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Extending the Scale of Reservoir Management

Leandro E. Miranda*
U.S. Geological Survey, Mississippi Cooperative Fish and Wildlife Research Unit
Post Office Box 9691, Mississippi State, Mississippi 39762, USA

Abstract.—Reservoir fishery managers have traditionally viewed reservoirs as stand-alone systems and emphasized in-lake management practices such as controlling selected fish populations, restraining and promoting harvest, and enhancing fish habitat. However, reservoirs do not always respond to in-lake approaches that ignore important factors operating outside the reservoir. I propose an expanded concept where reservoirs are viewed as parts of the landscape and influenced by tributaries, riparian zones, watersheds, and position in the river basin. The influence of tributaries over reservoir fish assemblages ranges from almost none in reservoirs positioned high in a basin where lacustrine fish assemblages prevail to a large effect in downstream reservoirs where riverine fish assemblages prevail. Many species inhabiting reservoirs typically require tributaries to complete their life cycle, or at least their abundance in the reservoir is enhanced by access to flowing water and upriver floodplain lakes. Riparian and buffer zones surrounding tributaries and the reservoir trap sediments and nutrients, reduce wind and associated wave action, provide bank stability and woody debris, and improve esthetics. Direct links between riparian zones and reservoir fish assemblages have received limited research attention, but evidence indicates that riparian plant debris enhances fish species richness, predator–prey interactions, and recruitment of selected species in the littoral zone. Imports from watersheds, including sediments, nutrients, and carbon from dissolved or particulate organic matter, interact to influence turbidity, water quality, primary production, and habitat quality. Fish assemblages are shaped by eutrophication, and organic detritus imported from highly disturbed watersheds may play a major role in promoting key detritivores. At the basin scale, abiotic characteristics, species richness, species and trophic composition, biomass, and population characteristics show longitudinal gradients along reservoir series. Basin-scale variables constrain the expression of processes at smaller scales but are seldom controllable, although an appreciation of basin patterns helps set limits for smaller-scale determinants and thereby management expectations. Extending the scale of reservoir management can enhance the manager's ability to impact reservoir fish populations and assemblages and increase the effectiveness of traditional in-lake management measures. Nevertheless, reaching outside the reservoir through potentially segregated efforts of isolated managers may not be sustainable, especially if reservoir managers lack jurisdiction and training to reach beyond the reservoir shores. Thus, managers must participate in landscape-level partnerships to advocate landscape changes likely to benefit reservoir environments. Extending the scale of reservoir management does not mean that reservoir managers must become watershed managers, but simply that they should think about reservoirs as part of bigger systems and thereby network with those working upstream and in the watershed to advance reservoir issues.

* Corresponding author: smiranda@usgs.gov

Introduction

Reservoir managers have traditionally considered reservoirs as stand-alone systems, separate from their tributaries, surrounding watersheds, and river basin. With this concept, traditional management approaches have focused on in-lake practices such as controlling selected fish populations, restraining and promoting fish harvest, and enhancing habitat conditions (Hall and Van Den Avyle 1986). For more than half a century, these management approaches have served reservoir fisheries well. Nevertheless, by focusing exclusively on the reservoir scale, reservoir workers have foregone the potential benefits of managing at multiple landscape scales. A broader scale has the advantage of lesser temporal variability and ability to integrate many abiotic, biotic, and socioeconomic characteristics active across the landscape (Bohn and Kershner 2002).

The emergence of reservoir management in the early 20th century was guided by concepts developed in natural lakes (Miranda 1996). However, we now recognize that the properties of reservoirs are different (Wetzel 1990) and that reservoirs are usually not independent aquatic systems in as much as they are connected to the river upstream and downstream, to other reservoirs in the basin, and to the surrounding landscape. Reservoir systems exhibit longitudinal patterns both within and among reservoirs (Kimmel et al. 1990; Miranda et al., in press). They are typically arranged sequentially as elements of an interacting network and filter water collected throughout their watersheds. Because of this interaction with the river, with other reservoirs in the basin, and with the watershed, effectiveness of reservoir management may be greatly enhanced if the scale of management is extended.

Traditional approaches to fishery management, such as stocking, harvest regulation, and in-lake habitat management, do not always produce the desired effects in reservoirs. Some reservoirs may not respond to traditional fishery management approaches that ignore important elements of the entire water system. As a result, managers may spend a great deal of resources with little benefit to either fish or fishing. Some locally expressed effects, such as turbidity and water quality, zooplankton density and size composition, and species growth rates and fish assemblage makeup are the upshot of broadscale factors operating outside the reservoir, which may not be under the direct control of reservoir managers. In reality, the fish assemblages of reservoirs are shaped by conditions inside and outside the reservoir, and the importance of internal and external factors differs among reservoirs.

With this perspective, I consider the relevance of the tributaries, the riparian zone, the watershed, and the whole basin to reservoir management. I view reservoirs within the framework of a conceptual model where reservoir characteristics are influenced by broadscale aspects outside the reservoir (Figure 1) and consider how elements of this conceptual model influence the fish assemblages in the reservoir. I suggest that comprehensive approaches and inclusion of unconventional partners may be necessary to advance reservoir science and management. Extending the scale of reservoir management beyond the reservoir can be challenging for biologists trained, and agencies structured, on traditional fishery management paradigms; thus, I also consider how management efforts beyond the reservoir might be organized.

The Tributaries

Tributary streams can play a major role in reservoir dynamics. Streams are elements of all reservoirs and include the main-stem river impounded by the reservoir and tributaries normally associated with reservoir bays. The discharge, width, and length of tributaries

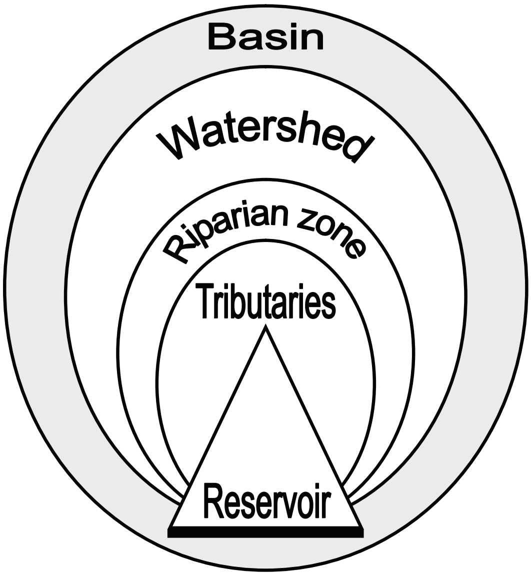

Figure 1. A continuum of interdependent scales ranging from the reservoir to the basin. A hierarchy is proposed where the larger spatial scales affect the smaller scales. For example, locally expressed effects such as turbidity, water quality, primary production, and fish community composition are the upshot of broadscale factors operating at various levels outside the reservoir, which cannot be controlled by operating solely at the reservoir scale. Fish management in reservoirs has traditionally focused on the reservoir scale, but might be more successful if it balanced all scales.

vary greatly and range from small creeks to major rivers. Thus, the influence of tributaries over reservoir fish assemblages varies, ranging from little or no effect on reservoirs positioned high in a basin where lacustrine fish assemblages are common to a large effect on reservoirs low in the basin where assemblages are more likely to support more of the original river fauna.

Links to Reservoir Fish

Reservoir fishes are commonly of riverine origin (Fernando and Holčík 1982) and frequently require conditions provided by tributaries to complete their life cycle, or at least their abundance in the reservoir is enhanced by access to riverine habitats in tributaries. Longnose gar *Lepisosteus osseus* migrated from a reservoir in Missouri to spawn in a tributary creek where they stayed 15–94 d and traveled as far as 10 km upstream to occupy pools next to riffles (Johnson and Noltie 1996). Similarly, white bass *Morone chrysops* entered Missouri tributaries during spring spawning migrations where they spawned over gravel or rock bottoms, but congregated in adjacent pools (Colvin 1993). Year-class strength of white bass fluctuated greatly in Virginia reservoirs, presumably due to annual variations in flow that controlled accessibility to high-quality substrates further upstream (DiCenzo and Duval 2002). Paddlefish *Polyodon spathula* often inhabit reservoirs but migrate to spawn over gravel bars in tributaries, and juveniles develop in backwaters and oxbow lakes (Hoxmeier and DeVries 1997; Paukert and Fisher 2001). Walleyes *Sander vitreus* frequently move upstream to spawn in riffles. In the Au Sable River, Michigan, walleyes overwintered in the reservoir but migrated upstream to spawn and some remained upriver for several months in low-velocity refuges (DePhilip et al. 2005). In Wyoming reservoirs, walleyes made spawning migrations upriver and were occasionally caught 70–80 km upstream from the reservoir in "salmonid water" (Hubert and O'Shea 1992). Likewise, many catostomids migrate into tributaries for spawning (Nelson 1980). Hladík and Kubečka (2003) classified the fish assemblage of Římov Reservoir, Czech Republic into obligatory tributary spawners (e.g., asp *Aspius aspius*, bleak *Alburnus alburnus*, chub *Leuciscus cephalus*, and white bream *Blicca bjoerkna*), generalists that spawned both in the tributary and the reservoir (e.g., bream [also known as zope] *Abramis brama*, roach *Rutilus rutilus*, Eurasian perch *Perca fluviatilis*, northern pike *Esox lucius*, and ruffe *Gymnocephalus cernuus*), and those that spawned in the main reservoir (common carp *Cyprinus carpio*, zander [also known as pikeperch] *Sander lucioperca* [also known as *Stizostedion lucioperca*], catfish [also known as wells] *Silurus glanis*, and European eel *Anguilla anguilla*).

Among salmonids, various reservoir species use the tributaries for reproduction. Kokanee *Oncorhynchus nerka* occupy pelagic habitats in reservoirs and spawn in graveled shorelines or stream gravel, depending on availability (Parsons and Hubert 1988), including artificially constructed spawning channels (Mullner and Hubert 1995). Brown trout *Salmo trutta* migrate between the reservoir and tributaries to spawn in pool-and-riffle habitat and avoid undesirable temperatures in the reservoir (Crisp et al. 1990; Garrett and Bennett 1995). Wild populations of rainbow trout *O. mykiss* and cutthroat trout *O. clarkii* spawn in tributary streams, with cutthroat trout spawning farther up in tributaries, and can often provide important fisheries in reservoirs if their spawning and rearing habitats in tributaries are protected (Stables et al. 1990). Brook trout *Salvelinus fontinalis* that reside in reservoirs also move upriver to spawn and juveniles use the streams as rearing grounds (Neve and Moore 1983). In all cases, these salmonids are seeking suitable substrates (i.e., gravel, sand, and rubble in riffles), current velocities for construction of redds, and temperatures. Use of the spawning habitats varies temporally among species. Kokanee migrate back to the reservoir immediately after emergence, whereas most trout will rear for months to years in the streams before returning to the reservoir.

In reservoirs with long riverine stretches upstream, large lateral tributaries, or extensive floodplains in incoming rivers, native potamodromous species comprise a large fraction of reservoir fish assemblages (Agostinho and Zalewski 1995). Because of large discharges or access to riverine environments, these reservoirs often may have low retention times and not be as conducive as storage reservoirs to development of lacustrine faunas (Gomes and Miranda 2001). Upriver from Itaipu Reservoir, Brazil, a 230-km stretch of the free-flowing Paraná River connects to an extensive floodplain to provide important spawning and rearing habitats for many species (Agostinho et al. 2001), including 6 out of the 10 species that sustain the reservoir's fisheries (Okada et al. 2005). At the urging of conservationists and fishers, this section of the river was set aside as a national park by the Brazilian government to prevent further impoundment, degradation, and enhance fisheries in Itaipu Reservoir. In four flood-control reservoirs in Mississippi that provide quality crappie *Pomoxis* spp. fisheries, age-0 crappie and sunfish *Lepomis* spp. were produced in much higher numbers in sloughs and oxbow lakes immediately upstream of the reservoirs than in the reservoirs (Meals and Miranda 1991). Those backwaters flooded annually or semiannually as water level rose, simulating a river's floodplain, and likely helped enhance populations in the reservoirs. In reservoirs with important riverine habitats upstream, restoration and conservation of such habitats should be a reservoir management priority.

Management Emphases

Management of tributaries to enhance reservoir species depends on the reservoir's fish assemblage but, in general, might include protecting gravel bars, maintaining bank stability, preserving access to wetlands and oxbow lakes, and providing suitable flow during key periods. Thus, a first step should be to inventory tributary habitats and rate their quality relative to reservoir species that might use it. There is a large body of literature relevant to stream habitat maintenance and restoration (e.g., FISRWG 1998; Downs and Gregory 2004; Mitsch 2006). This literature has concentrated on river restoration to benefit river species, rather than to benefit reservoir species that use the river part-time, although these two aims overlap. Future management of reservoir fish assemblages may require greater attention to upstream protection and restoration, as well as research directed at better understanding how reservoir fish populations interact with habitats in the tributaries.

The Riparian Zone

The riparian zone represents the strip of land immediately adjacent to the river and surrounding the reservoir, beginning at the shoreline and moving inland a loosely defined distance. In streams, it has been defined as encompassing the terrestrial landscape from the high-water mark towards the uplands up to where vegetation may be influenced by the elevated water tables and flooding (Naiman and Decamps 1997). The riparian zone may be narrow in headwater streams, larger in midsized reaches represented by a distinct band of vegetation whose width is determined by long-term channel dynamics and the annual discharge regime, and large in reaches characterized by well-developed and physically complex floodplains with long periods of seasonal flooding, lateral-channel migration, and oxbow lakes. In reservoirs, riparian zones are different and resemble that of streams only in the back of bays near the entrance of tributaries. Near the dam, reservoirs lack a true riparian zone because the original river channel has been submerged and the shoreline contours now consist of upland vegetation that provides a buffer zone, although not a true riparian zone.

Riparian and buffer zones are key systems for regulating aquatic-terrestrial linkages (Correll 1997). In streams, major roles of riparian zones include thermal buffering, shading, contribution of woody debris, bank stability, and sediment and nutrient interception (Pusey and Arthington 2003). In reservoirs, these roles remain relevant, but the importance of buffer zones shifts towards bank stability by armoring banks against erosion, sediment and nutrient interception, and protection from strong winds. Furthermore, riparian buffers present an esthetic visual barrier that help maintain quality of the recreational fishing experience.

Links to Reservoir Fish

Riparian zones have multiple effects on fish (Pusey and Arthington 2003). Without suitable riparian buffers, fine sediments are transferred from the watershed to shallow reservoir environments where they can impact littoral fish species. Increased turbidity and sedimentation alter food availability (e.g., benthic invertebrates and algae; Berkman and Rabeni 1987), affecting fish foraging behavior and efficiency (Bruton 1985) and altering intraspecific interactions. Other major effects include reductions in habitat suitability for spawning (Walser and Bart 1999) and increased egg mortality, as well as reductions in rates of larval development and survival (Jeric et al. 1995). As the banks and associated littoral habitats degrade, the density of fish that rely on the littoral zone during all or part of their ontogeny is likely to decrease. The fish community may shift towards dominance by species that do not rely on substrate-based resources but, instead, can occupy pelagic niches. Erosion of littoral areas and ensuing siltation and shallowing of reservoirs are not only linked to reductions in benthic production, but also to reductions in plankton production through increased murkiness of the water.

Riparian deforestation exposes lake surfaces to strong winds. A survey in Ontario showed that lakes around which riparian trees had been removed had thermocline depths more than 2 m deeper per unit fetch length compared to lakes surrounded by mature forests (France 1997). Excessive wind deepens thermoclines and reduces habitat for cold stenotherms such as some salmonids. Wind also mixes the hypolimnion and epilimnion, resulting in loss of thermal refugia for species such as striped bass *Morone saxatilis* (Coutant 1985), and in periodic declines in water quality, that might affect the entire fish assemblage. Excessive wind associated with deforestation of riparian zones has been linked to increased turbidity through sediment resuspensions produced by the interaction of fetch and depth in shallow oxbow lakes (Miranda and Lucas 2004).

With few exceptions, research about the contribution of riparian buffer zones to lake and reservoirs has focused on water quality and, for the most part, has ignored direct relationships with fish assemblages. In reservoirs of the southern United States, species richness and centrarchid abundance are generally higher in coarse woody habitat (Barwick 2004) provided by forests surrounding the reservoirs. In a lake in Wisconsin, experimental removal of coarse woody habitat originated from the riparian zone resulted in largemouth bass *Micropterus salmoides* consuming less fish and more terrestrial prey, and growing more slowly (Sass et al. 2006). Moreover, yellow perch *Perca flavescens* declined to extremely low densities as a consequence of predation and little or no recruitment.

Management Emphases

Buffer strips with multiple vegetation types may best protect water bodies against agricultural impact (e.g., Schultz et al. 1995). This concept uses three interactive zones that are in consecutive upslope order from shore, including a strip of permanent forest, a strip of shrubs and trees, and a strip of herbaceous vegetation; width and composition of this basic model is adapted to the geographical variability of terrestrial plant communities and riparian conditions (Sparovek et al. 2002). The first strip influences the aquatic environment directly (e.g., temperature, shading, bank stability, wind break, and source of coarse woody habitat). The second strip controls pollutants in subsurface flow and surface runoff and is where biological and chemical transformations, storage in woody vegetation, infiltration, and sediment deposits are maximized. The first two strips contribute to nitrogen, phosphorus, and sediment removal. Grasses in the third strip spread the overland flow, thus facilitating deposition of coarse sediments. Grassy riparian areas trapped more than 50% of sediments from uplands when overland water flows were less than 5 cm deep (Magette et al. 1989). In North Carolina, riparian areas removed up to 80–90% of the sediments leaving agricultural fields (Daniels and Gilliam 1997). Riparian buffer zones accumulate nutrients and absorb them into plant biomass, serving as nutrient filters. In Vermont, reductions of approximately 20% in mean total phosphorus concentration and 20–50% in mean total phosphorus load were observed (Meals and Hopkins 2002). In Lake Rotorua, New Zealand, riparian management reduced sediment loads by 85%, particulate phosphorus and soluble phosphorus by about 25%, and particulate nitrogen and soluble nitrogen by 40% and 26%, respectively (Williamson et al. 1996). These reductions were predicted to reduce the chlorophyll-a concentrations in the lake by about 5 mg/m^3 and help shift the lake's trophic state from eutrophic to mesotrophic. However, decreases in inorganic turbidity that reduce light limitation could potentially counteract the effect of reductions in nutrient loadings, turning reservoirs from brown to green. Also, the effectiveness of riparian zone restoration in sediment and nutrient reduction is reduced during periods of high runoff and outside the growing season that, depending on geography, is when the highest discharges occur.

Residential development reportedly can have substantial impact on riparian zones. Quantity of woody debris and size of sediment particles decreases in lakes with greater lakeshore development density (Christensen et al. 1996; Jennings et al. 2003). These changes can negatively affect fish assemblages, as a result of loss of refugia and resource heterogeneity (Scheuerell and Schindler 2004) and extirpation of benthivorous prey fish species (Roth et al. 2007). Moreover, riparian habitat, recreational opportunities, and the visual and other esthetic values are often marred by shoreline developments. Federal agencies that own land surrounding reservoirs are under increased pressure to sell their lakefront lands to commercial developers.

The Watershed

A watershed is a geographical area that drains into a river or reservoir and is thus a natural geographical unit for the management of water resources. Watershed land cover is a major determinant of water quality and thereby fish community composition. A watershed contributes nutrients to a reservoir that influence primary production. Nutrients, especially phosphorus and nitrogen, flow to the reservoir from all parts of the watershed by way of streams, groundwater, and runoff. Typically, watersheds experience various levels of deforestation, agricultural development, industrial growth, urban expansion, surface and subsurface mining activities, water diversion, and road construction. These changes destabilize runoff, change annual amplitudes and distributions of flow, and enhance downstream movement of nutrients, sediments, and detritus that are ultimately trapped by reservoirs. Depending on their extent, inputs can regulate primary productivity, species composition, and food web interactions.

Sediments are a major watershed export into reservoirs that affect the water column through turbidity and, after settling, through siltation. Mean total suspended solids in 135 Missouri reservoirs (Jones and Knowlton 2005) ranged from 1.2 to 47 mg/L and were positively related with the proportion of cropland in their watershed, negatively related to forest cover, and weakly related to grassland cover. Siltation rates in reservoirs are higher in agricultural watersheds and show major shifts in relation to shifts in agricultural land management (e.g., McIntyre and Naney 1990). Siltation of littoral areas in reservoirs often results in replacement of diverse substrates with fine uniform particles that blanket existing habitats, filling interstitial spaces and burying structure. Siltation not only affects the backwaters of the reservoir, but as the backwaters fill, siltation extends upwards beyond the reservoir into the tributaries.

Nutrient inputs from the watershed are a leading cause of eutrophication (Carpenter et al. 1998). Many studies have quantified the interdependence of land cover and nutrient export from a variety of watersheds modified by human activity (Beaulac and Reckhow 1982). In general, nutrient levels in aquatic systems are directly related to the fraction of cropland and inversely related to the fraction of forest cover. Row-crop agriculture with frequent tillage and fertilizer application represents a major disturbance to the watershed (Novotny 2003). Reportedly, nutrient exports from croplands are several folds that of grassland and forest (Beaulac and Reckhow 1982). Because phosphorus and nitrogen are the principal productionlimiting nutrients in freshwater, excessive loading of these nutrients can adversely affect receiving waters. In 135 Missouri reservoirs, phosphorus and nitrogen levels were high in reservoirs surrounded by croplands and lower in those surrounded by forests, resulting in a sevenfold minimum difference in nutrients between a reservoir dominated by forest and one dominated by cropland (Jones et al. 2004). Similar relations were reported in Connecticut (Field et al. 1996), Iowa (Arbuckle and Downing 2001), and Ohio (Knoll et al. 2003) lakes and reservoirs. The influences of grassland was less apparent in the Missouri reservoirs, with reservoirs dominated by grassland watersheds having about tripled the nitrogen and double the phosphorus levels of those dominated by forests. In Iowa, lakes in heavily cropped watersheds had higher nitrogen to phosphorus ratios than those in highly pastured basins (Arbuckle and Downing 2001). Nutrient input from urban watersheds often equals or exceeds that from agriculture, per unit land area, as impervious surfaces enhance runoff (Beaulac and Reckhow 1982).

Forests affect water quality, discharge, and the quality of lake sediments. Likens et al. (1970) showed a large rise in nitrate concentrations and transport following clearcutting in New Hampshire. In paired watershed studies in northwest Montana, Hauer and Blum (1991) demonstrated increases in nitrogen and phosphorous mobilization and significant increase in algal growth in streams draining watersheds with up to 30% of the total forest area harvested. Vitousek et al. (1982) showed wide variation in nitrification and nitrate mobility in forested watersheds of North America. In shallow natural lakes in Alberta, timber harvesting increased chlorophyll a and blue-green algae, and zooplankton decreased after edible phytoplankton biomass declined (Prepas et al. 2001). Woody debris is an important export from forested watersheds, but it is substantially reduced in managed forest relative to unmanaged ones (Duvall and Grigal 1999).

Livestock management and overgrazing can impair buffer zones and runoff (Belsky et al. 1999). Excessive consumption of vegetation in buffer zones reduces the vegetation's effectiveness and destabilizes banks of riparian areas, leading to increased sediment inputs and effects derived from turbidity and siltation (Platts 1979). Compaction of soils in buffer zones decreases infiltration and thereby increases surface runoff and sediment supply. Magilligan and McDowell (1997) documented improved stream conditions in areas where cattle enclosures were installed. Livestock feeding facilities are major sources of nutrients as dissolved nitrogen inputs are sensitive to cattle densities and feeding rates, and nutrient inputs into aquatic ecosystems are directly related to animal stocking densities (Stout et al. 2000). Where stocking rates are high, manure production exceeds agricultural needs for both nitrogen and phosphorus, causing surplus nutrients to accumulate in soils to be later mobilized by precipitation into aquatic ecosystems (Carpenter et al. 1998). Intensive dairy and hog-raising operations produce voluminous waste that rival that of small cities, but the impact of livestock animals on aquatic systems is likely to differ across climates, geological settings, and hydrologic conditions.

Urban encroachments into reservoir watersheds contribute to point and nonpoint inputs of nutrients. Point sources can include wastewater effluent and leaching from waste disposal sites of municipal and industrial facilities and storm sewer outfalls. Point and nonpoint sources also can include runoff and seepage from animal feedlots and from industrial, construction, and other sites. Although over recent decades, point sources of nutrient inputs have been reduced in many cases owing to their relative ease in identification and control, runoff from impervious surfaces (e.g., roads, commercial sites, and suburban areas) can be a major nonpoint source of nutrients (Carpenter et al. 1998).

Reservoirs are also the recipients of carbon released from dissolved organic matter or particulate organic matter produced upstream or within the watershed. Consumers can use allocthonous carbon (Polis et al. 1997), providing resources that enhance consumer abundance beyond levels supported by authoctonous primary production. Studies in small Michigan lakes indicated that 40–55% of particulate organic carbon and 22–50% of zooplankton carbon were derived from terrestrial sources through bacterial loops (Pace et al. 2004). Similarly, substantial microbial activity in the riverine and transitional zones of Sau Reservoir, Spain were promoted by enhanced organic carbon availability from the incoming river (Comerma et al. 2001). These authors suggest that a longitudinal web from bacteria to heterotrophic nanoflagellates, to ciliates, and to zooplankton is an important pathway through which allochthonous organic carbon enters reservoir food webs. In embayments of Kentucky Lake, the lowermost reservoir on the Tennessee River, concentrations of particulate carbon correlated with differential land-use practices (Yurista et al. 2001). Embayments associated with agricultural watersheds had elevated particulate carbon concentrations, whereas those associated with forested watersheds had concentrations similar to those in the main stem, although it was unclear whether this difference reflected carbon availability or the ability to export it. Thus, reservoir food webs are not simply based on internal primary production but are coupled to watershed inputs that support not only phytoplankton and bacteria, but also invertebrates and fish.

Links to Reservoir Fish

Increased nutrient inputs due to watershed practices stimulate aquatic plant growth and impact fish assemblages. Filamentous algae are favored under high nutrient and light availability conditions, but are not readily incorporated into aquatic food webs by invertebrate consumers (Pusey and Arthington 2003). Consequently, fish may find their food base drastically altered in composition and abundance. Moreover, with increased nourishment, phytoplankton communities shift from a domination by green algae to blue-green algae. Dominance may also shift seasonally, with blue-green algae dominating for an increasingly larger portion of the year in highly eutrophic reservoirs (Smith 1998). In turn, zooplankton composition is affected by phytoplankton availability. Macrofiltrators (usually large-bodied zooplankton) are more abundant in oligotrophic reservoirs, giving way to low-efficiency, small-bodied, algal and bacterial feeders as nutrients increase (Taylor and Carter 1998). In highly eutrophic reservoirs the food supply of zooplankton may actually decrease because of the dominance by blue-green algae (Porter and McDonough 1984).

High levels of suspended solids reduce light penetration and photosynthesis, reduce food availability and plant biomass, alter zooplankton communities, reduce visibility, and possibly reduce fish growth, decrease size at first maturity and maximum size, and produce a shift in fish-habitat use (Bruton 1985). Increases in turbidity driven by the sediments delivered by agricultural watersheds tend to interfere with the feeding of large zooplankton, but not of smaller taxa such as rotifers (Kirk and Gilbert 1990). Thus, changes from vegetated to cultivated watershed might favor dominance by small zooplankton taxa and fish that feed on small taxa.

Eutrophication induces change in yield and species composition of fish communities.

Early stages of eutrophication may enhance fish growth and fishery yield, but later stages may force changes in food habits, spatial distribution, and community composition (Larkin and Northcote 1969). In Florida lakes, fish biomass increased with eutrophication status to a maximum in mesoeutrophic lakes and fluctuated around the maximum value in hypereutrophic lakes (Kautz 1982). Game fishes reached maximum biomass and optimum densities in mesoeutrophic lakes with a total nitrogen concentration of 1.2 mg/L and a chlorophyll-*a* concentration of 11 μg/L, but suffered adverse effects with further enrichment (Bachmann et al. 1996). Reduction of nutrient input into U.S. reservoirs resulted in cleaner water, a shift in species composition, and reduced fishery output (Ney 1996). In Alabama reservoirs, oligotrophication that resulted in chlorophyll-a reductions to 10–15 μg/L improved water clarity and was not detrimental to black bass and crappie fisheries (Maceina et al. 1996).

The fish assemblages of many reservoirs in North America are dominated by gizzard shad *Dorosoma cepedianum*, a clupeid that depends on small zooplankton at larval stages (Miranda and Gu 1998) but is capable of consuming large amounts of detritus during postlarval stages (Mundahl and Wissing 1987). According to Vanni et al. (2005), gizzard shad represents a key link between reservoir fish assemblages and watersheds. Agricultural watersheds tend to export greater quantities of particulate organic matter than forested watersheds, and reservoirs in agricultural watersheds support higher abundances of gizzard shad, probably through various mechanisms operating on larval and adult stages. Thus, reliance on watershed exports gives species such as gizzard shad, buffalos *Ictiobus* spp., and carpsuckers *Carpiodes* spp. a large advantage over other reservoir fishes because they can utilize this food resource not available to all species. In Ohio reservoirs, the number and biomass of juvenile and adult gizzard shad increased with the extent of agriculture in watersheds (Vanni et al. 2005).

Management Emphases

The goal of watershed management is to facilitate self-sustaining natural processes and linkages among the terrestrial, riparian, and reservoir environments. It involves controlling the quantity, makeup, and timing of runoff flowing into the reservoir or tributaries from the surrounding terrain. The first and most critical step must be halting or eliminating those anthropogenic practices causing reservoir degradation. Such approaches can involve a wide range of adjustments to human activities. For example, it may involve increasing widths of buffer strips around fields, altering livestock grazing strategies to minimize impacts, moving tillage operations in fields farther away from riparian systems and water, changing tillage methods and timing, and stopping the release of industrial waste that cause water pollution. To this end, various protocols, labeled best management practices (BMPs) have been developed to target and minimize impacts from troublesome nonpoint sources in the watershed (Table 1). Best management practices are usually applied as systems of practices because one practice rarely solves all problems and the same practice will not work everywhere. There is a large body of literature about watershed management that is important for reservoir managers to be acquainted with; nevertheless, watershed management should not be the direct responsibility of the fishery manager (more below).

The Basin

A basin is the portion of land drained by a river and its tributaries and therefore includes multiple watersheds. I define the ba-

Table 1. An overview of selected best management practices (BMP; USEPA 1993).

BMP	Abridged description
	Riparian zone
Riparian buffer	An area adjacent to a solid blue line stream as shown on 7.5-min U.S. Geological Survey maps where a permanent, long-lived vegetative cover (sod, shrubs, trees, or a combination of vegetation types) and wetlands trap sediment and nutrients and limit shoreline erosion.
Riprap	Broken rock, cobbles, or boulders of sufficient size and thickness to resist the erosive forces of wave action. Used to protect shores and slopes on dams.
Shore stabilization	Reduces erosion and instream sediment by protecting and maintaining the bank so it does not erode or fall into the stream.
Vegetative stabilization	Reduces runoff, erosion, nutrient, and contaminant loads by maintaining vegetative cover at critical locations throughout the watershed such as highly erodible areas and riparian zones.
Zoning	Reduces runoff, erosion, nutrient, and contaminant loadings through legally enforceable regulations for permissible land uses.
Interception or diversion practices	Reduces runoff erosion, nutrient, and contaminant transport by intercepting runoff before the flow path becomes too long or by diverting the runoff away from a lake or reservoir.
Detention/ sedimentation basins	Reduces the flood peak, sediment, nutrient, and contaminant loading by retaining runoff and letting soil particles and attached nutrients/contaminants settle out in the basin.
	Agriculture
Animal waste management	Reduces nutrient and organic matter loading by controlling timing, amount, and form of manure application to fields.
Conservation tillage	Any tillage or planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce soil erosion; examples of conservation tillage include no-till, ridge-till, or mulch-till.
Long-term no-till	Planting of all crops for five consecutive years in at least 80% plant residue from preceding crops to reduce soil erosion.
Contour farming	Conducting field operations such as plowing, planting, cultivating, and harvesting, following the contours of the field.
Contour strip-cropping	Layout of crops and grass in a systematic arrangement of alternating strips on the contour.
Grassed waterways	Reduces erosion, nutrient, and contaminant loading by having runoff flow over a grassy area as it moves toward the stream or reservoir.
Crop rotation	Reduces soil erosion and nutrient applications by alternating with nitrogen-fixing legumes such as alfalfa.
Critical area planting	Where highly-erodible land cannot be stabilized by ordinary conservation treatment, a permanent perennial vegetative cover is established and protected.
Sediment basin	A basin constructed to trap and store sediments where physical conditions preclude other erosion control measures.

Table 1. Continued.

BMP	Abridged description
	Agriculture
Fertilizer management	Reduces nutrient loading by controlling timing, amount, and type of fertilizer added to crops and fields.
Integrated pest management	Reduces pesticide applications, improves effectiveness of application, and uses more resistant crops.
Livestock exclusion	Fencing livestock from highly erodible land and ground adjacent to streams and reservoirs to reduce erosion and nutrient loading. Water is delivered to animals in troughs.
Range and pasture management	Reduces runoff and erosion by maintaining vegetative cover. Reduces manure loadings to streams.
Terraces	Reduce erosion by shortening flow paths and improving drainage.
Buffer strips	Reduces runoff, erosion, and nutrient/contaminant loading by maintaining vegetation and ground cover along cultivated fields.
Sequential cropping	The practice of growing crops in a sequence that minimizes the amount of time bare soil is exposed on a field.
Grade stabilization structure	Reduce erosion by controlling the grade and head-cutting in natural or artificial channels (e.g., earth embankment and mechanical spillway).
Cropland conversion	Reduce erosion by establishing and maintaining a cover of grasses, trees, or wildlife plantings on fields previously used for crop production.
	Forestry
Ground cover	Reduces runoff and erosion by maintaining cover over soil so that it is not exposed to raindrops or runoff.
Streamside management zones	Reduces runoff, erosion, nutrient and contaminant loading by maintaining vegetative and ground cover next to waterways.
Pesticide/herbicide	Reduces contaminant loading by controlling the timing, amount, form, and location of pesticide applications.
Road/skid trails	Reduces length of runoff path and therefore erosion. Erosion from roads and skid trails is the major source of sediments from forested watersheds.
Log landings	Designed and located in a way that prevents sediment from entering waters.
	Urban
Flood storage	Reduces runoff, sediment, and attached nutrient/contaminant loading by settling sediment particles out of the water.
Porous pavement	Reduces runoff, erosion, and pollutant loading by rainfall soaking through the pavement into the underlying soil.
Street cleaning	Reduces nutrient and contaminant loading by removing them from the pavement so that pollutants will not be washed into streams during storms.
Constructed wetlands	Filter storm water and reduce runoff rate while producing wildlife habitat.

Table 1. Continued.

BMP	Abridged description
	Construction
Disturbed area limits	Reduces erosion by restricting the area of the construction site that is disturbed or from which ground cover is removed.
Nonvegetative soil stabilization	Reduces soil erosion by using matting, mulch, or similar ground cover over the soil to reduce rainfall eroding the soil surface.
Surface roughening	Reduces the length of runoff flow paths to slow the water, creating pools or depressions and reducing the energy of water to dislodge and transport soil off the construction site.

sin to include the watersheds upstream and downstream from the reservoir. Broad patterns of reservoir characteristics are evident at the river basin scale. In large basins, variability in climate and physical characteristics among geographically disparate sections of the basin influence diversity of hydrology. Patterns are also evident within basins in relation to longitudinal gradients along series of reservoirs. Basin-scale variables are rarely controllable but constrain the expression of processes at smaller scales. Thus, an appreciation of basin patterns helps set limits for smaller-scale determinants and thereby helps understand the potentials and limits of reservoir management.

The river continuum concept (RCC; Vannote et al. 1980) proposed a clinal view of rivers. According to the RCC, the physical character of the river shows a gradient of conditions from headwaters to downstream, with upstream processes affecting downstream processes. The RCC does not apply directly to reservoir series; in fact, reservoirs alter the river continuum (Ward and Stanford 1983). However, the notion of clinal change along a basin does apply to a reservoir series. Clinal trends in reservoir attributes are basin-specific, yet exhibit common patterns. In general, the upper reaches of most basins tend to be forested, whereas the lower reaches have received increasing levels of modifications to accommodate agriculture. Characteristics such as mean depth, relative size of the limnetic zone, water retention time, oxygen and thermal stratification, substrate size, and water-level fluctuations tend to increase in upstream reservoirs. Conversely, reservoir area, extent of the riverine and littoral zones, access to floodplains and associated wetlands, habitat diversity, and nutrient and sediment inputs tend to increase in downstream reservoirs. Many of these patterns are dictated by landscape characteristics and are also evident in chains of natural lakes (Kratz et al. 1997; Martin and Soranno 2006), but exceptions are common given the diversity of landscapes.

Nutrient trapping by reservoirs along a basin reportedly reduces productivity down the cascade, although in reservoirs with low retention time, nutrients and productivity may actually increase downstream. Lake Mead experienced a drastic drop in productivity after the impoundment of Lake Powell upstream in the Colorado River (Vaux et al. 1995). In the Tietê River, Brazil, the uppermost reservoir in a series of nine impoundments captured most of the nutrients released from São Paulo, the largest city in South America (Barbosa et al. 1999). In reservoirs in large rivers with low retention and/or multiple influential tributaries, the effects of upstream reservoirs may not be as pronounced as in the above examples (Bruns et al. 1984; Agostinho et al. 2004a).

In the Tennessee River, upstream reservoirs retained a greater portion of inflowing nutrients owing to greater water retention, although their net loads were lower owing to smaller watersheds with different geomorphology and land cover (Voigtlander and Poppe 1989). The net effect was increasing chlorophyll-*a* levels in reservoirs (Tennessee Valley Authority, unpublished data), which was also noted for a chain of natural lakes in Wisconsin (Riera et al. 2000). Thus, nutrients and associated primary productivity variables, and likely many water quality variables, show spatial gradients within the basin so that conditions in a given reservoir are predictable based on its position in the basin.

Links to Reservoir Fish

The RCC postulates that fish assemblages change continuously along lotic systems in response to physical and nutrient gradients. Analogously, in impounded basins, the reservoirs higher in the cascade tend to include few, largely lacustrine, generalist, ubiquitous taxa characteristic of the sluggish upper reaches of the basin (McDonough and Barr 1977). The reduction of riverine species is particularly evident for large migratory taxa often stopped by dams that lack passage or interrupted by multiple dams and passages (Agostinho et al. 1999). Depending on latitude, upstream reservoirs in high elevations may include coolwater and possibly coldwater species assemblages, and reservoirs lower in the cascade transition into warmwater species assemblages. Riverine species become more common in downstream reservoirs, an effect that is especially evident in reservoirs below long unimpounded stretches, unimpounded tributaries, or reservoirs with extensive upstream floodplains (Agostinho et al. 2004b).

In reservoirs of the Tennessee River, fish species richness, composition, and biomass changed longitudinally along the basin. Number of species increased from a low of less than 20 in high elevation impoundments to near 70 in the lowermost reservoir (McDonough and Barr 1977). Similarly, fish abundance increased in reservoirs further downstream. Additionally, species composition showed strong organization relative to position in the cascade (Miranda et al., in press). Reservoirs high in the basin were characterized by a greater composition of bluegill *Lepomis macrochirus*, smallmouth bass *Micropterus dolomieu*, and walleye. On the low end of the basin, reservoir fish assemblages included greater representation of shads, blue catfish *Ictalurus furcatus*, buffalos, gars *Lepisosteus* spp., yellow bass *Morone mississippiensis*, and redear sunfish *L. microlophus*. A relatively linear cline existed in between. Trophic guild composition also changed along the reservoir cascade, with percentage composition by number of detritivores and planktivores increasing down the basin and that of invertivores, invertivores/carnivores, and invertivores/detritivores increasing up the basin (Miranda et al., in press).

The Tennessee River reservoir cascade has several subcascades that discharge into the main stem. Position of a reservoir relative to a subcascade affected the fish community and trophic guild composition (Miranda et al., in press). The Holston and Hiwassee subcascades were particularly informative as representation of trophic guilds differed; yet, clinal trends relative to reservoir position in the cascade persisted. The Holston River originates in the Appalachian Mountains of Virginia and flows southwest, and the Hiwassee River originates in the Appalachian Mountains of Georgia and flows northwest. These two subcascades experience different microclimates mediated by the Appalachian Mountains and differ in vegetative cover as the Holston watershed has been affected by agriculture and urbanization, whereas the Hiwassee watershed has retained more of its forests. Thus, while longitudinal basin patterns occur, patterns may differ in subcascades and likely basins.

In addition to community and trophic guild composition, population metrics of usual interest to fishery managers, such as growth and recruitment, are likely to vary at the scale of the river basin. Because nutrient levels and prey availability and diversity increase downstream along the basin, fish growth rates are likely to be higher, contributing to greater fish production. Moreover, the relatively shallow reservoirs lower in the basin have proportionally larger littoral areas that may increase the amount of foraging habitat for species that depend primarily on littoral detritus, invertebrates, and fish prey. Recruitment of largemouth bass to fingerling stage (3–5 cm) tends to be high in deep reservoirs with substantial water level fluctuations usually located high in a basin. Available data document this occurrence in reservoirs of the Tombigbee River (L. E. Miranda, unpublished) and Tennessee River (Tennessee Valley Authority, unpublished), with fewer but larger fingerlings with higher prospect for survival evident in reservoirs lower in the basin. Due to lower species diversity and other factors, survival of larval largemouth bass increases in upstream reservoirs, but mortality may be higher later on their first year of life due to slower growth. A basin fishery management perspective based on these isolated examples suggests the need to liberalize harvest in downstream reservoirs, given higher recruitment and productivity, while restraining harvest in upstream reservoirs and focusing on promoting survival of abundant juveniles.

Management Emphases

Considering impoundments at a basin scale, by viewing them as sections in a river or links in a chain, may generate management insight not always available when considering them as isolated entities. An obvious feature of reservoir series is a predictable spectrum of fish assemblages that can provide a diversity of recreational and commercial fisheries. Traditional management approaches may be organized relative to features in the reservoir series. For example, the effectiveness with which the typical management efforts influence fish assemblages is likely to decrease downstream because reservoir size, species richness, and, therefore, fish assemblage stability increase. Correspondingly, stocking, harvest regulations, and habitat manipulation programs are likely to be increasingly more effective in upstream reservoirs. Efforts to diversify fisheries; to overlay commercial, subsistence, and recreational fisheries; and to provide multispecies fish-passage facilities that increase the longitudinal connectivity of the sections separated by the dams are likely to be more effective in downstream reservoirs because those reservoirs tend to have more habitat diversity, diversity of water regimes, species richness, and riverine species. These principles apply whether the basin has one or multiple reservoirs.

Fisheries managers may have viewed reservoirs as spatially independent entities and have seldom considered them as connected and organized across a basin. The concept of reservoir position within a river basin is concordant with the RCC, a model that has helped river ecology move forward in the last two to three decades (Miranda and Raborn 2000). The relevance of the RCC to rivers is still being debated globally, but regardless of its validity, it has provided a template to guide river research. The basin perspective professed by the RCC can also serve as a template for considering reservoirs that because they are impounded over streams, generally show longitudinal gradients at the scale of a river segment occupied by a single reservoir (Kimmel et al. 1990), as well as at the scale of a series of reservoirs constructed in line within a river basin.

Reaching out of the Reservoir

Agencies that have historically focused on reservoir-specific fish population dynamics might find it worthwhile to extend the scale of their involvement beyond the reservoir shores. Extending the scale of reservoir management can enhance the manager's ability to impact reservoir fish populations and communities and can also increase the effectiveness of traditional in-reservoir management measures. Given a potentially overwhelming expansion in management activities, there is a need to expand the level of human resources involved in management by partnering with other state and federal agencies, local governments, universities, nongovernment organizations, corporations, and the public. Within this environment, the traditional control exerted by fisheries managers over a resource is diminished, but the potential to bring big, long-lasting changes to reservoir environments and biota is increased.

The importance of considering a scale broader than the reservoir itself is likely to increase with the level of disturbance experienced by the landscape. Reservoirs in relatively undisturbed landscapes with high-quality tributaries and riparian zones are likely to require mainly landscape protection and traditional in-reservoir management approaches. In contrast, reservoirs in heavily disturbed landscapes with highly engineered tributaries may require considerable out-of-reservoir attention before in-reservoir efforts become effectual (Box 1). In this latter group, a focus on regulations and stocking is shortsighted and represents only short-term fixes to complicated landscape issues that are the underlying problems to maladies in reservoir fish assemblages.

If reservoir managers lack jurisdiction or expertise to reach beyond the reservoir shores, they can engage in landscape-level partnerships (Box 2). These partnerships can provide the organization needed to plan, fund, and complete restoration work and may give reservoir managers the political clout and cover they may not have outside the reservoir. Over the past two decades, watershed management organizations have shown unprecedented growth across the United States. Although an exact count is not available, as of May 2007, a database operated by the U.S. Environmental Protection Agency contained voluntary listings for nearly 4,000 organizations from across the United States involved in protecting local watersheds (www.epa.gov/adopt/network.html). Some of these are small and local and some basin-wide or statewide. Watershed organizations differ geographically given the diversity of landscapes as well as parallel diversity in the cultural, political, and economic scene. Thus, it is unlikely that a standard model for participation by reservoir managers in watershed organizations is workable in all localities. Rather, partnership involvement by reservoir managers needs to accommodate the range of organization structures.

Nevertheless, it is relevant to ask what strategic role reservoir managers should play in landscape partnerships. As partners, managers must be equipped to show the linkage between the reservoir and the landscape and to be activists for change that benefits fish in the reservoir. Managers should be equipped to contribute information suitable for developing restoration and protection plans, particularly relevant to how specific actions may affect reservoir water quality and biotic communities. To this end, a landscape inventory documenting features important to reservoir condition is essential, focusing on

Box 1. Iowa's comprehensive lake and watershed management program.

Iowa leads the nation with 72% of its land area converted to cropland, which combined with an additional 10% pastureland and 5% developed land results in 87% of Iowa's land area being directly disturbed (Heitke et al. 2006). As a result, many natural and constructed lakes in Iowa are impaired with poor water quality, sparse fisheries, and low recreational value (J. Larscheid, Iowa Department of Natural Resources, personal communication). Over the years, many lakes were renovated, some multiple times, resulting in improved fisheries that often degraded because the underlying problems of heavy sedimentation, excessive nutrients, and ensuing poor water quality were not addressed. A lake classification system was developed based on systematic assessment of both lake water quality and watersheds. This classification, combined with socioeconomic factors, resulted in a priority ranking of lakes and watersheds for restoration. Once local commitments are demonstrated and feasibility verified, comprehensive restoration is initiated to address both watershed and in-lake issues. Watershed models are used to simulate hydrologic processes and pinpoint the major sources of sediment and nutrient loading. These loads are reduced to acceptable levels through land-use changes and application of best management practices.

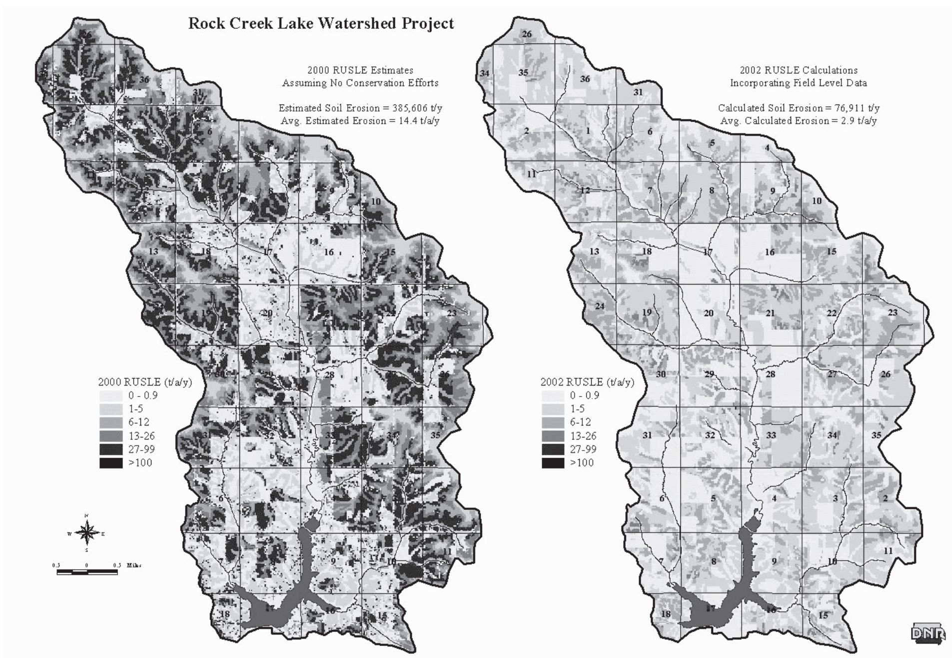

Figure. Geographic information systems representation of the Rock Creek Lake reservoir in central Iowa. The left plate shows soil erosion estimated by the Revised Universal Soil Loss Equation assuming no conservation efforts (32.3 metric tons/ha/year) and the right plate assuming various best management practices (6.5 metric tons/ha/year). Shades of gray identify an array of erosion rates (as per the accompanying scale). Plates courtesy of Iowa Department of Natural Resources.

Box 1. Continued.

Fisheries managers work within partnerships composed of government agencies, landowners, and nongovernment organizations and invest 25–30% of their efforts on watershed work associated with lake and stream projects (D. Bonneau, Iowa Department of Natural Resources, personal communications). Fisheries managers work in various capacities within partnerships, often as leaders in technical details of specific projects. According to Bonneau, this approach is intimidating at first, but it does work, does produce success stories, and does get the public support required to get the funding needed to work at this extended scale. These restorations can be expensive and require years to complete, but they are an investment in the local economy, fishing quality, and natural resources as a whole. Consequently, the Iowa legislature approved a state lakes program and allocated US$8.5 million in 2007 and a similar amount in 2008. This lake protection and improvement program is administered by the Fisheries Bureau with local and other matching funds expanding the program by more than $5.5 million each year.

critical areas representing major sources of problems likely to have large effects on the reservoir, such as large stretches of channelized tributaries without adequate gravel bars, ill-timed discharges from upstream impoundments, major tracts of wetlands disconnected from adjacent tributaries, agricultural ventures stretching down to the banks, and forest clear-cutting operations. A focus on critical areas would result in the greatest improvements and save time when gathering available information or conducting on-site surveys. An inventory of the tributaries, riparian zones, and watershed should include qualitative and quantitative data collected visually by boating, driving (e.g., winter windshield surveys), and walking to record and photograph key characteristics of the critical areas. These surveys are greatly assisted by geographic information systems land cover layers (Brenden et al. 2006), which in conjunction with spatial models of landscape change can be used to identify major hazards and nutrient and sediment sources and simulate improvement scenarios given various BMPs (Box 1). Rapid watershed assessment guidance is available (NRCS 2005) to serve as a framework for conducting such surveys; however, research is needed to establish survey protocols specific to reservoir needs, develop and refine quantitative metrics to prioritize and measure progress, and establish how to efficiently integrate reservoir needs into landscape planning. Additional structure and support for addressing landscapes issues may be available in the future through the National Fish Habitat Action Plan (www.fishhabitat.org), a fledging regional and national organization whose mission is to protect, restore, and enhance fish communities by fostering partnerships that address large-scale habitat management.

Considering that reservoir managers have focused mainly on in-lake processes, links between the reservoir fish assemblages and landscapes have not received sufficient attention and are likely to require research emphasis to build the capacity of managers to reach outside the reservoir. Fisheries researchers have shown links between eutrophication and fish community composition, that oligotrophication can reduce fishery

Box 2. Partnering for watershed management: Tennessee Valley Authority's watershed program.

The Tennessee River includes more than 30 major reservoirs operated by the Tennessee Valley Authority (TVA) for navigation, flood control, power production, water quality, and recreation. In 1991, TVA adopted a reservoir-operating plan that increased the emphasis placed on water quality and recreation (Poppe et al. 1997). This plan modified the drawdown of 10 tributary reservoirs to extend the recreation season and included a 5 year US$50 million program to improve conditions for aquatic life in tailwater areas by providing year round minimum flows and installing aeration equipment at 16 dams to increase dissolved oxygen levels. In 1992, to prevent these improvements from being negated by nonpoint pollution, TVA launched an effort to protect watersheds by forging alliances with governments, businesses, and citizen volunteers. The goal was to ensure that rivers and reservoirs in the basin were ecologically healthy, were biologically diverse, and supported sustainable uses. To accomplish this goal without regulatory or enforcement authority, TVA built action teams in each of 12 subbasins delimited as hydrologic units established throughout the United States (Omernik and Griffith 1991) and accepted by most agencies making them a logical choice for information exchange and management. These teams were responsible for assessing resource conditions and building partnerships to address protection and improvement needs.

The action teams represented a transformation of TVA's water management organization from a hierarchy organized around technical disciplines to a dynamic organization based upon cross functional teams. These teams were unique in that they combined the skills of aquatic biologists, environmental engineers, and other water resource professionals with the skills of community specialists and environmental educators. Team members learned to communicate with the public in nontechnical language and to build partnerships with farmers, waterfront property owners, businesses, recreationists, and local/state government officials. Assigning teams to a geographical area for the long term allowed members to gain a better understanding of resource conditions, build community trust, and enhance the development of cooperative relationships with stakeholders. The teams were self managed and empowered to decide how to focus resources and address protection and improvement needs, allowing a rapid response to evolving or newly discovered problems and opportunities.

The teams collected and reviewed aquatic resource data in existing agency reports, U.S. Environmental Protection Agency's computerized data base, geographic information systems, and interviews with state and federal natural resource management agencies, local governments, county health departments, and planning commissions. The TVA used these data to rate each hydrologic unit for its degree of degradation and to identify areas needing remediation. This information was used to focus resources and to evaluate improvement activities. Team members shared monitoring information with key stakeholders (e.g., regulatory agencies, state and local governments, businesses and industries, citizen based action groups, and watershed residents) and sought their support in developing and implementing protection and mitigation plans.

Box 2. Continued.

Team efforts to build partnerships paid off. In 1995, volunteers contributed 22,500 h in monitoring, habitat enhancement, cleanup, and protection activities. Acting as catalysts for change, action teams helped start or worked in partnership with many local coalitions to solve water quality problems, conducted more than 400 stream and reservoir assessments, established 20 native aquatic plant stands in reservoirs, installed 4,500 habitat structures, stabilized shorelines, and implemented watershed management practices, including construction of wetlands, fencing, and streambank revegetation. Team members also organized a variety of communication activities designed to educate people about water quality and involve them in solving pollution problems. By focusing on partnerships, action teams were able to accomplish what TVA could not have done acting as an independent government agency.

output, and have developed target ranges for optimum nutrient levels in some regions of the United States. Nevertheless, the associations between watershed imports and reservoir fish assemblages are tenuous at best and only beginning to be worked out. The importance of riparian and buffer zones as filters has been studied extensively in streams, but their contribution to littoral habitats in reservoirs has largely been ignored. Although reservoir managers know that some reservoir fish use the reservoir tributaries, the relationships between the tributaries, their backwaters, river discharges, and the fish assemblages that develop in reservoirs have received little or no attention in North America, although have gotten more attention in South America where native fish assemblages have more riverine species (Gomes and Miranda 2001). Furthermore, the natural gradient in abiotic and biotic features of reservoirs along a river basin is seldom or never systematically considered in developing local or large-scale reservoir management plans.

Organizational fragmentation and inadequate communication among agencies is often a major obstacle to effective watershed management. In the United States, there are many governmental agencies with watershed-related responsibilities (Table 2), often with contradictory goals, which is inevitable in a governmental structure that is designed to represent a diversity of stakeholders. For example, a fisheries management agency may disagree with the water rule curve established by the water management authority controlling a dam or with the decision of an environmental quality agency to allow an animal production facility in the vicinity of a stream discharging into the reservoir. Within this organizational structure, decisions allocating watershed resources among competing uses are made through a bargaining process in which the fishery manager must participate or risk not having the needs of the reservoir taken into account.

Perhaps the greatest challenge to extending the scale of reservoir management is the managers themselves. Fisheries managers have traditionally been trained to work within the reservoir to address issues about selected fish populations, their habitats, and the resource users. Nevertheless, activities in the watershed may be outside the fishery manager's realm of expertise or direct control. Therefore, reaching outside the reservoir cannot be done through the

Table 2. Watershed-related responsibilities of selected U.S. federal agencies (adapted from Graf et al. 1999). X = significant responsibilities; O = some related responsibilities.

Federal agency	Estuaries	Wetlands	Research	Hydropower	Navigation	Recreation	Preservation	Wildlife	Fisheries	Flow regimes	Ecological diversity restoration	Erosion/sediment control	Water qualtiy	Flood risk management	Water supply	Land use
Department of Agriculture																
Farm Service Agency		O									O	X				X
Forest Service		O	O			X	X	X	X		X	O	O	O	O	X
Natural Resources Conservation Service		X								O	O	X	O	O		X
Agricultural Research Service												O	O		O	X
Department of Commerce																
National Marine Fisheries Service	X	O			O			O	X				O			
National Oceanic and Atmospheric Administration	X								X				X	X		
Department of Defense																
Army Corps of Engineers		X	O	X	X					X	O	O	O	X	O	O
Department of Energy																
Federal Energy Regulatory Commission				X												
Department of the Interior																
Bureau of Land Management		X	O			O		X		X	X	O	O			X
Bureau of Reclamation			O	X		O		O	O		O	O	O	X	X	X
Fish and Wildlife Service		X	O			O	X	X	X		X		O			O
Geological Survey			X													
National Park Service	O	O				X	X	X	X		X	O	O			X
Bureau of Indian Affairs		O						O	O		O	O	X	O		O
Department of State																
International Boundary Commission	O												X	X	X	
Other Federal Independent Units																
Environmental Protection Agency	O	X	X			O	O	O	O	O	X	O	X		O	O
Tennessee Valley Authority		O	O	X	X	O		O	O	X	O	X	X	X	X	
Bonneville Power Administration		O		X	X			O	X	O	X	O	X	X	X	
Federal Emergency Management Agency														X		

segregated efforts of isolated managers and requires partnering with land-based agencies (Miranda 2003; Margerum and Whitall 2004). Such partnering approach is likely to be facilitated by an organizational structure and culture substantially different from that of most contemporary fishery management agencies. Depending on built-in flexibilities, agencies currently organized as isolated fish and game departments are likely to find it more difficult to reach out of the reservoir than those organized as departments of natural resources. Many agencies might require reorganization to develop the mission, mandate, resource authority, and skills required to effectively manage reservoirs at broader scales. In many cases, institutions that have served us well in the past outlive their intended missions and usefulness. Over time, existing agencies are reorganized to create new complexes of organizations to make decisions and meet new needs. This means rethinking the role of natural resource management agencies. The present move toward landscape-based management may bring a new wave of reorganizations. Nevertheless, change is often slow because the institutions responsible for managing our natural resources may well be the most significant barriers to the adoption of new, more integrated approaches to management (Slocombe 1993). Reaching outside the reservoir, in many cases, also requires longer time scales to show positive and enduring results, and therefore, these approaches are often ignored by agencies in search of quick solutions.

Conclusions

Reservoir management originated in response to the need to address issues associated with the growing number of reservoirs emerging in the first half of the 1900s. At that time, reservoir construction was rising quickly while freshwater ecology was a young science, although limnology had existed as a discipline for about half a century. There were many questions and challenges presented by large reservoirs, which were approached by applying concepts and methods developed by limnologist in freshwater lakes. Based on the foundation laid by Forbes (1887), lakes and eventually reservoirs were studied with reductionist methods and viewed as water bodies that functioned independent of streams and their watersheds. Although reservoirs are essentially large artificial pools in a stream, because streams and reservoirs had unique characteristics and unknowns, they were considered, studied, and managed as independent units producing a fragmentation in disciplines that, although successful up to a point, now cannot adequately deal with broadscale issues.

Our understanding of freshwater systems has evolved, human populations and their capacity to alter the environment have grown exponentially, most river basins have experienced substantial alterations, and the public has become more knowledgeable and involved in environmental issues. As reservoir managers enter the 21st century, they are becoming increasingly aware that natural resources management requires a broader perspective, and they may find themselves at a crossroads in unfamiliar territory. Managers should step off the narrow path defined in the early 1900s that forced them to focus almost exclusively on reservoirs as lake units independent of their watersheds or basin. Instead, they should shift paradigms to think of reservoirs and fish assemblages as parts of a broader system influenced longitudinally and laterally by the complexity of the basin, despite the fact that fishery management has not yet developed a way to easily integrate landscape concepts into fish management. Extending the scale of reservoir management does not mean that reservoir managers must become watershed managers, but simply that they should think about reservoirs as part of a bigger system and thereby network with those working upstream and on land. Such redefined conceptualization may in turn produce new management concepts, directions, and solutions to solve reservoir management problems.

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