For example, classification of a reservoir into a class wrought by siltation-related impairments may indicate the long-term need for watershed planning and collaboration with land-use agencies, rather than installation of gravel beds. In contrast, a class less prone to siltation but lacking in substrate diversity for other reasons may benefit long-term by installation of gravel beds.

The classification system also opens the door to development of an assessment system for large U.S. reservoirs. As aforementioned, a classification system provides the framework within which an assessment mechanism can function. An assessment system similar to that developed by Miranda and Hunt (2010) would quantify and rank variations in habitat impairment levels within classes. The ability to conduct assessments at the national level enhances prioritization of rehabilitation and protection efforts and facilitates more efficient use of limited resources. Reservoirs with high levels of habitat impairment can be targeted for rehabilitation, whereas reservoirs with low levels of habitat impairment can be targeted for protection of their current state. Additionally, issues in the recreational fishery may be related to specific habitat impairments, and solutions addressing the underlying issues may be quantitatively justified. The reservoir habitat classification system presented here can serve as the framework for a reservoir assessment mechanism.

3.6 Tables

Table 3.1 Habitat impairment characteristics by WSA region.

Variable	Code	CPL	NAP	NPL	SAP	SPL	TPL	UMW	WMT	XER
Excessively shallow	SHALLOW	●	●	●	○	●	●	●	●	●
Excessive mudflats	MUDFLAT	●	○	●	○	●	●	○	●	●
Lack adjoining backwaters & wetlands	BKWATER	●	○	●	○	●	●	○	●	○
Lack conn backwaters and wetlands	CONN_BW	●	○	○	○	○	●	○	○	○
Lack connectivity to tribs due to sed	CONN_TR	●		○	○	●	○			○
Excessive macrophytes	X_MACRO	●	○	○	○	○	○	●	○	○
Insufficient macrophytes	N_MACRO	●	●	●	●	●	●	○	●	○
Invasive plants	NN_PLNT	●		○	○	○	○	○	○	
Invasive animal	NN_ANIM	○	○	●	○	○	●	●	●	●
Lack structural habitat	N_STRUC	●	●	●	●	●	●	○	●	●
Excessively shallow littoral zone	SHAL_LZ	●	●	●	○	●	●	○	○	●
Deep or steep littoral zone	DEEP_LZ	○	●	○	○	○	○		●	○
Lack bank shading	N_SHADE	○	○	●	○	●	●		●	●
Lack allochthonous inputs	N_ALLOC	○	○	○	○	●	○		○	○
Disturbance of riparia	DIST_RZ	●	●	●	●	●	●	●	○	○
Harmful levels agriculture	WS_AGRI	●	○	●	○	●	● (black)	●	○	●
Harmful levels livestock	WS_ANIM		○	●	○	○	●	●	○	●
Harmful levels forestry	WS_LOGS	●			○				○	
Harmful levels mining	WS_MINE	○	○	○	○		○	○	○	○
Harmful levels of urbanization	WS_URBN	○	○	○	○	○	●	●	○	○
Excessive nutrients	X_NUTRI	●	○	●	●	●	●	●	●	●
Insufficient nutrients	N_NUTRI	○	●	○	●	○	○		●	○
Excessive SS or inorganic turbidity	IN_TURB	●	●	○	●	●	●	●	○	●
Excessive organic turbidity	OR_TURB	○	○	○	○	○	●	●	○	○
Extreme seasonal variation in turbidity	VAR_TUR	○	○	○	○	○	●	●	○	○
Harmful algae blooms	ALGAE	○	○	●	○	○	●	●	●	●
Extreme diel variation in DO	VAR_DO2	○		○	○		○	○	○	○
Oxygen stratification	O_STRAT	○	●	○	●	○	○	○	●	○

Table 3.1 (continued)

Excessively high temperatures	HI_TEMP	○		○	○	○	◍	○	○	○
Excessively low temperatures	LO_TEMP			○				○	○	○
Temperature stratification	T_STRAT	○	◍	○	◍	○	○	○	○	○
Untimely or frequent turnovers	DESTRAT	○		○			○		○	○
Thermal pollution	THERMAL	○		○	○	○	○	○	○	○
Contaminants	CONTAMN	◍	○	○	○	○	○	○	◍	◍
Point-source pollution	POLL_PS	○	○	○	○	○	○	○	○	○
Non-point source pollution	POLLNPS	◍	◍	◍	◍	◍	◍	◍	◍	◍
Unfavorable hydrograph	HYDROGR	○	○	◍	○	◍	◍	◍	◍	◍
Effects upstream impoundments	RESIDUP	○	○	◍	○	○	○	○	○	◍
Insufficient retention time	LOWRETE	○		◍	○	○	◍	○	○	◍
Insufficient water storage	LOWSTOR	○	○	◍	○	◍	◍	○	○	◍
Mistimed water level fluctuations	WL_SEAS	○	○	◍	◍	◍	◍	○	◍	◍
Excessive yearly drawdown	WL_DROP	○	◍	◍	○	◍	○	○	◍	◍
Excessive long-term drawdowns	WL_LONG	○	◍	◍	○	◍	○	○	◍	◍
Excessive short-term fluctuations	WLSHORT	○	○	○	○	○	◍	○	◍	◍
Rapid water level change	WL_FAST	○	○	◍	○	○	◍	○	◍	◍
Sedimentation	SEDIMEN	◍	○	◍	◍	◍	●	◍	◍	◍
Shoreline erosion	SHOREER	◍	○	◍	○	◍	◍	◍	○	○
Loss of cove habitat due to sed	NOCOVES	◍	○	◍	○	◍	◍	◍	○	○
Shoreline homogenization	SHOREHO	◍	◍	◍	○	◍	◍	◍	○	◍
Homogenization of littoral substrates	SUBSTHO	◍	○	○	○	◍	◍	◍	○	◍
Disturbances in upstream watersheds	DIST_UP	◍	○	◍	◍	◍	◍	◍	○	◍
Disturbances in adjacent watersheds	DIST_AD	◍	○	◍	○	○	◍	◍	○	◍

Symbols indicate the percentage of reservoirs within a region with greater than moderate impairment. Blank = Less than or equal to 1%, ○ = 1-10%, ◍ = 10-50%, ● = Greater than 50%.

Table 3.2 Fish community and fishery characteristics by WSA region.

Code	Variable	CPL	NAP	NPL	SAP	SPL	TPL	UMW	WMT	XER
STANSTK	Standing stock						▲	▲	▲	
PREYSTK	Prey standing stock	▲			▲		▲			▼
PREDSTK	Predator standing stock				▲	▼		▲	△	
PPRATIO	Prey-predator ratio	▲								▽
EXOTSTK	Standing stock of undesirable exotic fish species*	▼			△		▲			△
SP_RICH	Species richness	▼				▼		▲	▼	▽
SP_EVEN	Species evenness	▼		▼	▼	▼	▼		▼	▼
STOCK_N	Supplementary stocking of native species*		▼	▼	▲	▼	▲	▼		▼
STOCKNN	Maintenance stocking of non-native species*	▼		▲			▽	▼		
INTRONN	Undesirable species introductions*	▼	▼			▼	▲	▼		
FSHKILL	Fish kills*	▲	▲	▲	▲	▲	▲	▲	▲	▲
PRESSURE	Fishing pressure				▲	▼				▽
CATCH_R	Catch rates					▼		▲		▼
FSHSIZE	Size of fish caught	▲	▲	▲	▲		△			△
CATCH_V	Annual variability in catch rates	▼	▽	▲	▼					
SATSFXN	Angler satisfaction								▲	
TOURN_F	Frequency of tournaments*	▲			▲	▼	▲		▼	▼
FISHING	Ratio of fishing to other recreation	▲	▲	▲	▲	▲	▲	▲	▲	▲

Symbols indicate the significance of a Wilcoxon signed rank test for most variables (sign test indicated with an asterisk). ▲/△ = Median score is above national average ($P < 0.05$ and $P < 0.10$); ▼/▽ = Median score is below national average ($P < 0.05$ and $P < 0.10$).

Table 3.3 Habitat impairment characteristics by reservoir class.

Code	CPL				NAP		NPL		SAP			SPL				TPL			UMW	WMT		XER		
	1	2	3	4	1	2	1	2	1	2	3	1	2	3	4	1	2	3	1	1	2	1	2	3
SHALLOW	○	●	◐	◐	◐	◐	◐	◐		◐	◐	○	◐	◐	●	◐	◐	○	◐		◐	◐		◐
MUDFLAT	○	●	◐	◐	○	◐	○	◐		◐	◐		◐	◐	●	◐	◐	○	○		◐	◐		◐
BKWATER	○	◐	○	◐	○			◐	○	◐	○	○	○	○		◐	◐	◐	○	○	◐		◐	◐
CONN_BW	○	●	○	◐	○			○	○	○	○		○	○		○	◐	◐	○	○	○		◐	◐
CONN_TR	○	●	○	◐				◐	○	◐	○	○	○	○		○	◐							◐
X_MACRO	◐	●	◐	◐	○	◐		○	○	○	◐	○	○	○	●	○	○	○	◐		○	○	○	◐
N_MACRO	○	○	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	●		◐	●	◐	○	◐	○			◐
NN_PLNT	◐	●	◐	◐				○	○	○	◐	○		○	◐	○	○	◐	○	○	○			
NN_ANIM	○		○	◐	○	◐	○	◐	○	◐	○	○		◐		◐	●	◐	◐	○	◐	◐	○	◐
N_STRUC	○	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	●	◐	◐	◐	○		◐	◐	◐	◐
SHAL_LZ	○	●	◐	◐	○	◐		◐		○	◐	○	◐	◐	●	◐	◐		○		◐	◐	○	◐
DEEP_LZ	○		○	○	◐	◐	◐		◐	○	○	○	○	○		○	○	◐		◐	◐		◐	○
N_SHADE	○		○	◐		○	◐	◐	○	○	○	◐	○	◐	◐	◐	◐	◐			◐	◐	◐	◐
N_ALLOC			◐	◐	○	○	○		○	○	○	◐	○	○	●		○	○		○	○		◐	◐
DIST_RZ	○	◐	◐	◐	○	◐	○	◐	○	◐	○	○		◐		◐	●	◐	◐		○			◐
WS_AGRI		○	○	◐		◐	○	◐		◐	◐	○		◐	●	●	●	○	◐		○			◐
WS_ANIM				○		○	◐	◐		◐	◐	○	○	○	●	◐	◐	○	◐		○		◐	◐
WS_LOGS	○	◐	◐	◐						○	○										○			
WS_MINE	○	○	○	○	○			○	○	◐	○					○	○		○		○			◐
WS_URBN		◐	◐	◐	○	○		○	○	◐	◐	○	○	○		◐	◐	◐	◐		○		○	◐
X_NUTRI		◐	◐	◐	○	◐		◐	○	◐	◐	◐		◐	●	●	●	◐	◐		◐			◐
N_NUTRI	○	○	◐	○	◐	◐	○		◐	○	○	◐	◐	○			○	○		◐	○		◐	○
IN_TURB	○	◐	◐	◐	○	◐		○	○	◐	◐	○	○	◐	●	◐	●		◐		◐	○	○	◐

Table 3.3 (continued)

OR_TURB	○	◍	◍	◍		◍		◍		○	○	○		○	●	◍	◍	○	◍		◍	◍		◍
VAR_TUR	○	◍	○	◍	○	○		◍	○	◍	○	○		○	◍	◍	●	○	◍		◍	○		◍
ALGAE		◍			○			◍		○	◍	○	○	○		◍	◍	○	◍	○	◍		◍	◍
VAR_DO2	○	◍	○	○				○		○	○					○	○	○	○		◍			○
O_STRAT	○	◍	◍	◍	○	◍		○	○	◍	◍	○	○	○		○	○	○	○	○	◍	○	○	○
HI_TEMP	○	◍	○	◍				◍	○	◍	◍		○	○		○	○	◍	○	○	◍	○		○
LO_TEMP	○		○				○		○										○	○	○			○
T_STRAT			○	◍	◍	◍		○	◍	◍	◍	○	○	○		○	○	◍	○	○	○	○		◍
DESTRAT		◍	○					○						○		○	○	○		◍	○			○
THERMAL	○	○	○	○				○	○	○	○	○	○	○		○	○	◍	○		○			○
CONTAMN	○	◍	◍	◍	○		○		○	◍	○	○	○	○		○	◍	○	○		◍	○		◍
POLL_PS	○	○		○	○		○			◍	○	○		○		○	◍	○	○		○			◍
POLLNPS	○	◍	○	◍	○	◍	◍	◍	○	◍	◍	○	○	◍		●	●	○	◍		◍		○	◍
HYDROGR			○	◍	○	○	◍	◍	○	◍	○		○	○	●	○	●	○	◍	◍	◍	○	○	◍
RESIDUP	○	○	○	◍	○	○	◍	○	○	◍		○	○	○	●	○	◍	○	○	○	○			◍
LOWRETE		○	○	◍			◍	○	○	◍	○		○	○	●	○	●	○	○	◍	○	○	○	◍
LOWSTOR		◍	○	◍	○	○	◍	◍	○	◍	○		◍	○	●	○	◍	○	○		◍	◍	◍	◍
WL_SEAS	○		○	◍	◍	○	●		○	◍			○	◍	●	◍	●	○	○	◍	◍		○	◍
WL_DROP	○		○	◍	◍		●	◍	○	◍	○		○	◍	●	○	◍	○	○	◍	◍	◍		●
WL_LONG	○		○	◍	◍	○	●	◍	○	○		○	◍	◍	●	○	○	○	○	○	◍	◍	◍	●
WLSHORT		◍	○	◍	○		◍	○	○	◍				○	●	○	◍	○	○	◍	◍			◍
WL_FAST	○	◍	○	◍	○		◍	○	○	◍	○		○	○	●	○	◍	○	○	◍	◍			◍
SEDIMEN	○	●	◍	●		◍	◍	◍	○	◍	◍	○	◍	◍	●	●	●	○	◍	○	◍	○		◍
SHOREER		●	◍	●	○	◍	◍	◍	○	◍	○	○		◍	◍	◍	●	○	◍		○		○	◍
NOCOVES	○	●	◍	◍		◍	◍	◍	○	◍	◍	○	○	◍		◍	●	○	◍		○	○		◍
SHOREHO	○	●	◍	◍	◍	◍	○	◍	○	◍	○	○	○	◍	●	◍	●	◍	◍		◍		◍	◍

Table 3.3 (continued)

SUBSTHO	●	◍	◍	○	◍	○	○	○	◍	○	○	○	◍	●	◍	◍	○	◍	◍	◍	◍
DIST_UP	◍	○	◍	○	○	○	◍	○	◍	◍	○	○	○		◍	●	○	◍	◍	○	◍
DIST_AD	◍	○	◍	○		○	◍	○	◍	◍	○	○	◍		◍	◍		◍	○	○	◍

Symbols indicate the percentage of reservoirs within the region with greater than moderate impairment. Blank = Less than or equal to 1%, ○ = 1-10%, ◍ = 10-50%, ● = Greater than 50%

Table 3.4 Fish community and fishery characteristics by reservoir class.

Variable		CPL				NAP		NPL		SAP			SPL				TPL			UMW	WMT		XER		
Code	Name	1	2	3	4	1	2	1	2	1	2	3	1	2	3	4	1	2	3	1	1	2	1	2	3
STANSTK	Standing stock	▲					▲					▲	▼				▲			▲		▲			
PREYSTK	Prey standing stock	△		▲			▲				△	▲	▼			▲	▲	▲	△		▽				
PREDSTK	Predator standing stock	▲	▽							△		△	▼					▼		▲		▲			
PPRATIO	Prey-predator ratio	△			▲						△		▼					▲			▽				▼
EXOTSTK	Standing stock of undesirable exotic fish species*	▼	▼	▲	▲				▲		▲	▲	▼		▲	▲	▲	▲			△	▲			▲
SP_RICH	Species richness	▼	▼									▲	▼		▼	▼				▲		▽		▽	
SP_EVEN	Species evenness	▼	▼	▼				▽	▼	▼	▼	▼	▼		▼	▼	▼	▼	▽		▼	▼	▼	▼	▼
STOCK_N	Supplementary stocking of native species*							▽		▲	▲		▼				▲	▲	▲	▼	▽		▼		▼
STOCKNN	Maintenance stocking of non-native species*	▼	▽				▲	▲	▲	▽	△			▲	▲	△		▼		▼	▲	▲	▲		
INTRONN	Undesirable species introductions*	▼	▼		▲			▼	△			▲	▼	▼	△		▲	▲		▼		▲			
FSHKILL	Fish kills*	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
PRESSURE	Fishing pressure					▼	▲			△			▼		▽	▽							▽		
CATCH_R	Catch rates		▼				△						▼		▽				▲	▲		△			▼
FSHSIZE	Size of fish caught	▲					▲			▲		▲							▲			▲			
CATCH_V	Annual variability in catch rates	▼	△			▼		▲				▼	▼												
SATSFXN	Angler satisfaction	▲	▼				▲			▲								▽	▲			▲			
TOURN_F	Frequency of tournaments*	▲		▲	▲		▲			▲	▲	▲					▲	▲	▲						
FISHING	Ratio of fishing to other recreation	▲		▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	△	▲	△	▲	▲	▲	▲	△	▲	▲		▲

Symbols indicate the significance of a Wilcoxon signed rank test for most variables (sign test indicated with an asterisk). ▲/△ = Median score is above national average ($P < 0.05$ and $P < 0.10$); ▼/▽ = Median score is below national average ($P < 0.05$ and $P < 0.10$).

Table 3.5 Five most important fish species in the recreational fishery of each reservoir class, ranked by relative popularity.

Variable	CPL				NAP		NPL		SAP			SPL				TPL			UMW	WMT		XER		
	1	2	3	4	1	2	1	2	1	2	3	1	2	3	4	1	2	3	1	1	2	1	2	3
Largemouth bass	1	1	1	1	1	2			1	1	1	1	1	3	4	1	3	1	5	5	2	2	2	1
Channel catfish	5		4	3					4	2	3	2	3	2	1	3	1	2					5	3
White crappie	3	2	2	2						3	5	4	2	5	2	2	2	3				5		
Walleye					3	3	2	1	3	5		3		1	3		4	5	1			3		
Black crappie	2		3	5		1			2		2					5		4	2		5			4
Bluegill	4	3	5		5	4					4					4			3				4	
Rainbow trout							1	2												1	1	1	1	2
Smallmouth bass					2			5											4		3			5
White bass													5	4	5		5							
Blue catfish		4								4		5												
Yellow perch						5	4	3														4		
Hybrid striped bass													4											
Spotted bass		5		4					5															
Northern pike							3	4																
Cutthroat trout							5													3	4		3	
Brown trout					4																			
Lake trout																				2				
Brook trout																				4				

Table 3.6 Results of permutational MANOVA tests for differences among reservoir classes by region in terms of environmental variables, the fish community, and the recreational fishery.

Region	Classes	Reservoir morphology	Watershed characteristics	Fish community	Recreational fishery
CPL	4	0.004	0.143	0.001	0.003
NAP	2	0.055	0.641	0.045	0.001
NPL	2	0.007	0.035	0.006	0.104
SAP	3	0.003	0.001	0.007	0.001
SPL	4	0.186	0.001	0.001	0.001
TPL	3	0.006	0.001	0.001	0.001
UMW	1	-	-	-	-
WMT	2	0.335	0.337	0.044	0.102
XER	3	0.319	0.430	0.050	0.314

P-values are shown for each set of variables.

3.7 Figures

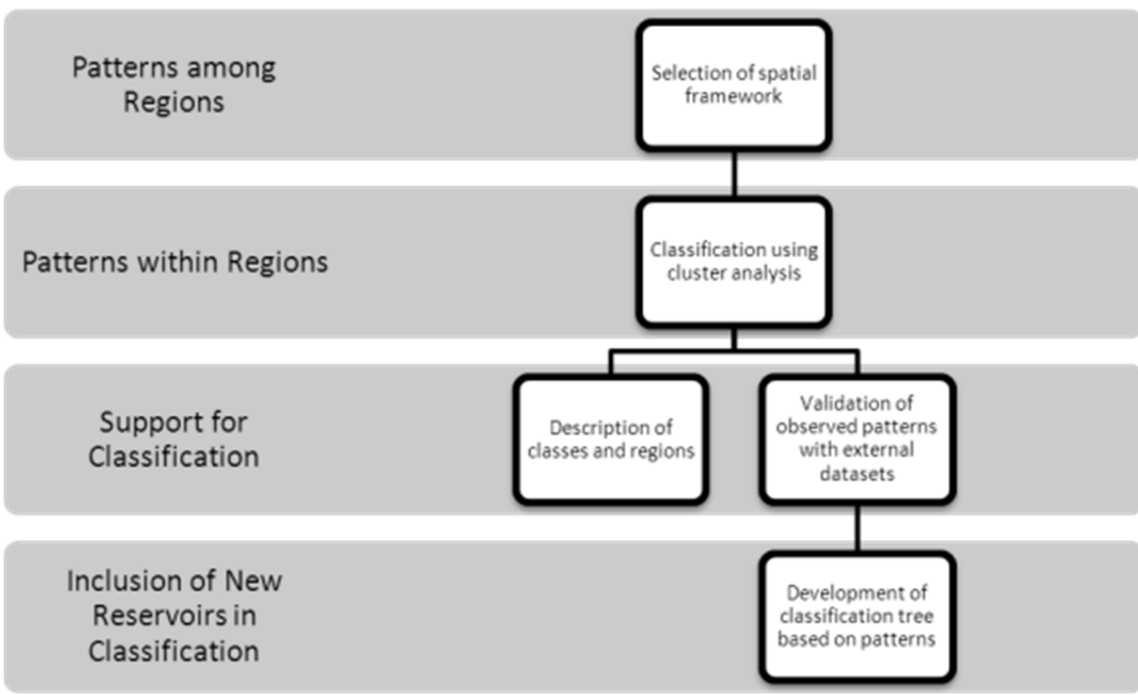

Figure 3.1 Outline of analytical approach for establishing a classification system for large reservoirs in the conterminous U.S. based on fish habitat impairment.

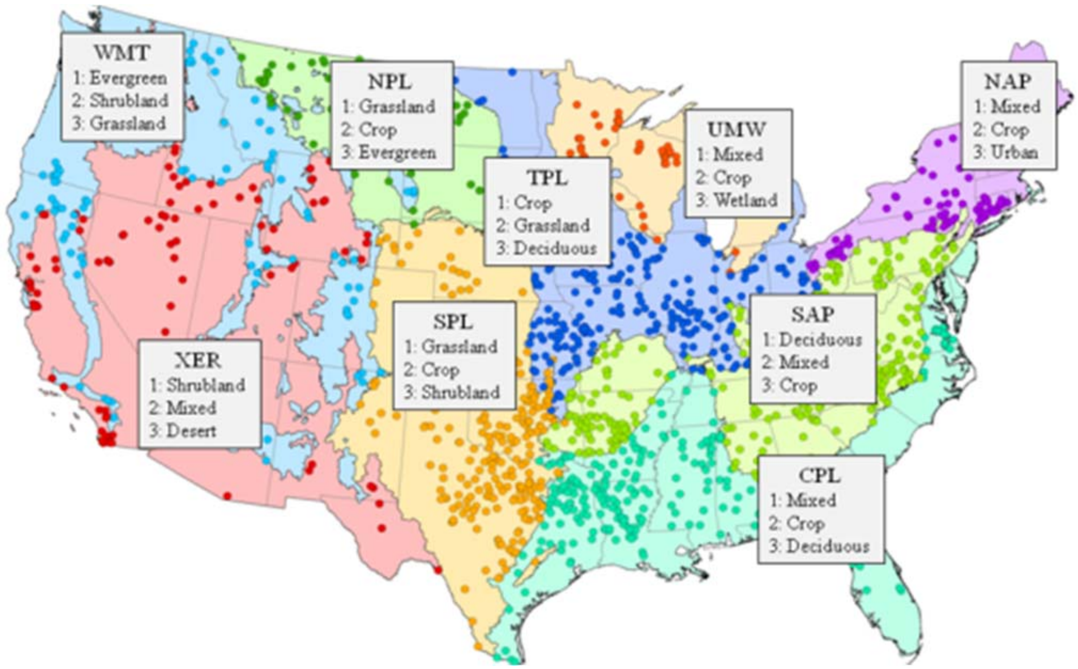

Figure 3.2 Wadeable Streams Assessment regions of the conterminous U.S. with responses from the reservoir habitat survey marked (points).

Regions include Xeric (XER), Western Mountains (WMT), Northern Plains (NPL), Temperate Plains (TPL), Southern Plains (SPL), Upper Midwest (UMW), Coastal Plains (CPL), Southern Appalachian (SAP), and Northern Appalachian (NAP). Dominant landcover types are indicated below each region name.

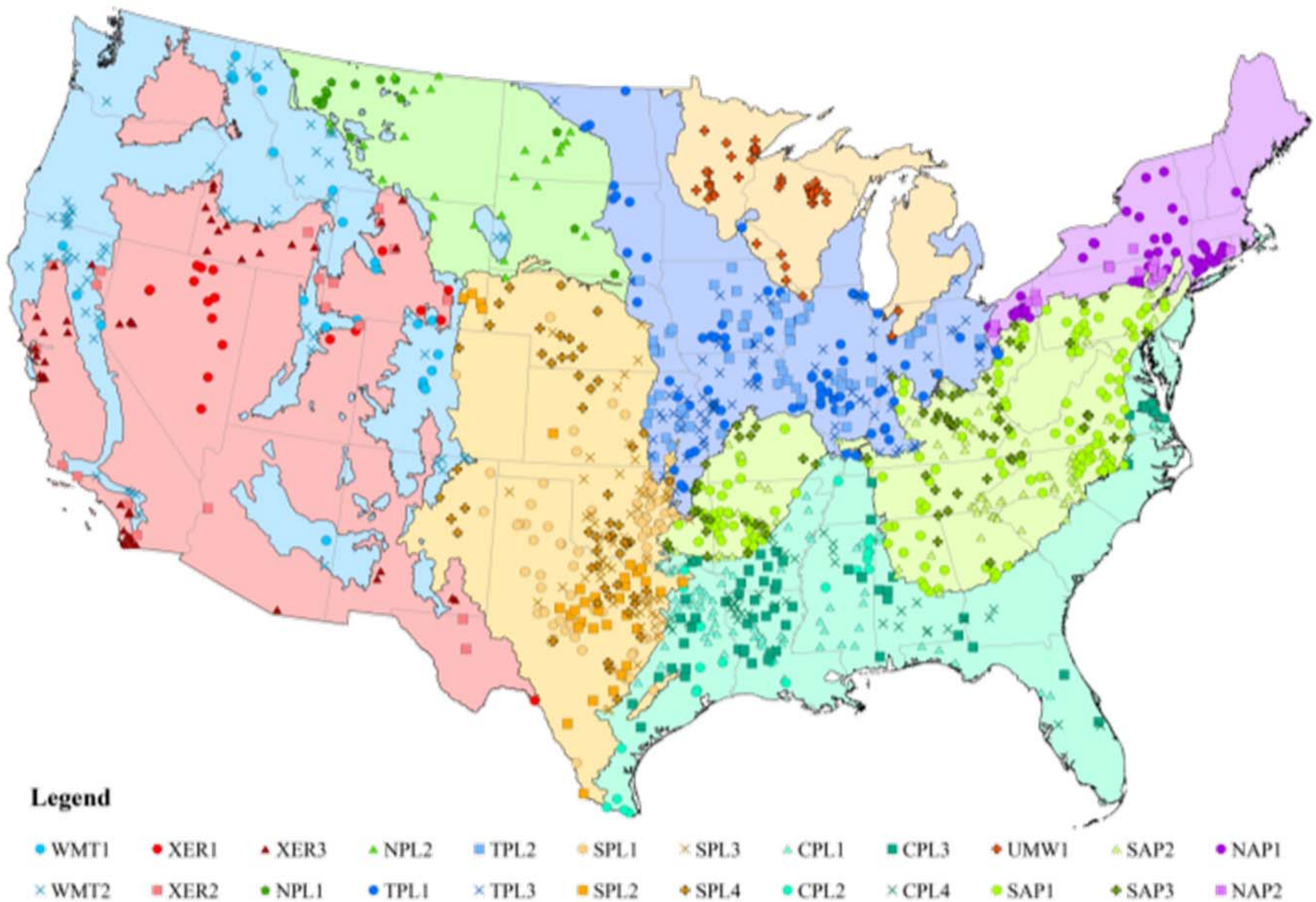

Figure 3.3 Twenty-four reservoir classes identified for large reservoirs in the conterminous U.S. For WSA region names, refer to Figure 3.2.

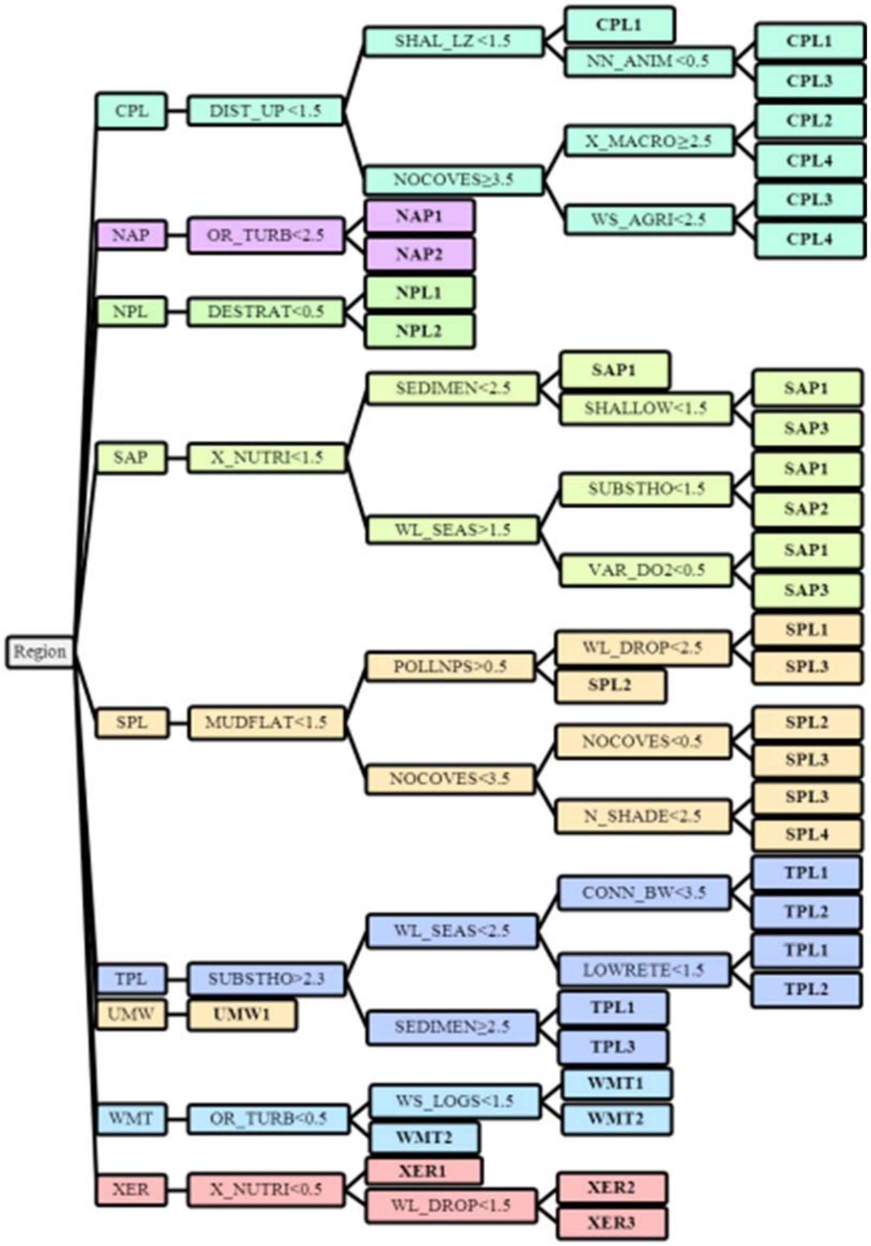

Figure 3.4 Classification tree for large reservoirs in the conterminous U.S. based on fish habitat impairment.

For WSA region names, refer to Figure 3.2. For habitat impairment variable definitions, refer to Table 3.1. All terminal nodes in bold text represent reservoir classes. The classification tree is read from left to right. If a statement is true, move right to the next upper node; if a statement is false, move to the next lower node. For example, in the CPL region, if the score for "DIST_UP" (i.e., disturbances in the upstream watershed) is less than 1.5, move right and up to the "SHAL_LZ" (i.e., excessively shallow littoral zone) node. If the score for "DIST_UP" is not less than 1.5, move right and down to the "NOCOVES" (i.e., lack or loss of cove habitat due to sedimentation) node.

3.8 References

Abell, R., M. L. Thieme, C. Revenga, M. Bryer, M. Kottelat, N. Bogutskaya, B. Coad, N. Mandrak, S. C. Balderas, W. Bussing, M. L. J. Stiassny, P. Skelton, G. R. Allen, P. Unmack, A. Naseka, R. Ng, N. Sindorf, J. Robertson, E. Armijo, J. V. Higgins, T. J. Heibel, E. Wikramanayake, D. Olson, H. L. López, R. E. Reis, J. G. Lundberg, M. H. S. Pérez, and P. Petry. 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. Bioscience 58(5):403-414.

Agostinho, A. A., L. E. Miranda, L. M. Bini, L. C. Gomes, S. M. Thomaz, and H. I. Suzuki. 1999. Patterns of colonization in neotropical reservoirs, and prognoses on aging. Pages 227-265 *in* J. G. Tundisi and M. Straškraba, editors. Theoretical Reservoir Ecology and its Applications, Brazilian Academy of Sciences, Rio de Janeiro, Brazil.

Anderson, M. J., R. N. Gorley, and K. R. Clarke. 2008. PERMANOVA+ for PRIMER: Guide for Software and Statistical Methods. PRIMER-E, Plymouth, United Kingdom.

Angermeier, P. L., and J. R. Karr. 1984. Relationships between woody debris and fish habitat in a small warmwater stream. Transactions of the American Fisheries Society 113:716-726.

Aycrigg, J. L., A. Davidson, L. Svancara, K. J. Gergely, A. McKerrow, and J. M. Scott. 2010. Gap analysis of ecological systems nationwide. Gap Analysis Bulletin 18:39-40.

Bachmann, R. E., T. A. Hoyman, L. K. Hatch, and B. P. Hutchins. 1994. A classification of Iowa’s lakes for restoration. Department of Animal Ecology, Iowa State University: Ames, Iowa.

Bachmann, R. E., M. R. Johnson, M. V. Moore, and T. A. Noonan. 1980. Clean lakes classification study of Iowa’s lakes for restoration: final report. Iowa Cooperative Fisheries Research Unit and Department of Animal Ecology, Iowa State University: Ames, Iowa.

Baldwin, C. M., D. A. Beauchamp, and C. P. Gubala. 2002. Seasonal and diel distribution and movement of cutthroat trout from ultrasonic telemetry. Transactions of the American Fisheries Society 131(1):143-158.

Barwick, D. H. 2004. Species richness and centrarchid abundance in littoral habitats of three southern U.S. reservoirs. North American Journal of Fisheries Management 24:76-81.

Blom, G., E. H. S. Van Duin, and L. Lijklema. 1994. Sediment resuspension and light conditions in some shallow Dutch lakes. Water Science and Technology 30(10):243-252.

Bulley, H. N. N., J. W. Merchant, D. B. Marx, J. C. Holz, and A. A. Holz. 2007. A GIS-based approach to watershed classification for Nebraska reservoirs. Journal of the American Water Resources Association 43:605-621.

Burns, N. M., J. C. Rutherford, and J. S. Clayton. 1999. A monitoring and classification system for New Zealand lakes and reservoirs. Journal of Lake and Reservoir Management 15(4):255-271.

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22(2):361-369.

Dolman, W. B. 1990. Classification of Texas reservoirs in relation to limnology and fish community associations. Transactions of the American Fisheries Society 119(3):511-520.

Downing, J. A., J. Li, G. Antoniou, D. Kendall, C. Kling, J. Herriges, R. Castro, P. Van Meter, D. Woolnough, K. Egan, Y. Jeon, R. Andrews, S. Conrad, and L. Boatwright. 2005. Iowa Lakes Classification for Restoration. Iowa Department of Natural Resources, Des Moines.

Duarte, C. M. 1995. Submerged aquatic vegetation in relation to different nutrient regimes. Ophelia 41:87-112.

Edmiston, H. L., and V. B. Myers. 1984. Florida lakes assessment: combining macrophyte, chlorophyll, nutrient, and public benefit parameters into a meaningful lake management scheme. Lake and Reservoir Management 1(1):25-31.

Engel, S., and S. A. Nichols. 1994. Aquatic macrophyte growth in a turbid windswept lake. Journal of Freshwater Ecology 9(2):97-109.

Finch, W. H. 2010. Imputation methods for missing categorical questionnaire data: a comparison of approaches. Journal of Data Science 8:361-378.

Finch, H., and M. Margraf. 2008. Imputation of categorical missing data: a comparison of multivariate normal and multinomial methods. SAS Conference Proceedings S05-2008. Midwest SAS User Group, Indianapolis, Indiana.

Godinho, F. N., M. T. Ferreira, and M. I. Portugal e Castro. 1998. Fish assemblage composition in relation to environmental gradients in Portuguese reservoirs. Aquatic Living Resources 11(5):325-334.

Gower, J. C. 1971. A general coefficient of similarity and some of its properties. Biometrics 27(4):857-871.

Graham, K. 1999. A review of the biology and management of blue catfish. American Fisheries Society Symposium 24:37-49.

Gresswell, R. E. 1995. Yellowstone cutthroat trout. Pages 36-54 *in* M. K. Young, editor. Conservation assessment for inland cutthroat trout. General Technical Report RM-256. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Ground, T. A., and A. W. Groeger. 1994. Chemical classification and trophic characteristics of Texas reservoirs. Lake and Reservoir Management 10(2):189-201.

Hawkins, C. P., R. H. Norris, J. Gerritsen, R. M. Hughes, S. K. Jackson, R. K. Johnson, and R. J. Stevenson. 2000. Evaluation of the use of landscape classifications for the prediction of freshwater biota: synthesis and recommendations. Journal of the North American Benthological Society 19(3):541-556.

Hill, K. R. 1986. Classification of Iowa lakes and their fish standing stock. Lake and Reservoir Management 2(1):105-109.

Kimmel, B. L., and A. W. Groeger. 1986. Limnological and ecological changes associated with reservoir aging. Pages 103-109 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir Fisheries Management: Strategies for the 80's. Southern Division Reservoir Committee, American Fisheries Society, Bethesda, Maryland.

Lara, G., L. Encina, and A. Rodríguez-Ruiz. 2009. Trophometric index: a predictor for fish density, biomass and production in Mediterranean reservoirs in Spain. Fisheries Management and Ecology 16:341-351.

Leite, W., and S. N. Beretvas. 2010. The performance of multiple imputation for Likert-type items with missing data. Journal of Modern Applied Statistical Methods 9(1):64-74.

Miranda, L. E. 1999. A typology of fisheries in large reservoirs of the United States. North American Journal of Fisheries Management 19:536-550.

Miranda, L. E. 2008. Extending the scale of reservoir management. Pages 75-102 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Miranda, L. E., and K. M. Hunt. 2010. An index of reservoir habitat impairment. Environmental Monitoring and Assessment172:225-234.

Miranda, L. E., M. Spickard, T. Dunn, K. M. Webb, J. N. Aycock, and K. Hunt. 2010. Fish habitat degradation in U.S. reservoirs. Fisheries 35(4):176-184.

MNDNR (Minnesota Department of Natural Resources). 2012. Shoreland management lake classifications. Available: http://www.dnr.state.mn.us/waters/watermgmt_section/shoreland/lake_shoreland_classifications.html. (May 2012).

Omernik, J. M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1):118-125.

Omernik, J. M. 1995. Ecoregions: a spatial framework for environmental management. Pages 49-62 *in* W. Davis and T. P. Simon, editors. Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making, Lewis Publishing, Boca Raton, Florida.

Platts, W. S. 1980. A plea for fishery habitat classification. Fisheries 5(1):2-6.

Rodgers, K., and R. Green. 2011. A national reservoir database of geographical, physical, and morphological metrics for classification and discrimination for fisheries habitat assessment. U.S. Geological Survey. Created for the Reservoir Fisheries Habitat Partnership. Not yet available online.

Romesburg, H. C. 2004. Cluster analysis for researchers. Lulu Press, North Carolina.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody debris habitat. Fisheries 31(7):321-330.

Schafer, J. L. 1997. Analysis of Incomplete Multivariate Data. Chapman & Hall, Boca Raton, Florida.

Schafer, J. L., M. Khare, and T. Ezzati-Rice. 1993. Multiple imputation of missing data in NHAMES III. Proceedings of the 1993 Annual Research Conference. Washington, D. C., U.S. Bureau of the Census.

Schindler, D. W. 1971. A hypothesis to explain the differences and similarities among lakes in experimental lakes area, northwestern Ontario. Journal of the Fisheries Research Board of Canada 28:295-301.

Seaber, P. R., F. P. Kapinos, and G. L. Knapp. 1987. Hydrologic Unit Maps: U.S. Geological Survey, Water-Supply Paper 2294. U.S. Government Printing Office.

Tonn, W. M., J. J. Magnuson, and A. M. Forbes. 1983. Community analysis in fishery management: an application with northern Wisconsin lakes. Transactions of the American Fisheries Society 112:368-377.

USACE (U.S. Army Corps of Engineers). 2009. National Inventory of Dams (NID). Available: http://geo.usace.army.mil/pgis/f?p=397:1:3514628094309333. (December 2010).

USEPA (U.S. Environmental Protection Agency). 2006. Wadeable streams assessment: a collaborative survey of the nation's streams. USEPA, Report 841-B-06-002, Office of Research and Development, Office of Water, Washington, D.C.

USFWS (U.S. Fish and Wildlife Service). 2006. National survey of fishing, hunting, and wildlife-associated recreation. U.S. Government Printing Office, Washington, D.C.

USFWS. 2010. LCC information bulletin #2: developing the National Geographic Framework. Office of the Science Advisor, USFWS. 18 pages.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Technical Report DAS/SCI/68.27, Organisation for Economic Cooperation and Development, Directorate for Scientific Affairs, Paris, France.

Westlake, D. F. 1965. Some basic data for investigations of the productivity of aquatic macrophytes. Mem. Ist. Ital. Idrobiol. 18:229-248.

Wetzel, R. G. 1990. Reservoir ecosystems: conclusions and speculations. Pages 227-238 *in* K. W. Thornton, B. L. Kimmel, and F. E. Payne, editors. Reservoir Limnology: Ecological Perspectives. Wiley Interscience, New York.

Wiken, E., F. Jiménez Nava, and G. Griffith. 2011. North American terrestrial ecoregions – Level III. Commission for Environmental Cooperation, Montreal, Canada. 149 pages.

CHAPTER IV

SYNTHESIS AND RECOMMENDATIONS FOR FUTURE WORK

This project fills a substantial void in reservoir fish habitat research. Namely, it addresses the need for a nationally-applicable classification system based on fish habitat. Classes were identified using a tiered approach cognizant of landscape-scale ecological patterns and localized fish habitat patterns. Suites of habitat impairments are unique to each class, thereby encouraging the development of class-specific management strategies. Common reservoir habitat issues—including siltation, eutrophication and declining water quality, water regime, structural habitat, and aquatic plants—do not emerge simultaneously in all reservoirs; they vary depending on landscape and local variables. Although some efforts at reservoir classification have been made in the past, this is the first to directly address fish habitat impairments for the purpose of enhancing large-scale conservation planning.

The fish habitat classification system is applicable to large reservoirs of the conterminous U.S. It should be used early in the conservation planning process to facilitate assessment of project reservoirs. Membership in a reservoir class can help pinpoint major habitat impairments, indicate potential for additional impairments, and identify management strategies that target the impairments directly. For example, classification of a reservoir into a class wrought by siltation-related impairments may indicate the long-term need for watershed planning and collaboration with land-use agencies, rather than installation of gravel beds. In contrast, a class less prone to siltation but lacking in substrate diversity for other reasons may benefit long-term by installation of gravel beds.

The classification system also opens the door to development of an assessment system for large U.S. reservoirs. As aforementioned, a classification system provides the framework within which an assessment mechanism can function. Direct assessment of reservoir fish habitat, fish community condition, or fishery quality has been conspicuously lacking. Hickman and McDonough (1996) developed a reservoir fish assemblage index as a bioassessment tool for Tennessee Valley reservoirs. The index was functionally similar to an index of biotic integrity (Karr et al. 1986) and used various characteristics of the fish community as metrics (i.e., taxa richness and composition, trophic composition, reproductive composition, total abundance, and fish health; McDonough and Hickman 1999). Diversity in habitat characteristics was actually considered a source of unexplained variation. Similar to other indices of biotic integrity, the reservoir fish assemblage index required extensive fish sampling and was specific to the region sampled. A similar bioassessment tool was developed for Lake Sinclair, Georgia, which received thermal loading from a hydropower facility (Cheek et al. 2008). Reference conditions were based on the fish and macroinvertebrate communities present in portions of the reservoir that were unaffected by thermal loading; deviations in various community characteristics were attributed to thermal pollution. Again, this method required extensive sampling and was specific to Lake Sinclair. For assessment of reservoir condition to become possible on a broad scale (e.g., the entire U.S.), alternative methods must be developed.

Miranda and Hunt (2011) used a novel approach to reservoir assessment focused on fish habitat. A fish habitat survey similar to the one used in this study was sent to reservoir biologists of large U.S. reservoirs ≥200 ha. Factor analysis of habitat impairment variables yielded the five degradation factors aforementioned (i.e., siltation, eutrophication and water quality, water regime, structural habitat, and aquatic plants). Based on factor loadings, five constructs were created, and construct scores were added to create an index of reservoir habitat impairment (IRHI; Miranda and Hunt 2010). Application of the IRHI to sample reservoirs resulted in an approximately normal distribution of scores, and information from the individual components of the IRHI was not lost. Although geographic patterns in degradation factors were apparent, a spatial component was not incorporated in the IRHI. The IRHI methodology provides a basis from which to develop a more extensive, more detailed assessment of reservoir habitat that is tied to fish community characteristics. A revised IRHI created within the classification system's framework would better account for geographic patterns and account for inherent differences among classes.

Also, relationships between reservoir fish habitat and fish communities need to be further investigated. Specifically, landscape-level variables related to differences among reservoir classes could be used to predict fish community characteristics, as has been done in natural Michigan lakes (Wehrly et al. 2012), whereas landscape-level variables driving changes in the fish community could be targeted for remediation. Quantification of the relationship between reservoir classes and measures of the fish community and recreational fishery would also help to identify benefits gained from fish habitat improvement, as well as to develop realistic expectations for the fish community and fishery.

4.1 References

Cheek, T. E., A. R. Dodd, R. G. King, S. Hendricks, and B. Evans. 2008. Conduct of a reservoir multimetric bioassessment to address a Clean Water Act Section 316(a) demonstration for Georgia Power Company's Plant Branch, Lake Sinclair, Georgia. Pages 655-680 *in* M.S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing Fisheries Management and Water Uses for Impounded River Systems. American Fisheries Society, Symposium 62, Bethesda, Maryland.

Hickman, G. D., and T. A. McDonough. 1996. Assessing the reservoir fish assemblage index: a potential measure of reservoir quality. American Fisheries Society Symposium 16:85-97.

Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. Assessing biological integrity in running waters: a method and its rationale. Illinois Natural History Survey, Special Publication 5, Champaign.

McDonough, T. A., and G. D. Hickman. 1999. Reservoir fish assemblage index development: a tool for assessing ecological health in Tennessee Valley Authority impoundments. Pages 523-540 *in* T. P. Simon, editor. Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities. CRC Press, Boca Raton, Florida.

Miranda, L. E., and K. M. Hunt. 2010. An index of reservoir habitat impairment. Environmental Monitoring and Assessment172:225-234.

Wehrly, K. E., J. E. Breck, L. Wang, and L. Szabo-Kraft. 2012. A landscape-based classification of fish assemblages in sampled and unsampled lakes. Transactions of the American Fisheries Society 141:414-425.

APPENDIX A

RESERVOIR HABITAT SURVEY

The Reservoir Habitat Survey was initially conducted online, enabling dynamic content such as 1) the ability to skip irrelevant pages based on responses to specific questions, and 2) the appearance of complete definitions for variables on mouse-over of the variable (see Appendix B). The PDF version of the survey was used for late respondents and is shown on the following pages.

Introduction

To address habitat issues in reservoirs, the National Fish Habitat Reservoir Partnership was created in 2009 under the auspices of the National Fish Habitat Action Plan. The goal of the reservoir partnership is to set a strategy for tackling habitat issues at a national scale leading to enhanced quality of life for both fish and humans. To gather baseline information for the development of a blueprint for a national reservoir habitat strategy, we are asking you to complete a survey about reservoirs in your jurisdiction.

This survey takes a broad view of reservoirs by considering their watershed, tributaries, riparian zone, and the tailwater below the dam. Much of the specifics about watersheds and tributaries are currently being assembled from existing databases, so most of this survey focuses on in-reservoir habitat and the reservoir's tailwater. In addition, the survey includes general questions about the fish communities, selected fish populations, and the fisheries.

We estimate it may take you **20 minutes** to complete the survey for each reservoir. **If other responsibilities require you to leave the survey partly finished, leave the browser window open.** You may return at a later time without losing your work. Your participation is completely voluntary and your responses will be strictly confidential, with data reported only in the aggregate. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any questions, you can withdraw from the survey at any point.

In questions where an answer may depend on the time period considered, your response should reflect the current status of the reservoir (i.e., situation within the last 5 years). In questions where an answer requires that you contrast among reservoirs, answer in relation to similar reservoirs within your geographical region whether within your state or a nearby state. If there is another staff member in your agency that has more experience with this reservoir than you, please collaborate with that individual in formulating your responses. Because blank responses complicate analyses, a good guess is preferred over a blank response, but a blank response is better than a bad guess.

For further questions about this survey, feel free to get in touch with your agency contact, Rebecca Krogman(641-780-5201; rebecca.krogman@gmail.com) or Steve Miranda (662-325-3217; smiranda@cfr.msstate.edu).

Thank you very much for your time and support. Please start the survey by clicking on the **Next** button below.

PLEASE NOTE: Dropdown menus do NOT work in the PDF version. Please enter your response by typing.

Choose Reservoir

* 1. Please choose your reservoir from the dropdown list.

The reservoir database is currently organized **by the name of the dam**. If multiple structures are listed for the same reservoir, choose the primary impounding structure. You will then be directed to a page for entering the most commonly used name of the reservoir. If the reservoir is not listed, select "NOT IN LIST" and you will be directed to a page for entering a new reservoir.

Dam name - River - County

Please skip this page in the PDF version.

Update Reservoir

* 2. Please enter the name most commonly used for the reservoir.

Reservoir Name:

Please enter the surface area of the entire reservoir at normal pool elevation (enter exact area if known, otherwise select from approximate area):

Exact surface area (acres)

Approximate surface area (acres)

Please skip this page in the PDF version.

Enter New Reservoir

* 2. Please enter as much of the following information as possible. For reservoir name, enter the name most commonly used for the reservoir.

Reservoir Name:

Dam Name:

River Name:

County:

Please enter the surface area of the entire reservoir at normal pool elevation (enter exact area if known, otherwise select from approximate area):

Exact surface area (acres)

Approximate surface area (acres)

Please fill out all information possible to help us identify the correct reservoir. If you have "Typewriter" capability, GPS coordinates would also be helpful.

Basic Information

3. Please indicate the primary uses of the reservoir (check **primary** uses only):

- [ ] Flood control
- [ ] Navigation
- [ ] Hydroelectric power
- [ ] Irrigation
- [ ] Municipal/industrial water supply
- [ ] Cooling for factory or plant effluents
- [ ] Water quality improvement downstream
- [ ] Assimilation of waste effluents
- [ ] Fish/wildlife habitat or conservation
- [ ] Recreation (camping, fishing, etc.)
- [ ] Unknown
- [ ] Other (please specify)

4. Please rank the dominant landcover types in the portion of the watershed that you believe has the most influence on the reservoir (rank up to three):

	First	Second	Third
Evergreen forest	○	○	○
Deciduous forest	○	○	○
Mixed evergreen-deciduous forest	○	○	○
Shrubland	○	○	○
Grassland	○	○	○
Wetland	○	○	○
Cropland	○	○	○
Barren rock	○	○	○
Desert	○	○	○
Urban	○	○	○

Habitat Availability

5. Based on your experience with this reservoir, please indicate the extent to which the following fish habitat concerns apply to this reservoir (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	None (0)	Low (1)	Low to Moderate (2)	Moderate (3)	Moderate to High (4)	High (5)
Excessively shallow reservoir	○	○	○	○	○	○
Excessive littoral mudflats	○	○	○	○	○	○
Insufficient adjoining backwaters and wetlands	○	○	○	○	○	○
Insufficient connectivity to backwaters and wetlands	○	○	○	○	○	○
Insufficient connectivity to tributaries due to sedimentation	○	○	○	○	○	○
Excessive aquatic macrophytes	○	○	○	○	○	○
Insufficient aquatic macrophytes	○	○	○	○	○	○
Invasive plant species	○	○	○	○	○	○
Invasive animal species capable of altering habitat	○	○	○	○	○	○
Insufficient structural habitat	○	○	○	○	○	○
Excessively shallow littoral zone	○	○	○	○	○	○
Deep or steep littoral zone	○	○	○	○	○	○
Insufficient bank shading	○	○	○	○	○	○
Insufficient allochthonous inputs	○	○	○	○	○	○
Excessive disturbance of riparian zone	○	○	○	○	○	○
Harmful levels of agriculture in the surrounding watershed	○	○	○	○	○	○
Harmful levels of livestock production in the surrounding watershed	○	○	○	○	○	○
Harmful levels of logging in the surrounding watershed	○	○	○	○	○	○
Harmful levels of mining in the surrounding watershed	○	○	○	○	○	○
Harmful levels of urbanization in the surrounding watershed	○	○	○	○	○	○

Water Quality

6. Based on your experience with this reservoir, please indicate the extent to which the following water quality concerns apply to this reservoir (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	None (0)	Low (1)	Low to Moderate (2)	Moderate (3)	Moderate to High (4)	High (5)
Excessive nutrients	○	○	○	○	○	○
Insufficient nutrients	○	○	○	○	○	○
Excessive suspended sediments or inorganic turbidity	○	○	○	○	○	○
Excessive organic turbidity	○	○	○	○	○	○
Extreme seasonal variation in turbidity	○	○	○	○	○	○
Harmful algae blooms	○	○	○	○	○	○
Extreme diel variation in dissolved oxygen	○	○	○	○	○	○
Oxygen stratification	○	○	○	○	○	○
Excessively high temperatures	○	○	○	○	○	○
Excessively low temperatures	○	○	○	○	○	○
Temperature stratification	○	○	○	○	○	○
Untimely or frequent turnovers	○	○	○	○	○	○
Thermal pollution	○	○	○	○	○	○
Contaminants (heavy metals, biocides)	○	○	○	○	○	○
Point-source pollution	○	○	○	○	○	○
Non-point source pollution	○	○	○	○	○	○

Water Regime

7. Based on your experience with this reservoir, please indicate the extent to which the following water regime concerns apply to this reservoir (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	None (0)	Low (1)	Low to Moderate (2)	Moderate (3)	Moderate to High (4)	High (5)
Unfavorable seasonal hydrograph (or rule curve, if one exists)	○	○	○	○	○	○
Residual effects of upstream impoundments	○	○	○	○	○	○
Insufficient retention time	○	○	○	○	○	○
Insufficient water storage	○	○	○	○	○	○
Seasonally mistimed water level fluctuations	○	○	○	○	○	○
Excessive yearly drawdown	○	○	○	○	○	○
Excessive long-term drawdowns	○	○	○	○	○	○
Excessive short-term fluctuations	○	○	○	○	○	○
Rapid water level change	○	○	○	○	○	○

Processes

8. Based on your experience with this reservoir, please indicate the extent to which the following processes burden this reservoir (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	None (0)	Low (1)	Low to Moderate (2)	Moderate (3)	Moderate to High (4)	High (5)
Sedimentation	○	○	○	○	○	○
Shoreline erosion	○	○	○	○	○	○
Loss of cove habitat due to depositional filling	○	○	○	○	○	○
Shoreline homogenization	○	○	○	○	○	○
Homogenization of littoral substrates	○	○	○	○	○	○
Disturbances in upstream watersheds	○	○	○	○	○	○
Disturbances in adjacent watersheds	○	○	○	○	○	○

9. Are there any other habitat problems that you believe have a large effect on fish habitat in this reservoir, and if so, to what extent?

Fish Community

10. Please score the following fish community characteristics in this reservoir in relation to reservoirs with similar geomorphology, whether within your state or within nearby states (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	Low (1)	Below average (2)	Average (3)	Above average (4)	High (5)
Standing stock	○	○	○	○	○
Prey standing stock	○	○	○	○	○
Predator standing stock	○	○	○	○	○
Prey-predator ratio	○	○	○	○	○
Standing stock of undesirable exotic fish species	○	○	○	○	○
Species richness	○	○	○	○	○
Species evenness	○	○	○	○	○
Supplementary stocking of native species	○	○	○	○	○
Maintenance stocking of non-native species	○	○	○	○	○
Undesirable species introductions	○	○	○	○	○
Fish kills	○	○	○	○	○

11. Does the reservoir support a recreational fishery, or has it supported a recreational fishery in the past?

○ Yes

○ No

If no, you may skip the "Fishery" section below.

The Fishery

11a. Please score the following fishery characteristics in this reservoir in relation to reservoirs with similar geomorphology, whether within your state or within nearby states (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	Low (1)	Below Average (2)	Average (3)	Above Average (4)	High (5)
Fishing pressure	○	○	○	○	○
Catch rates	○	○	○	○	○
Size of fish caught	○	○	○	○	○
Annual variability in catch rates	○	○	○	○	○
Angler satisfaction	○	○	○	○	○
Frequency of tournaments	○	○	○	○	○
Ratio of fishing to other recreational activities	○	○	○	○	○

11b. Please identify the top 1, 2, or 3 most important target species in the recreational fishery (select one from each drop-down menu; if it is not listed, please enter it in the text box provided):

First Most Important:

Second Most Important:

Third Most Important:

Please be species-specific if possible. In addition, scientific name would be the clearest for us to interpret as some common names are regional.

11c. For the **first most important species** identified above, check the approximate composition of the catch...

	<25%	25-50%	50-75%	>75%
In the total recreational fishery:	○	○	○	○
Made up of fish large enough to satisfy anglers:	○	○	○	○
Made up of stocked fish:	○	○	○	○

11d. Please score the following population characteristics for the **first most important species** in relation to reservoirs with similar geomorphology, whether within your state or within nearby states (check appropriate column):

Descriptions are available by hovering the pointer over each variable.

	Low (1)	Below Average (2)	Average (3)	Above Average (4)	High (5)
Population density	○	○	○	○	○
Quality of size structure	○	○	○	○	○
Condition	○	○	○	○	○
Growth rate	○	○	○	○	○
Natural mortality	○	○	○	○	○
Recruitment to age 1	○	○	○	○	○
Recruitment to adulthood	○	○	○	○	○

APPENDIX B

DEFINITIONS OF HABITAT AND FISH VARIABLES

Table B.1 Impairment variables queried in the Reservoir Fish Habitat Survey, abbreviation, and definition provided in the survey.

Impairment Variable	**Abbreviation**	**Definition**
Excessively shallow reservoir	SHALLOW	Entire reservoir is excessively shallow, with no or few deep water refuges
Excessive littoral mudflats	MUDFLAT	Seasonally flooded and exposed expansive layers of soft sediments; terrestrial vegetation seldom grows unless the mudflats are exposed for many months
Insufficient adjoining backwaters and wetlands	BKWATER	The reservoir or tributaries have no or limited adjoining backwaters or wetlands and therefore lack the benefits of those habitats
Insufficient connectivity to backwaters and wetlands	CONN_BW	Disconnectivity of a reservoir to adjacent backwater areas and wetlands may prevent fish from accessing these habitats
Insufficient connectivity to tributaries due to sedimentation	CONN_TR	Sedimentation has resulted in decreased connectivity to tributaries during low-flow periods, acting as a barrier to fish movement
Excessive aquatic macrophytes	X_MACRO	Overabundance of native or non-native aquatic plants
Insufficient aquatic macrophytes	N_MACRO	Lacking or deficient aquatic plants for structural fish habitat
Invasive plant species	NN_PLNT	Presence of non-native aquatic macrophytes that may negatively impact reservoir systems, reduce public access or present other problems to reservoir managers
Invasive animal species capable of altering habitat	NN_ANIM	Presence of non-native fish or other animals that may negatively impact fish habitat
Insufficient structural habitat	N_STRUC	Lacking or deficient structure such as large woody debris, gravel substrates, and diverse bottom relief
Excessively shallow littoral zone	SHAL_LZ	Littoral zone is mostly shallow and therefore heavily influenced by temperature, wind, and other atmospheric changes
Deep or steep littoral zone	DEEP_LZ	Littoral zone is missing the habitat benefits of shallower water due to excessive bank slope
Insufficient bank shading	N_SHADE	Littoral zone receives no or limited shade or cover from terrestrial vegetation or other physical features
Insufficient allochthonous inputs	N_ALLOC	Debris from terrestrial plants (e.g., tree branches, leaves, and other vegetation) rarely falls into or is washed into shore areas
Excessive disturbance of riparian zone	DIST_RZ	Incompatible land management practices (e.g., clearing, mowing, agriculture, bulkheading) and/or development (e.g., housing, industry) extend near the shoreline of the reservoir
Harmful levels of agriculture in the surrounding watershed	WS_AGRI	The watershed surrounding the reservoir, and above the reservoir since the last dam, supports deleterious row-crop agriculture practices.
Harmful levels of livestock production in the surrounding watershed	WS_ANIM	The watershed surrounding the reservoir, and above the reservoir since the last dam, supports deleterious grazing practices and/or feedlot production
Harmful levels of logging in the surrounding watershed	WS_LOGS	The watershed surrounding the reservoir, and above the reservoir since the last dam, supports long-term deleterious logging practices

Table B.1 (continued)

Harmful levels of mining in the surrounding watershed	WS_MINE	The watershed surrounding the reservoir, and above the reservoir since the last dam, supports deleterious mining practices
Harmful levels of urbanization in the surrounding watershed	WS_URBN	The watershed surrounding the reservoir, and above the reservoir since the last dam, supports excessive urban development
Excessive nutrients	X_NUTRI	Excessive chemical nutrients in water, primarily nitrogen or phosphorus, which may result in an increase in primary productivity and lead to excessive plant growth and decay, lack of oxygen, and reductions in water quality
Insufficient nutrients	N_NUTRI	Lack of nutrients, primarily nitrogen and phosphorus, to foster primary production
Excessive suspended sediments or inorganic turbidity	IN_TURB	Particulate inorganic matter, typically fine sediments, suspended in the water column that may inhibit primary production or affect foraging by fish and other aquatic organisms
Excessive organic turbidity	OR_TURB	Particulate organic matter, other than algae blooms, suspended in the water column
Extreme seasonal variation in turbidity	VAR_TUR	Marked seasonal changes in suspended sediments
Harmful algae blooms	ALGAE	Frequent occurrence of algal blooms that may be toxic to aquatic ecosystems or inhibit public use or enjoyment of the reservoir
Extreme diel variation in dissolved oxygen	VAR_DO2	Potentially harmful daily changes in dissolved oxygen
Oxygen stratification	O_STRAT	Development of high and low oxygen (i.e. hypoxic or anoxic) layers in the water column, which may reduce the amount of suitable habitat for aquatic organisms
Excessively high temperatures	HI_TEMP	High temperatures regularly exceed the tolerance limitations of fish or other aquatic organisms
Excessively low temperatures	LO_TEMP	Low temperatures regularly exceed the tolerance limitations of fish or other aquatic organisms
Temperature stratification	T_STRAT	Development of a thermocline separating the warmer epilimnion and the colder hypolimnion
Untimely or frequent turnovers	DESTRAT	Excessive or untimely destratification events are potentially harmful to aquatic animals or inhibit public use or enjoyment of the reservoir
Thermal pollution	THERMAL	Sudden changes in ambient water temperature caused by external processes, such as when water used as a coolant is returned to the natural environment at a higher temperature
Contaminants (heavy metals, biocides)	CONTAMN	Chemical substances such as heavy metals or other fat-soluble pollutants that disrupt or harm physical processes or ecosystems and may present human health concerns (e.g., mercury in fish tissue) Contaminants may be foreign substances or naturally occurring; when naturally occurring, they are considered contaminants when they exceed natural levels
Point-source pollution	POLL_PS	An isolated, or several isolated, source(s) of pollution such as a discharge pipe from a factory or sewage treatment plant

Table B.1 (continued)

Non-point source pollution	POLLNPS	Diffuse pollution that does not originate from a single discrete source and is usually found spread throughout a large area
Unfavorable seasonal hydrograph (or rule curve, if one exists)	HYDROGR	The seasonal hydrograph targeted by the water-controlling authority is inconsistent with the life-history requirements and habitat needs of fish. If no rule curve exists, click NONE
Residual effects of upstream impoundments	RESIDUP	One or more reservoirs upstream adversely affects water regime in this reservoir
Insufficient retention time	LOWRETE	Quick flushing of the reservoir maintains high turbidity and precludes development of plankton communities
Insufficient water storage	LOWSTOR	Amount of water stored in the reservoir is not enough to sustain key fish populations, often due to siltation, decreased depth, and long-term drawdowns
Seasonally mistimed water level fluctuations	WL_SEAS	Timing of annual filling and emptying is inconsistent with the life-history requirements and habitat needs of fish
Excessive yearly drawdown	WL_DROP	Extent of annual water level drop conflicts with the life-history requirements and habitat needs of fish
Excessive long-term drawdowns	WL_LONG	Water level remains below desired levels most years and only occasionally rises to levels consistent with the life-history requirements and habitat needs of fish
Excessive short-term fluctuations	WLSHORT	Water level fluctuates frequently, exposing shallow areas on a daily to weekly basis
Rapid water level change	WL_FAST	The rate of water level increase or decrease is usually too fast and conflicts with the ecology of some fish species
Sedimentation	SEDIMEN	Settling of suspended sediments, which over time may reduce depth and homogenize substrates
Shoreline erosion	SHOREER	Removal of soil and associated terrestrial vegetation from the land-water interface due to weathering of banks or adjacent land slopes by water, ice, wind, or other factors
Loss of cove habitat due to depositional filling	NOCOVES	Sedimentation has produced changes in cove habitat such as surface area reduction, cove isolation, fragmentation, and establishment of terrestrial vegetation in newly deposited land
Shoreline homogenization	SHOREHO	A reduction of the shoreline's original habitat diversity by erosion or other processes
Homogenization of littoral substrates	SUBSTHO	A reduction of the substrate's original diversity by erosion and sedimentation
Disturbances in upstream watersheds	DIST_UP	Disturbances in watersheds upstream of the reservoir, as opposed to disturbances in the watershed surrounding the reservoir, affect habitat impairment in the reservoir
Disturbances in adjacent watersheds	DIST_AD	Disturbances in the watershed surrounding the reservoir, as opposed to disturbances in upstream watersheds, affect habitat impairment in the reservoir

Table B.2 Fish community variables included in the Reservoir Habitat Survey.

Term	Code	Definition
Standing stock	STANSTK	Density, by number or biomass, of the fish community in the reservoir
Prey standing stock	PREYSTK	Density, by number or biomass, of prey fish species in the reservoir
Predator standing stock	PREDSTK	Density, by number or biomass, of predator fish species in the reservoir
Prey-predator ratio	PPRATIO	Quantity of prey in relation to quantity of predators, regardless of their standing stock
Standing stock of undesirable exotic fish species	EXOTSTK	Density, by number or biomass, of unwanted introduced species
Species richness	SP_RICH	Number of fish species that occupy the reservoir full-time or part-time
Species evenness	SP_EVEN	The equitability of abundance distribution among species
Supplementary stocking of native species	STOCK_N	One or more populations of native species are periodically supplemented with hatchery fish
Maintenance stocking of non-native species	STOCKNN	One or more populations of non-native species are periodically supplemented with hatchery fish
Undesirable species introductions	INTRONN	Introductions of undesirable species not native to the basin
Fish kills	FSHKILL	Localized die-offs associated with unsuitable water chemistry (not temperature)

Table B.3 Recreational fishery variables included in the Reservoir Habitat Survey.

Term	Code	Definition
Fishing pressure	PRESSURE	The relative amount of fishing effort received by the reservoir
Catch rates	CATCH_R	Pace at which anglers hook fish, regardless of size
Size of fish caught	FSHSIZE	Average length of fish caught
Annual variability in catch rates	CATCH_V	Large fluxes of catch between years
Angler satisfaction	SATSFXN	Overall contentment of anglers with catch rates and fish size
Frequency of tournaments	TOURN_F	Regularity with which the reservoir is chosen for organized tournaments, whether small or large tournaments
Ratio of fishing to other recreational activities	FISHING	Importance of fishing in the reservoir in comparison to other recreational activities

Table B.4 Population variables included in the Reservoir Habitat Survey, pertaining to the most important target species.

Term	**Definition**
Population density	Relative abundance of principal target species
Quality of size structure	Length distribution of the target population
Condition	Average observed weight of individual fish in the population relative to expected weight for the species
Growth rate	Rate of increase in length
Natural mortality	Mortality attributed to factors such as environmental conditions or interactions with other species; does not include mortality due to fishing
Recruitment to age 1	Juveniles that survive their first year of life
Recruitment to adulthood	Juveniles that reach reproductive maturity

APPENDIX C

SPATIAL FRAMEWORKS

Table C.1 Comparison of five spatial frameworks considered during classification of large reservoirs of the conterminous U.S.

Spatial framework	# of Regions	P-value of main test	Pairs not significantly different	P-value of pairwise comparison	# of pairs not significantly different of total	%
Omernik's L1	8	.001	8, 12	0.122	2/28	7.1
			12, 13	0.336		
Omernik's L2	18	.001	8.3, 12.1	0.123	15/153	9.8
			8.3, 13.1	0.104		
			8.5, 12.1	0.108		
			8.5, 13.1	0.166		
			8.5, 9.6	0.278		
			12.1, 13.1	0.348		
			12.1, 10.2	0.209		
			12.1, 9.2	0.135		
			12.1, 9.5	0.123		
			12.1, 9.6	0.234		
			13.1, 9.6	0.621		
			10.2, 11.1	0.133		
			10.2, 9.3	0.159		
			10.1, 9.6	0.171		
			9.2, 8.2	0.236		
WSA	9	.001	0	-	0/36	0
LCC	16	.001	3, 16	0.154	9/120	7.5
			7, 16	0.297		
			8, 16	0.17		
			15, 16	0.134		
			12, 13	0.118		
			21, 3	0.45		
			21, 4	0.161		
			21, 10	0.276		
			21, 16	0.217		
HUC2	18	.001	6, 15	0.271	9/153	5.9
			6,14	0.144		
			3, 15	0.16		
			7, 9	0.147		
			8, 15	0.12		
			15, 16	0.325		
			15, 14	0.553		
			15, 17	0.169		
			15, 12	0.408		

P-values of permutational MANOVA main tests and, where appropriate, pairwise comparisons are shown for each framework.

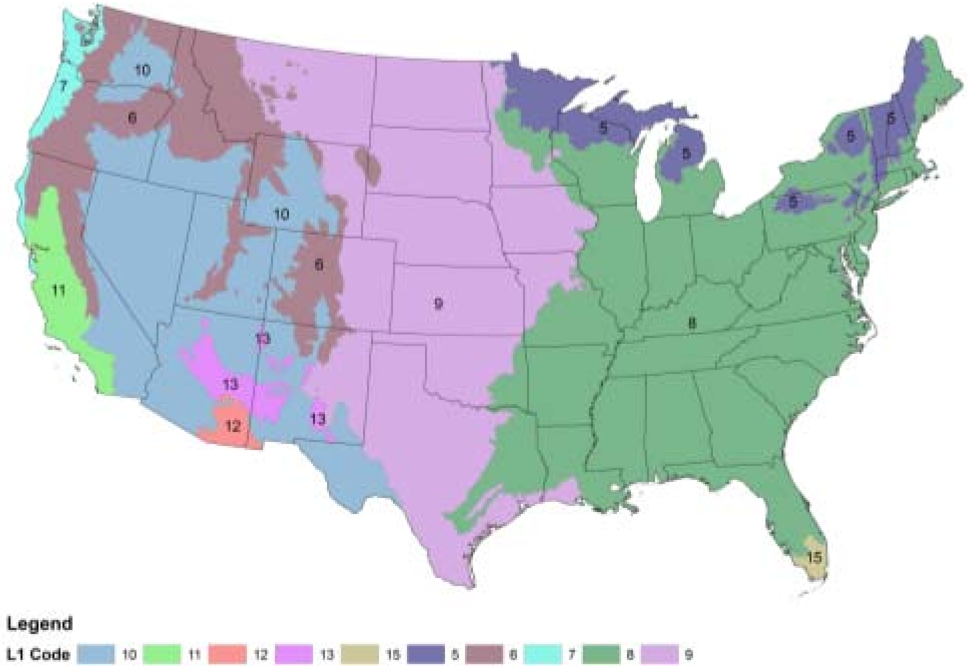

Figure C.1 Omernik’s Level I ecoregions. (Adapted from Omernik 1987.)

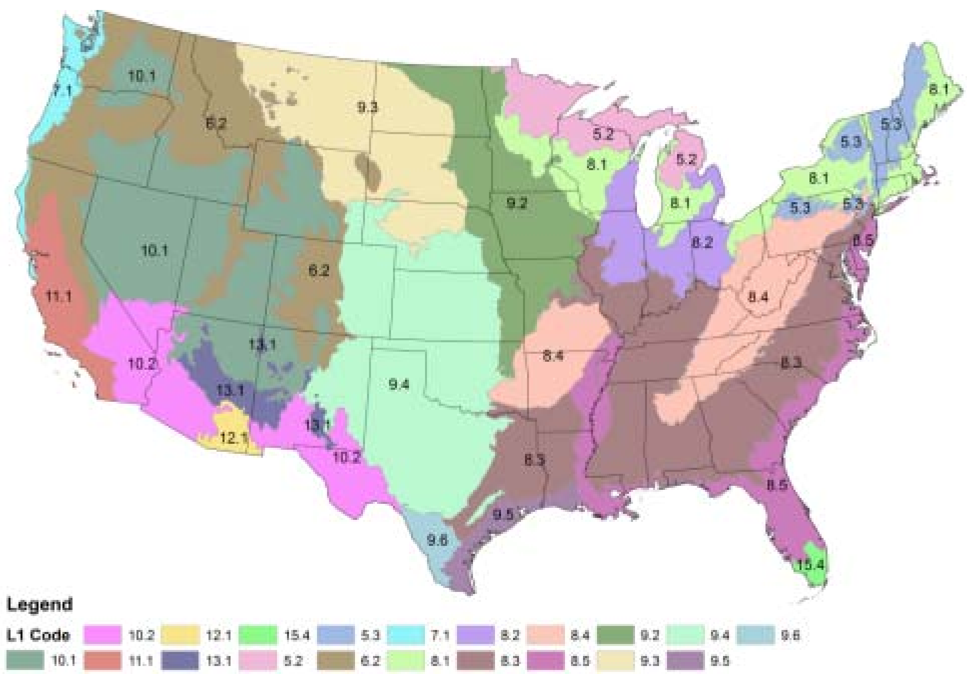

Figure C.2 Omernik’s Level II ecoregions. (Adapted from Omernik 1995.)

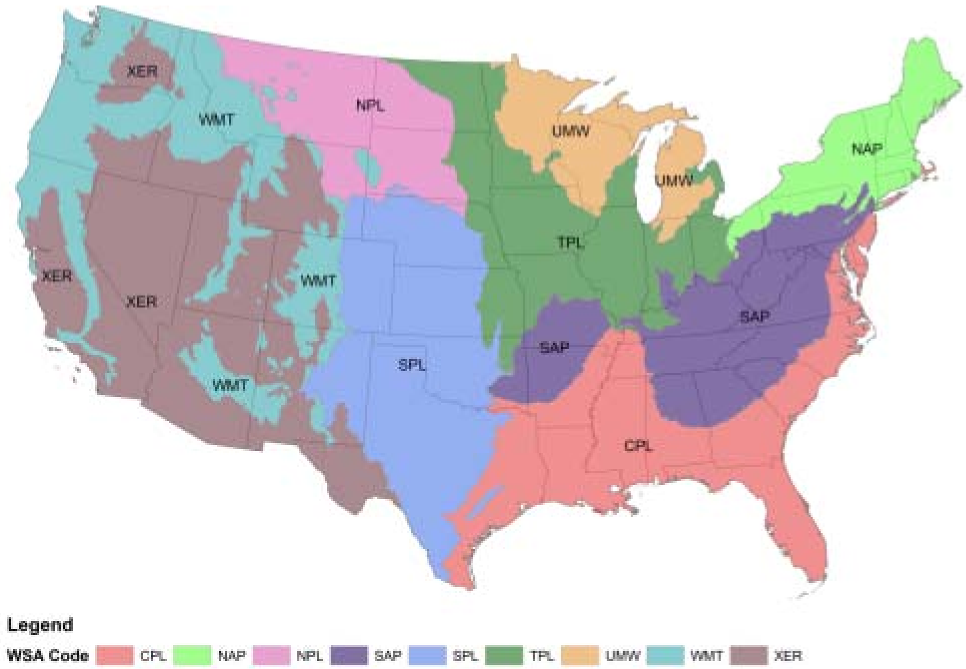

Figure C.3 Wadeable Streams Assessment regions. (Adapted from USEPA 2006.)

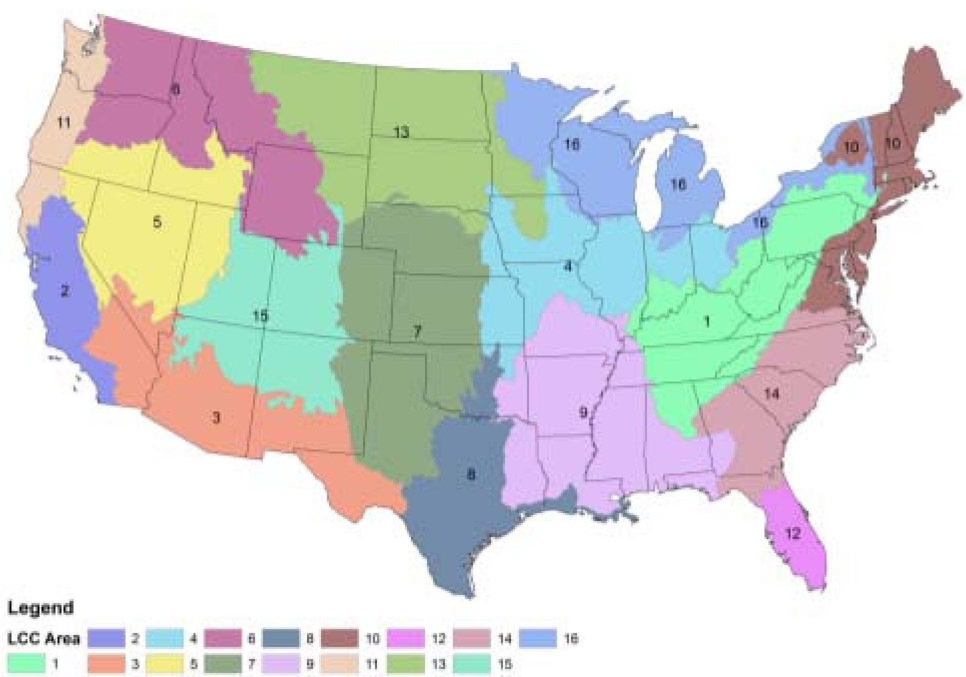

Figure C.4 Landscape Conservation Cooperative areas. (Adapted from USFWS 2010.)

Figure C.5 Hydrologic Unit Codes, region level (HUC2). (Adapted from Seaber et al. 1987.)

APPENDIX D

RFHP DATABASE

Table D.1 A selection of data fields included in a reservoir database created by Kirk Rodgers, University of Arkansas – Little Rock, and W. Reed Green, USGS Arkansas Water Science Center, for the Reservoir Fisheries Habitat Partnership.

Metric	Included in Analysis
Year completed	
Elevation	
Dam length and height, as a surrogate for reservoir size	
Surface area at normal retention level	X
Perimeter	
Shoreline development, the shoreline distance divided by the perimeter of a circle with equivalent area	X
Watershed area	X
Watershed area:surface area ratio	X
Volume	
Development of volume, a measure of the departure of basin shape from that of a cone	
Index of basin permanence, a morphometric index reflecting the littoral effect on basin volume	
Mean depth	X
Maximum depth	
Depth ratio, the ratio of mean depth:maximum depth	
Residence time and flushing rate, the inverse of residence time	
Mean flow rate	
Measures of nitrogen loading and concentration	
Measures of phosphorus loading and concentration	
Total population in the watershed, from 1990 U.S. Bureau of Census	
Percent coverage urban and recreational grasses	X
Percent coverage high-intensity residential land	X
Percent coverage water	X
Percent coverage commercial/ industrial/transportation land	X
Percent coverage wetlands	X
Percent coverage deciduous forested land	X
Percent coverage low-intensity residential land	X
Percent coverage evergreen forested land	X
Percent coverage mixed forested land	X
Percent coverage cultivated land, including row crops, small grains, and fallow land	X
Percent coverage grass and herbaceous lands	X
Percent coverage quarries and barren, transitional lands	X
Percent coverage shrubland	X
Percent coverage orchards, vineyards, other	X
Percent coverage pasture/hay land	X

(Adapted from Rodgers and Green 2011.)