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A classification system for large reservoirs of the contiguous United States

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Abstract Degradation of reservoir fish habitat has become a serious concern. Habitat issues—such as sedimentation, excessive nutrient loadings, and lack of submerged structure—may emerge and worsen over time and are accompanied by undesirable shifts in the fish community and fisheries. To prioritize habitat rehabilitation efforts in reservoirs, we developed a classification system for large reservoirs in the contiguous U.S. We used a four-step classification approach based on over 50 variables descriptive of habitat impairment in a sample of almost 1300 reservoirs. To account for the broad geographic heterogeneity in climate and landscape, reservoirs were assigned to a spatial framework relevant to aquatic resources, selected based on how well it recognized regional differences in fish habitat. To account for differences among reservoirs within geographical regions, we used cluster analysis to identify classes of reservoirs with similar characteristics. Classes were compared regarding habitat impairment, the fish community, the recreational fishery, and other variables from an external dataset to seek support for the classification system. A method for classifying new reservoirs not included in the original sample was also developed. The resulting classification system identified nine geographical regions distributed throughout the contiguous U.S. and 24 reservoir classes within the nine regions. The system can serve as the framework for a reservoir assessment mechanism. Our approach may be applicable elsewhere a broad-scale dataset is not available and needs to be obtained quickly and inexpensively, whether in regards to fish habitat or other environmental information needs.

Keywords Reservoirs · Habitat · Fish · Classification

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Introduction

Large reservoirs provide invaluable services, including municipal and industrial water supply, flood control, hydroelectric power, and navigation. In the U.S., nearly every major river has been impounded somewhere along its reaches, along with many thousands of tributaries. As of 2012, over 83,000 dams or other water control structures had been built in the U.S. (USACE 2009). Reservoirs also provide important recreational benefits. Recreational fishing in freshwater generates US$23.8 billion annually and approximately 84 % of freshwater anglers in the U.S. target reservoirs and lakes, spending 336 million days fishing each year (USFWS 2011). Given the high socioeconomic value of reservoir fisheries, fish habitat degradation has become a serious concern. Habitat issues such as excessive suspended sediments, excessive nutrient loadings, and lack of submerged structure may emerge and worsen over time (Kimmel and Groeger 1986; Wetzel 1990; Miranda 2008), accompanied by undesirable shifts in the fish community (Vanni et al. 2005) and fishery (Agostinho et al. 1999).

Organizing habitat rehabilitation efforts in reservoirs requires recognition of similarities and differences among reservoirs generalized in terms of a classification system. It is difficult to describe the characteristics of a large number of reservoirs unless they are grouped into categories, whose members share characteristics. This reductionism facilitates communication among reservoir managers, researchers, and stakeholders. Classification systems can improve our predictive powers. If, for example, we know that reservoirs in agricultural areas tend to lose shallow habitat at fast rates and experience water quality problems, we can expect that a newly created reservoir or a reservoir for which no data are available will also experience similar difficulties and respond to management strategies developed to treat this general condition. Classifications also improve our ability to explain relationships among reservoirs. For reservoir managers, classification is especially important when they attempt to reconstruct the pathways that produce certain desirable or undesirable conditions. Lastly, by imposing order on diversity among factors that affect habitat impairment in reservoirs, a classification provides the avenue through which limited research funding can be allocated in a rigorously systematic manner.

Various authors have previously classified reservoirs based on fish communities and fisheries and subsequently linked classes to environmental conditions (e.g., Dolman 1990; Godinho et al. 1998; Miranda 1999). Other authors have classified reservoirs based on narrow aspects of fish habitat including water quality (Carlson 1977; Jones et al. 2008), reservoir morphometry (Schupp 1992) and watershed characteristics (Hill 1986; Downing et al. 2005; Bulley et al. 2007). Although not focused directly on fish habitat, these approaches have identified patterns at a landscape level and increased understanding of the diversity of reservoirs but have not produced a national-level classification approach suitable for identifying common patterns and developing strategy for addressing emerging issues in reservoir fish habitat impairment.

In accordance with the need to assess reservoir fish habitat on a national scale, we sought to develop a classification system for large reservoirs in the contiguous U.S. based on a wide-ranging ensemble of habitat impairments. To this end, we surveyed reservoirs nationwide relative to issues that potentially impair fish habitat, including structural habitat, water quality, water regime, and degradation processes, and applied a four-step classification approach to organize reservoirs spatially and relative to the type of habitat impairment that afflicted them. Moreover, we developed a method for classifying new reservoirs not included in the original sample.

Methods

Study scope

Large reservoirs within the contiguous U.S. were defined by the Reservoir Fish Habitat Partnership (RFHP) as any river impoundment equaling or exceeding 100 ha in surface area. Natural lakes with water level control devices were excluded from this definition. Only those reservoirs ≥100 ha in surface area and open to the public were considered. With this 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 water levels in natural lakes. Thus, our sampling frame included over 4300 water bodies ≥100 ha, but not all were reservoirs as defined by the RFHP. We relied on the respondents to help us remove from our analysis natural lakes controlled by a dam.

Data collection

Survey instrument We developed an online fish habitat survey that included 83 habitat and fish-related variables (provided as Supplementary Material). Habitat impairment questions 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. 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. Respondents were instructed to interpret average as the typical conditions expected in reservoirs within their state or region. In addition, respondents identified the first, second, and third most important recreational fish species in the reservoir.

Survey implementation The link for the online survey was distributed to state natural resource agency fish biologists responsible for managing fish in reservoirs. After an introduction outlining the purpose of the survey, as well as the voluntary and confidential nature of responses, respondents were asked to complete the survey for reservoirs under their jurisdiction. Reservoirs with which respondents were unfamiliar, including privately owned and small reservoirs not considered in regular monitoring, were excluded to avoid guessing. The survey was conducted online via the host SurveyMonkey (http://www.surveymonkey.com) beginning in June 2010. Responses were sought for as many reservoirs as possible. Non-respondents were contacted multiple times to encourage participation. The survey was concluded after 3 months when returns had declined to almost zero.

Data analysis

All survey responses were examined for completeness and duplication (i.e., one entry per reservoir). Surveys returned with >30 % item non-response, or duplicated cases were identified and removed from analyses. Remaining missing values were estimated using the Markov chain Monte Carlo method of multiple imputation (MI procedure, SAS Corporation 2011). Missing values are replaced with a set of plausible values from the data distribution; this process allows for valid statistical inferences that reflect uncertainty due to the missing values while also enabling use of the full dataset.

Patterns in habitat impairment We followed a four-step approach to elucidate and describe patterns in habitat impairment (Fig. 1); the methods for each of the four steps are detailed in sections that follow this introductory paragraph. 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

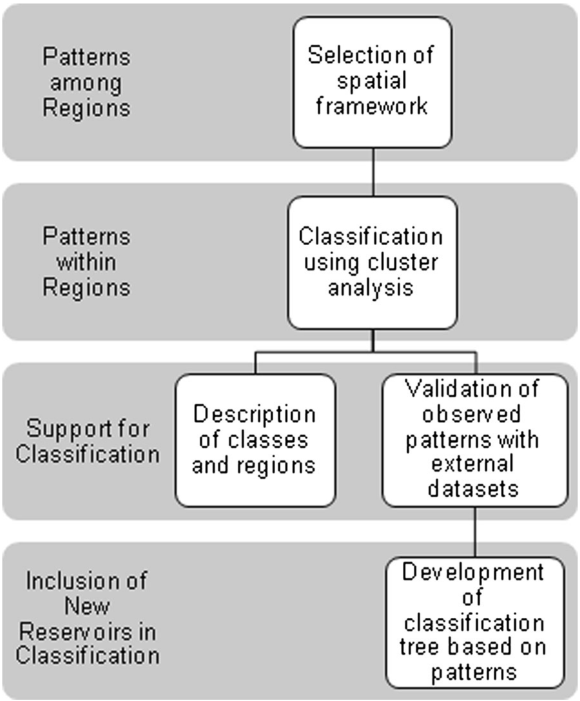

Fig. 1 Outline of analytical approach for establishing a classification system for large reservoirs in the continental U.S. based on fish habitat impairment

the greatest differences in reservoir habitat impairment among geographical regions. Second, habitat impairment patterns within regions were investigated using cluster analysis to identify relevant reservoir classes. Third, classes were compared descriptively and statistically regarding habitat impairments, the fish community, the recreational fishery, and environmental variables from an external dataset (Table S1). Support for the classification system was sought by testing if classes differed relative to factors not included in development of the classification. Last, a method for classifying new reservoirs not included in the original sample was developed.

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 (8 and 18 ecoregions, respectively; Figures S1 and S2; Omernik 1987, 1995), U.S. Environmental Protection Agency's Wadeable Streams Assessment regions (9 WSAs; Figure S3; USEPA 2006), U.S. Department of the Interior's (USDOI) Landscape Conservation Cooperatives (16 LCCs; Figure S4; USFWS 2010), and Hydrologic Unit Code 2 regions (18 HUC2s; Figure S5; Seaber et al. 1987). Boundaries for Level I and II ecoregions were established by Omernik (1987) based on regional landscape patterns including land use and land cover, land surface form, potential natural vegetation, and soil types. Boundaries for WSAs were established by the 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. Boundaries for LCCs were established by the 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 fidelity to Bird Conservation Regions and terrestrial homogeneity, fidelity to aquatic homogeneity, and fidelity to national partnerships. 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).

A between-reservoir similarity matrix was derived based on scores assigned by respondents to the 52 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). The coefficient averages the difference among reservoirs across all variables, each normalized for the range of its values.

For each of the five spatial frameworks, we applied a permutational multivariate analysis of variance (MANOVA) to the similarity matrix to test if habitat impairment differed among regions (α= 0.10; PRIMER with PERMANOVA+, PRIMER-E 2008). If differences were identified in the main test, pairwise comparisons established where the differences occurred. We selected the most parsimonious framework that identified significant differences among regions and minimized pairwise regional similarities, yet was functional in terms of the level of geographical partitioning. In the event of a tie in the proportion of pairwise regional similarities, the simpler framework was selected.

Additionally, habitat variables collected with the survey were summarized descriptively at the regional level. For each region, the proportion of reservoirs characterized by moderate-to-high or high 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 community and fishery variables, a Wilcoxon signed rank test was used; for a few variables that were not distributed symmetrically, a sign test was used.

Patterns within regions Within each region of the chosen spatial framework, we applied a non-hierarchical cluster analysis to the between-reservoir similarity matrices to identify within-region groups of reservoirs with similar habitat impairment characteristics (Ward's algorithm, CLUSTER procedure, SAS Corporation 2011). 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, SAS Corporation 2011). Clusters that reflected similar habitat impairments within a region, but were separated by the procedure due to differences in impairment intensity, were combined to uphold parsimony. Clusters within a region were designated as unique reservoir classes.

Habitat, fish community, and recreational fishery variables were summarized at the reservoir class level using the same methods applied to the region level (see *Patterns among regions* section). In addition, the recreational fishery was characterized by its most popular species as:

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

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
n_{rj} = number of reservoirs with rank r for focal species j

In this study, r ranges from 1 to 3 because survey respondents identified only the first, second, and third most important recreational species in each reservoir. The index range differs based on the ranges of input variables and yields a relative value meaningful to the n_{ri} locations and k species considered.

Support for the classification system We expected that reservoir classes would also differ on (1) major environmental characteristics that might affect habitat (Table S1) and (2) fish community and fishery characteristics affected by habitat. Therefore, we assessed differences among classes using environmental variables compiled by (Rodgers and Green 2011), including reservoir morphology and watershed characteristics, and fish community and recreational fishery variables collected during the survey. Within each region, we applied a permutational MANOVA to test if reservoir classes differed based on environmental and fish-related variables (α=0.10).

Development of the classification tree for inclusion of new reservoirs After establishing a working classification system, we developed a classification tree for classifying new reservoirs not already classified by the cluster analysis (rpart function, R Foundation for Statistical Computing). Within each region, a classification tree was grown and pruned using the 52 habitat impairment variables from the survey as input variables and the reservoir class from cluster analysis as the response variable. Splits were required to decrease the overall lack of fit by a cost complexity factor of 0.01; otherwise, the nodes were pruned. Error rate was assessed by leaving one third of the dataset out of tree development, then applying the tree logic to classify the excluded observations; accuracy was determined by comparing tree classifications to reservoir classes as determined by cluster analysis. Tree accuracy is not necessarily dependent on how many classes are in the region, but rather on the effectiveness of available variables in differentiating among classes. Regional trees were then combined, and an overall error rate was calculated as a weighted average. New reservoirs can be classified by completing a fish habitat survey for the location and applying the habitat impairment responses to the classification tree.

Results

We received 1599 total responses. Of those, 1299 matched our study scope (i.e., surface area ≥100 ha and not a natural lake fitted with a water control structure) and were complete enough for analysis. A total of 1010 responses had no missing data (78 %); an additional 274 responses were missing no more than five habitat impairment variables (21 %). Considering the NID identifies 4300 regulated water bodies ≥100 ha; we observed a 30 % response rate as a conservative estimate. Reservoirs were distributed throughout the contiguous U.S. and ranged in surface area from 100 to 156,000 ha (with an average of 3001±338 ha [mean± standard error]), in mean depth from 0.3 to 181.2 m (average 22.9±0.7 m), and in age from 10 to 178 years (average 61.5±0.8 years).

Patterns among regions All spatial frameworks considered had a significant MANOVA, suggesting they had regions that differed significantly from each other (all main test P values≤0.01). Subsequent pairwise comparisons among regions indicated all WSA regions (36 paired comparisons) differed from each other (all P values≤0.07). For LCC, HUC2, Level I ecoregion, and Level II ecoregion, 9 of 120, 9 of 153, 2 of 28, and 15 of 153 pairs did not differ, respectively. Further analyses were based on the WSA spatial framework because it was the only framework within which all pairs of regions differed significantly. Conceivably, some resolution might have been given up in some parts of the contiguous U.S. by not choosing one of the other spatial frameworks, but the WSA framework balanced our goal for a functional and parsimonious partitioning.

Patterns within regions We identified 25 clusters within the nine WSA regions (Fig. 2). Within individual regions, the number of clusters ranged from one to four. Two clusters in the Southern Appalachian (SAP) region were combined because they displayed similar habitat impairments differing only on degrees of intensity, reducing the reservoir classes to 24. Five observations in

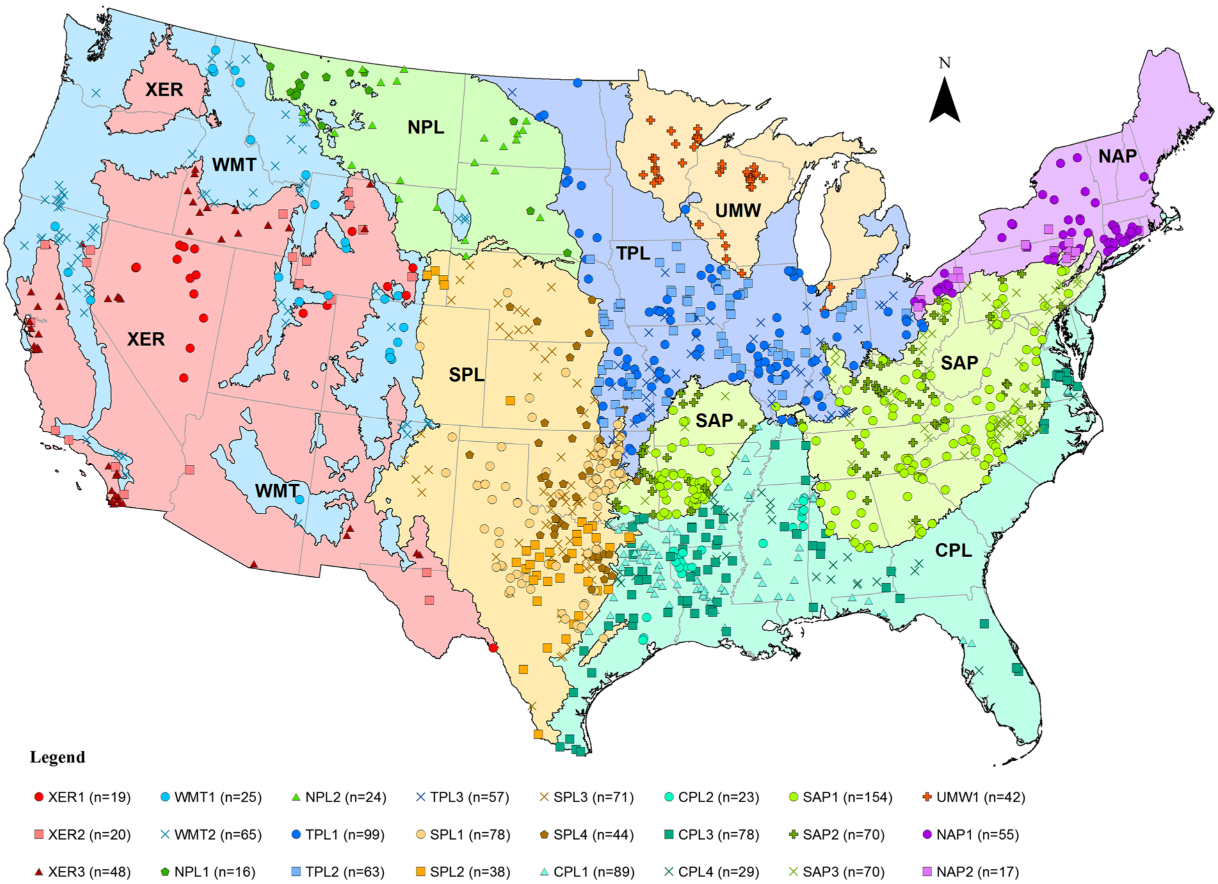

Fig. 2 Wadeable Streams Assessment (WSA) regions of the contiguous U.S. identifying position of reservoirs (*points*) included in this study. Regions include Xeric (XER), Western Mountains (WMT), Northern Plains (NPL), Temperate Plains (TPL), Southern Plains (SPL), Upper Midwest (UMW), Coastal Plains (CPL), Southern Appalachian (SAP), and Northern Appalachian (NAP). Twenty-four reservoir classes were identified within the WSA regions

the Southern Plains (SPL) region were removed because their responses were highly unusual and geographically close, indicating response bias, thus yielding 1294 classifiable reservoirs.

Each reservoir class had a unique set of habitat impairment issues; habitat impairments are summarized by class and region in Table 1. Overall and pairwise permutational MANOVAs showed that all classes differed regarding fish habitat impairments (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.

Classes also varied in terms of fish community and recreational fishery characteristics (Table 2). 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 non-native fish invasions than others (e.g., CPL1 and CPL2 versus CPL4; NPL1

Table 1 Habitat impairment characteristics by reservoir regions and classes listed in Fig. 2

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
Excessively shallow	○	●	◍	◍	◍	◍	◍	◍		◍	◍	○	◍	◍	●	◍	◍	○	◍		◍	◍		◍
Excessive mudflats	○	●	◍	◍	○	◍	○	◍		◍	◍		◍	◍	●	◍	◍	○	○		◍	◍		◍
Lack adjoining backwaters and wetlands	○	◍	○	◍	○			◍	○	◍	○	○	○	○		◍	◍	◍	○	○	◍		◍	◍
Lack conn backwaters and wetlands	○	●	○	◍	○			○	○	○	○		○	○		○	◍	◍	○	○	○		◍	◍
Lack connectivity to tribs due to sed.	○	●	○	◍				◍	○	◍	○	○	○	○		○	◍							◍
Excessive macrophytes	◍	●	◍	◍	○	◍		○	○	○	◍	○	○	○	●	○	○	○	◍		○	○	○	◍
Insufficient macrophytes	○	○	◍	◍	◍	◍	◍	◍	◍	◍	◍	◍	◍	●		◍	●	◍	○	◍	○			◍
Invasive plants	◍	●	◍	◍				○	○	○	◍	○		○	◍	○	○	◍	○	○	○			
Invasive animal	○		○	◍	○	◍	○	◍	○	◍	○	○		◍		◍	●	◍	◍	○	◍	◍	○	◍
Lack structural habitat	○	◍	◍	◍	◍	◍	○	◍	◍	◍	◍	◍	◍	◍	●	◍	◍	◍	○		◍	◍	◍	◍
Excessively shallow littoral zone	○	●	◍	◍	○	◍		◍		○	◍	○	◍	◍	●	◍	◍		○		◍	◍	○	◍
Deep or steep littoral	○		○	○	◍	◍	◍		◍	○	○	○	○	○		○	○	◍		◍	◍		◍	○
Lack bank shading	○		○	◍		○	◍	◍	○	○	○	◍	○	◍	◍	◍	◍	◍			◍	◍	◍	◍
Lack allochthonous inputs			◍	◍	○	○	○		○	○	○	◍	○	○	●		○	○		○	○		◍	◍
Disturbance of riparia	○	◍	◍	◍	○	◍	○	◍	○	◍	○	○		◍		◍	●	◍	◍		○			◍
Harmful levels agriculture		○	○	◍		◍	○	◍		◍	◍	○		◍	●	●	●	○	◍		○			◍
Harmful levels livestock				○		○	◍	◍		◍	◍	○	○	○	●	◍	◍	○	◍		○		◍	◍
Harmful levels forestry	○	◍	◍	◍						○	○										○			
Harmful levels mining	○	○	○	○	○			○	○	◍	○					○	○		○		○			◍
Harmful levels of urbanization		◍	◍	◍	○	○		○	○	◍	◍	○	○	○		◍	◍	◍	◍		○		○	◍
Excessive nutrients		◍	◍	◍	○	◍		◍	○	◍	◍	◍		◍	●	●	●	◍	◍		◍			◍
Insufficient nutrients	○	○	◍	○	◍	◍	○		◍	○	○	◍	◍	○			○	○		◍	○		◍	○
Excessive SS or inorganic turbidity	○	◍	◍	◍	○	◍		○	○	◍	◍	○	○	◍	●	◍	●		◍		◍	○	○	◍
Excessive organic turbidity	○	◍	◍	◍		◍		◍		○	○	○		○	●	◍	◍	○	◍		◍	◍		◍
Extreme seasonal variation in turbidity	○	◍	○	◍	○	○		◍	○	◍	○	○		○	◍	◍	●	○	◍		◍	○		◍
Harmful algae blooms		◍			○			◍		○	◍	○	○	○		◍	◍	○	◍	○	◍		◍	◍
Extreme diel variation in DO	○	◍	○	○				○		○	○					○	○	○	○		◍			○
Oxygen stratification	○	◍	◍	◍	○	◍		○	○	◍	◍	○	○	○		○	○	○	○	○	◍	○	○	○
Excessively high temperatures	○	◍	○	◍				◍	○	◍	◍		○	○		○	○	◍	○	○	◍	○		○
Excessively low temperatures	○		○				○		○										○	○	○			○
Temperature stratification			○	◍	◍	◍		○	◍	◍	◍	○	○	○		○	○	◍	○	○	○	○		◍
Untimely or frequent turnovers		◍	○					○						○		○	○	○		◍	○			○
Thermal pollution	○	○	○	○				○	○	○	○	○	○	○		○	○	◍	○		○			○
Contaminants	○	◍	◍	◍	○		○		○	◍	○	○	○	○		○	◍	○	○		◍	○		◍
Point-source pollution	○	○		○	○		○			◍	○	○		○		○	◍	○	○		○			◍
Non-point source pollution	○	◍	○	◍	○	◍	◍	◍	○	◍	◍	○	○	◍		●	●	○	◍		◍		○	◍
Unfavorable hydrograph			○	◍	○	○	◍	◍	○	◍	○		○	○	●	○	●	○	◍	◍	◍	○	○	◍
Effects upstream impoundments	○	○	○	◍	○	○	◍	○	○	◍		○	○	○	●	○	◍	○	○	○	○			◍
Insufficient retention time		○	○	◍			◍	○	○	◍	○		○	○	●	○	●	○	○	◍	○	○	○	◍

Table 1 (continued)

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
Insufficient water storage		◐	○	◐	○	○	◐	◐	○	◐	○		◐	○	●	○	◐	○	○		◐	◐	◐	◐
Mistimed water level fluctuations	○		○	◐	◐	○	●		○	◐			○	◐	●	◐	●	○	○	◐	◐		○	◐
Excessive yearly drawdown	○		○	◐	◐		●	◐	○	◐	○		○	◐	●	○	◐	○	○	◐	◐	◐		●
Excessive long-term drawdowns	○		○	◐	◐	○	●	◐	○	○		○	◐	◐	●	○	○	○	○	○	◐	◐	◐	●
Excessive short-term fluctuations		◐	○	◐	○		◐	○	○	◐				○	●	○	◐	○	○	◐	◐			◐
Rapid water level change	○	◐	○	◐	○		◐	○	○	◐	○		○	○	●	○	◐	○	○	◐	◐			◐
Sedimentation	○	●	◐	●		◐	◐	◐	○	◐	◐	○	◐	◐	●	●	●	○	◐	○	◐	○		◐
Shoreline erosion		●	◐	●	○	◐	◐	◐	○	◐	○	○		◐	◐	◐	●	○	◐		○		○	◐
Loss of cove habitat due to sed	○	●	◐	◐		◐	◐	◐	○	◐	◐	○	○	◐		◐	●	○	◐		○	○		◐
Shoreline homogenization	○	●	◐	◐	◐	◐	○	◐	○	◐	○	○	○	◐	●	◐	●	◐	◐		◐		◐	◐
Homogenization of littoral substrates		●	◐	◐	○	◐	○	○	○	◐	○	○	○	◐	●	◐	◐	○	◐		◐		◐	◐
Disturbances in upstream watersheds		◐	○	◐	○	○	○	◐	○	◐	◐	○	○	○		◐	●	○	◐		◐		○	◐
Disturbances in adjacent watersheds		◐	○	◐	○		○	◐	○	◐	◐	○	○	◐		◐	◐		◐		○		○	◐

Symbols indicate the percentage of reservoirs within the region that were scored at moderate-to-high or high impairment. Blank≤1 %, ○=1–10 %, ◐=10–50 %, ●≥50 %. The variables correspond to those listed in the survey instrument provided as Supplementary Material

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, fish size, and angler satisfaction. Classes with fishing pressure less than the national average did not have any uniformly distinguishing fishery characteristics.

Each reservoir class had a unique recreational fishery comprising different sets of species with varying levels of popularity (Table 3). Largemouth bass *Micropterus salmoides* was typically the most popular species in classes of the eastern and midwestern U.S., whereas rainbow trout *Oncorhynchus mykiss* was typically most popular in classes of the western U.S. Channel catfish *Ictalurus punctatus* was the most popular species in SPL4 and TPL2, and walleye *Sander vitreus* was most popular in NPL2, SPL3, and UMW1. Black crappie *Pomoxis nigromaculatus* was the most popular species in NAP2. Although less popular overall, additional species were more useful in differentiating among the fisheries of reservoir classes. Blue catfish *Ictalurus furcatus*, hybrid striped bass *Morone saxatilis*×*Morone chrysops*, and spotted bass *Micropterus punctulatus* were more popular in the southern U.S., whereas yellow perch *Perca flavescens* and northern pike *Esox lucius* were more popular in the northern U.S. Within WSA regions, where environmental conditions were more likely to be similar, reservoir classes were distinct, with no classes sharing the same ranking of fish species in their recreational fisheries.

Support for the classification system A total of 876 reservoirs in the RFHP database (Rodgers and Green 2011) were matched to reservoirs from the survey. Of these, 643 were available to test whether classes of reservoirs differed relative to morphology and 556 relative to watershed composition. Several depth-based indices were also available from Rodgers and Green (2011) but would have required a reduction in sample size of over 100 reservoirs; the indices were excluded because mean depth was already included in the analysis (see Supplementary Material for list of variables derived from Rodgers and Green [2011]). Similarly, 1274 surveys were complete enough to test whether classes differed relative to fish community characteristics and 1217 relative to fisheries characteristics. All reservoir classes were unique in terms of at least one of these four variable groups, and in most regions, classes differed in three of the four groups (Table 4). In the TPL and SAP regions, classes differed for all four groups, whereas in the WMT region, classes differed in only one group.

Table 2 Fish community and fishery characteristics by reservoir regions and classes listed in Fig. 2

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
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*	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Fishing pressure					▼	▲			△			▼		▽	▽							▽		
Catch rates		▼				▽						▼		▽				▲	▲		△			▼
Size of fish caught	▲					▲			▲		▲							▲			▲			
Annual variability in catch rates	▼	▽			▼		▲				▼	▼												
Angler satisfaction	▲	▼				▲			▲								▽	▲			▲			
Frequency of tournaments*	▲		▲	▲		▲			▲	▲	▲					▲	▲	▲						
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; ▼/▽ =median score is below national average. Closed triangles identify $P \leq 0.05$; open triangles indicate $0.05 \leq P < 0.10$; blanks indicate no statistical significance $P > 0.10$. The variables correspond to those listed in the survey instrument provided as Supplementary Material

Development of the classification tree for classification of new reservoirs The classification tree yielded overall accuracy of 75 % (Fig. 3). The greatest regional accuracy was in the Northern Plains (NPL) region (92 %), and the least regional accuracy was in the SPL region (58 %). Other regions varied between 75 and 90 %.

Discussion

We propose a new classification system for U.S. reservoirs based on methodology applicable elsewhere. The system is based on fish habitat impairment and includes nine geographic regions and 24 classes. Each region reflects a separate geographical section in the U.S., and each class within a section is defined by a unique ensemble of habitat impairments. The system is hierarchical in that the classes are organized within regions. This classification provides a large-scale understanding of the factors afflicting reservoir habitat in the U.S. and may help guide research, management, and allocation of resources. Potentially, the broader vision obtained through a large-scale spatial classification can generate hypotheses and management strategies to be tested at smaller scales or single reservoirs.

Although 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

Table 3 Five most important fish species in the recreational fishery of each reservoir class listed in Fig. 2, ranked by relative popularity

Species	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
Centrarchidae																								
Lepomis macrochirus	4	3	5		5	4					4					4			3				4	
Micropterus dolomieu					2			5											4		3			5
M. punctulatus		5		4					5															
M. salmoides	1	1	1	1	1	2			1	1	1	1	1	3	4	1	3	1	5	5	2	2	2	1
Pomoxis annularis	3	2	2	2						3	5	4	2	5	2	2	2	3				5		
P. nigromaculatus	2		3	5		1			2		2					5		4	2		5			4
Esocidae																								
Esox lucius							3	4																
Ictaluridae																								
Ictalurus furcatus		4								4		5												
I. punctatus	5		4	3					4	2	3	2	3	2	1	3	1	2					5	3
Moronidae																								
Morone chrysops													5	4	5		5							
Morone hybrids													4											
Percidae																								
Perca flavescens						5	4	3														4		
Sander vitreus					3	3	2	1	3	5		3		1	3		4	5	1			3		
Salmonidae																								
Oncorhynchus clarkii							5													3	4		3	
O. mykiss							1	2												1	1	1	1	2
Salmo trutta					4																			
Salvelinus fontinalis																				4				
S. namaycush																				2				

of enhancing large-scale conservation planning. It is applicable to large reservoirs ≥100 ha in the contiguous U.S., although a similar approach could apply to systems of any size in any location around the globe. 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, as well as pointing to in-lake sediment removal strategies. 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 or other bottom structures.

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 observed but not typically quantified during onsite surveys, providing new perspective on reservoir fish habitat. This approach may be applicable elsewhere a broad-scale dataset is not available and needs to be obtained quickly and inexpensively, whether in regards to fish habitat or other environmental information needs. However, our approach does have some problems. First, variables were measured on a Likert-type ordinal scale, thereby limiting direct comparison of our results to studies in which interval- or ratio-scale variables are used. Second, missing data are a common problem when analyzing responses to questionnaires as respondents may skip

Table 4 Results of permutational MANOVA main tests for differences among reservoir classes listed in Fig. 2

Region	Classes	df	Reservoir morphology	Watershed characteristics	Fish community	Recreational fishery
CPL	4	3	2.5637	1.8161	8.1072	1.9811
			(0.036)	(0.123)	(0.001)	(0.003)
NAP	2	1	4.1797	0.0547	2.7671	4.7808
			(0.022)	(0.985)	(0.045)	(0.001)
NPL	2	1	3.9418	0.1113	3.6484	1.6733
			(0.052)	(0.903)	(0.006)	(0.104)
SAP	3	2	6.9219	4.3467	3.4445	3.7658
			(0.002)	(0.01)	(0.007)	(0.001)
SPL	4	3	1.1287	2.0189	6.4686	6.443
			(0.32)	(0.086)	(0.001)	(0.001)
TPL	3	2	2.5505	3.2146	6.9422	3.831
			(0.049)	(0.013)	(0.001)	(0.001)
UMW	1					
WMT	2	1	1.2754	0.9031	2.4597	1.5589
			(0.271)	(0.35)	(0.044)	(0.102)
XER	3	2	3.825	2.7458	1.9981	1.1281
			(0.012)	(0.076)	(0.050)	(0.314)

Tests were conducted for selected environmental variables (Table S1), the fish community, and the recreational fishery. Pseudo-F and associated *P* values (in parentheses) are shown for each set of variables. Blanks indicate comparisons not applicable because of a single class in the region

questions for which they have no knowledge or are unsure. Multivariate analyses like the ones we applied require complete data sets, so we had to impute missing values with a statistical procedure. Reportedly, multiple imputation can be safely used to estimate Likert-type data if the overall percentage of missing data is less than or equal to 10 %, whether values are missing at random or not (Leite and Beretvas 2010). Third, our survey depended on the perception of professionals, but perceptions may vary geographically depending on exposure. The extent of this effect depends on the extent of the geographic area; to promote equivalence of responses among participants in our study, each question was coupled with an expanded narrative to help focus the respondent. Moreover, respondents were instructed to exclude little-known reservoirs not part of frequent monitoring.

Support for the classification system using tangential reservoir characteristics such as reservoir morphology, watershed characteristics, and fish assemblage descriptors upheld our conclusion that the proposed classes truly differed from each other. The variables examined to seek support for our classification have often been applied to classify reservoirs (e.g., Dolman 1990; Godinho et al. 1998; Miranda 1999; Bulley et al. 2007), predict reservoir characteristics (Jenkins 1970; Ground and Groeger 1994; Verstraeten et al. 2003; Jones et al. 2004), or explain reservoir phenomena (Townsend et al. 1996; Shoup et al. 2007). This agreement among data sets suggests that habitat impairment is linked to key physical and chemical characteristics of the reservoir basin and its watershed, and that this impairment is in turn reflected on the fish assemblages and fisheries. For example, reservoirs in the Northern Appalachian (NAP) region were classified into one class characterized by water regime issues (NAP1) and a second class characterized by nutrients, turbidity, excessive plant growth, and other eutrophication issues (NAP2). Within each class are reservoirs spanning a potentially wide range in degree of impairment, and in fact, NAP2 reservoirs may support better recreational fisheries overall. NAP2 scored above average in fishing pressure, angler satisfaction, catch rates, size of fish caught, and other fishery metrics. NAP1 and NAP2 differed in terms of reservoir morphology, fish community, and recreational fishery characteristics, but not in watershed characteristics.

Clearly, in cases where habitat impairment can be measured relatively accurately and precisely, it is best to measure impairment directly rather than through proxy variables or professional judgment. We suggest that when applying our classification to make important decisions about funding habitat conservation or restoration in specific reservoirs, an effort is made to gather relevant empirical data about habitat and fish to confirm the classification made by our procedure. Validation of our

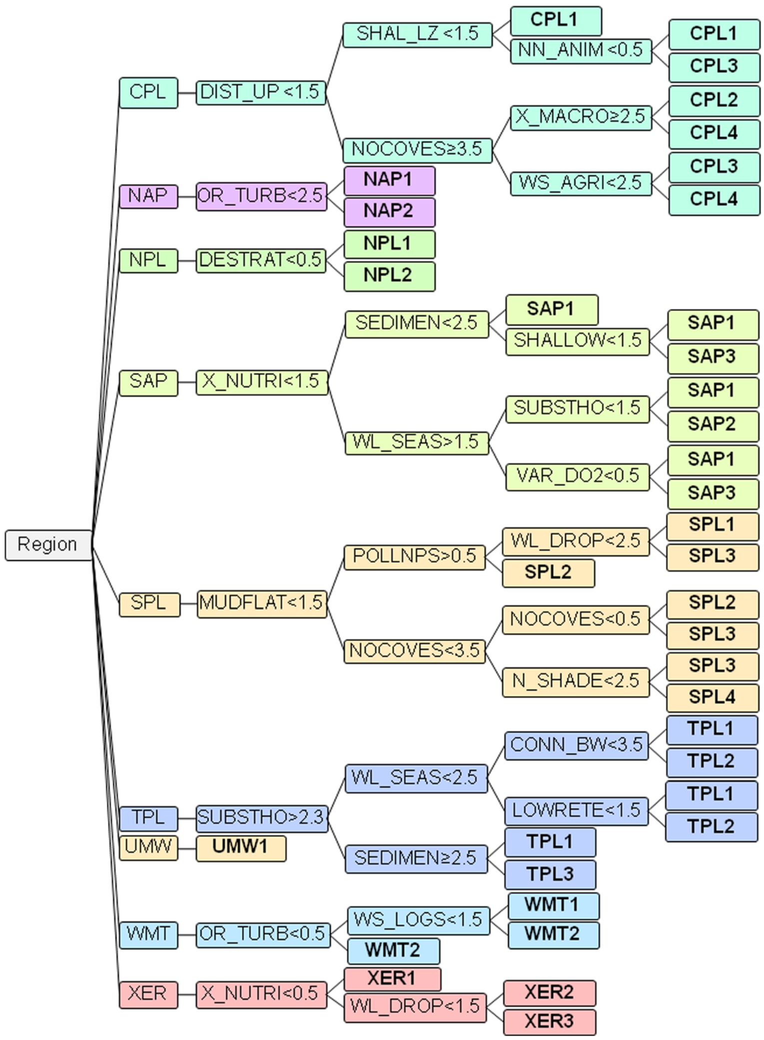

Fig. 3 Classification tree for large reservoirs in the contiguous U.S. based on fish habitat impairment. For WSA region names, refer to Fig. 2. All terminal nodes in bold text represent reservoir classes. The classification tree is read from left to right. If a statement is true, move right to the next 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" is less than 1.5, move right and up to the "SHAL_LZ" node. If the score for "DIST_UP" is not less than 1.5, move right and down to the "NOCOVES" node. Variable definitions: *DIST_UP* disturbances in upstream watersheds, *SHAL_LZ* excessively shallow littoral zone, *NN_ANIM* invasive animal, *NOCOVES* loss of cove habitat due to sedimentation, *X_MACRO* excessive macrophytes, *WS_AGRI* harmful levels of agriculture, *OR_TURB* excessive organic turbidity, *DESTRAT* untimely or frequent turnovers, *X_NUTRI* excessive nutrients, *SEDIMEN* sedimentation, *WL_SEAS* mistimed water level fluctuations, *SHALLOW* excessively shallow, *SUBSTHO* substrate homogenization, *VAR_DO2* extreme diel variation in dissolved oxygen, *MUDFLAT* excessive mudflats, *POLLNPS* nonpoint source pollution, *WL_DROP* excessive yearly dropdown, *N_SHADE* lack of bank shading, *CONN_BW* lack of connectivity to backwaters and wetlands, *LOWRETE* insufficient retention time, *WS_LOGS* harmful levels of forestry

classification with empirical data is not possible at this time because the data necessary are either not available for many reservoirs, or the measurements are poor quality due to inadequate methodology or instrumentation, and often not sufficiently better than professional judgment. We anticipate that improvements in technology and methodology along with the growing need to manage reservoir habitats may produce the empirical data necessary to validate our classification. One promising effort is the U.S. Environmental Protection Agency's National Lakes Assessment, which collected structural habitat data for 275 large impoundments ≥100 ha during 2007 (Kaufmann et al. 2014). Although we described aspects of fish habitat in addition to structure in this paper (i.e., water regime, water quality), the National Lakes Assessment dataset could provide essential quantitative field data to validate our system. Furthermore, the connection between habitat information and fish community health is essential to ensure that real ecological and social benefits are derived from rehabilitation efforts.

The classification system also opens the door to development of an assessment system. A classification system provides the framework within which an assessment mechanism can function. An assessment system similar to that developed by Miranda and Hunt (2011) would quantify and rank variations in habitat impairment levels within and among classes. For instance, a reservoir in one class may be subject to a different suite of impairments than a reservoir in a different class; these two reservoirs may receive similar assessment scores but require different management techniques to address their respective impairments. Additionally, issues in the recreational fishery may be related to specific habitat impairments, and solutions addressing the underlying issues may be quantitatively justified. The ability to conduct assessments at the national level enhances prioritization of rehabilitation and protection efforts and facilitates more efficient use of limited resources. The reservoir habitat classification system presented here can serve as the framework for a reservoir assessment mechanism.

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