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History of Striped Bass Management in the Colorado River

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Abstract.—The discovery of landlocked populations of striped bass *Morone saxatilis* in Santee–Cooper Reservoir, South Carolina and Kerr Reservoir, Virginia prompted a rush to stock striped bass in other inland waters of the United States, including impoundments in the Colorado River. Fisheries managers responsible for Colorado River waters studied existing literature and predicted that it would be unlikely for successful natural reproduction of striped bass in these systems. Striped bass population development proved unique in the Colorado River system, which is marked by nutrient-poor, well-oxygenated waters with limited forage. Natural reproduction did occur in these reservoirs despite the lack of current previously thought to be essential for successful reproduction, resulting in high survival. Developing populations were sometimes overabundant to the point of forage elimination from pelagic zones. Lack of prey limited growth and temporarily reduced reproduction. Eventually forage returned, increasing striped bass growth and maturity, which led to more reproduction (a "boom and bust" cycle). Planned low-impact, low-abundance adult trophy fisheries produced by managed stocking were replaced by high-abundance juvenile fisheries with high catch rates produced by natural reproduction. In most years, juvenile striped bass living in warm surface waters proved to have the competitive advantage over adults for limited forage.

Colorado River Historical Overview

The preimpoundment Colorado River was characterized by harsh environmental conditions ranging from muddy spring floods exceeding 8,495 m^3/s to flows less than 8 m^3/s in drought plagued summer months. Hoover Dam was completed in 1935, creating Lake Mead, the first impoundment on the river and one of the largest reservoirs by volume in the United States (Figure 1). At full pool, Lake Mead is 63,900 ha with a maximum depth of 177 m and maximum length of approximately 184 km. Two smaller but significant reservoirs followed. Lake Havasu (1938) and Lake Mohave (1952) were constructed downstream (Stewart and Burrell 2013, this volume). The last impoundment was completed in 1963 when Glen Canyon Dam was closed, forming Lake Powell (Utah and Arizona), which is 300 km long with a surface area of 65,000 ha when full.

The Colorado River watershed is mostly devoid of agricultural and commercial development, which has been the main cause of nutrient enrichment in many of the nation's impoundments and river systems. Colorado River impoundments are characterized by low phosphorus and nitrogen levels. The new lakes filled deep canyons carved out by the Colorado River with limited littoral zones. Seven native fish species that thrived in the river prior to impoundment were poorly suited for life in the new lake environment. Introduced nonnative

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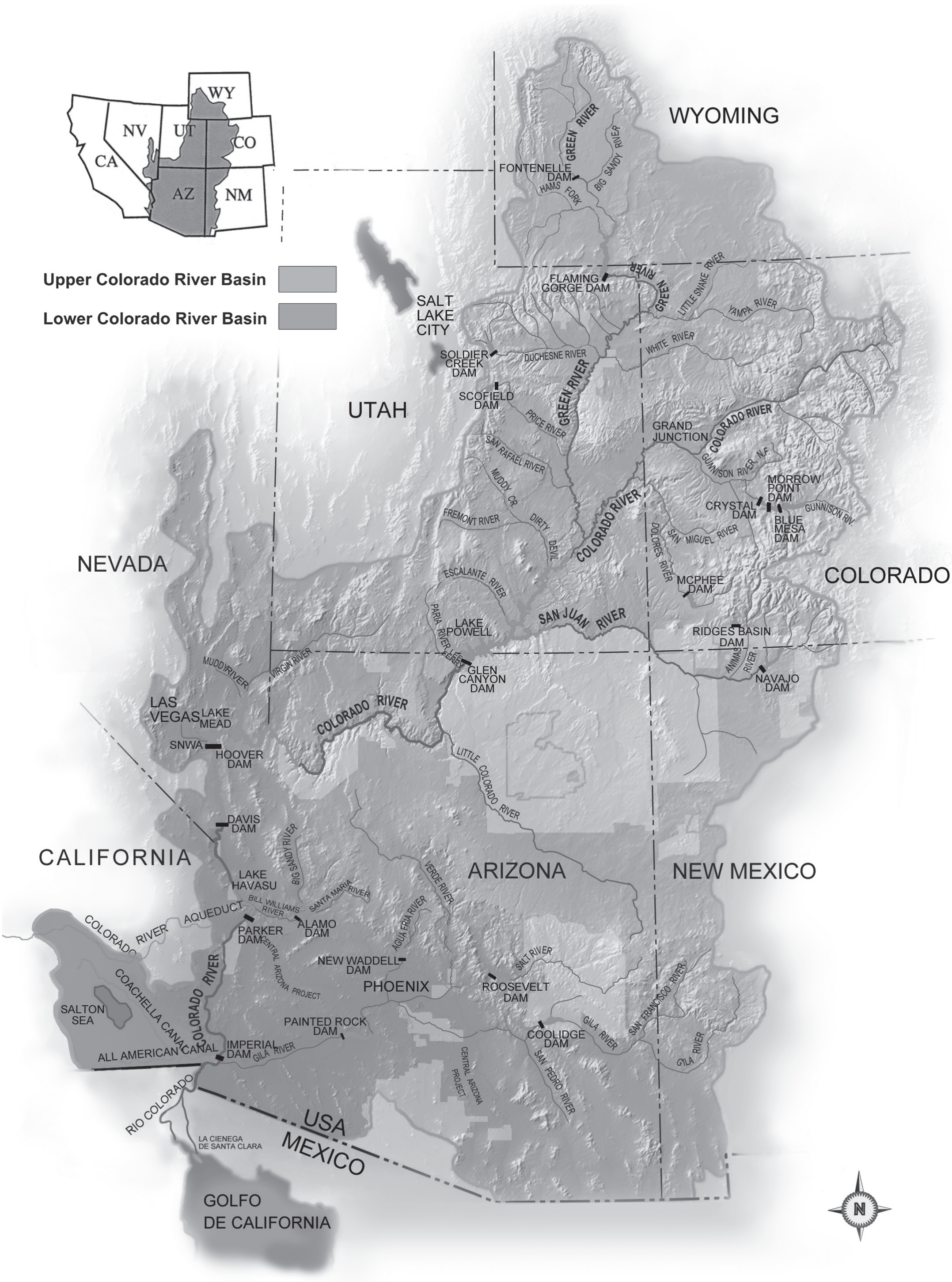

FIGURE 1. Map of Colorado River drainage with large reservoirs included.

sport and forage fish species dominate the fish communities that developed in these reservoirs.

Striped Bass History

Many new impoundments were constructed in the United States between 1930 and 1970. Striped bass *Morone saxatilis* trapped in Santee–Cooper Reservoir (South Carolina) impoundments and Kerr Reservoir (Virginia–North Carolina) survived and reproduced (Van Horn 2013, this volume). Land-locked striped bass provided fisheries managers a top-level predator that produced charismatic trophy fish for anglers while controlling overabundant forage fish populations. A nationwide rush to stock striped bass in reservoirs ensued as fish managers hoped to reap the biological and recreational rewards. Biologists in the Southeast quickly determined that most striped bass populations in reservoirs failed to reproduce because the semibuoyant eggs would settle to the bottom without supporting water currents and die due to siltation or lack of dissolved oxygen. Barkuloo (1970) proclaimed that "striped bass eggs and larvae must be suspended by current to prevent settling and death by suffocation." This finding guided managers in the Colorado River basin who contemplated introduction of striped bass.

Biologists at the California Department of Fish and Game stocked the first striped bass into the Colorado River in 1959 (St. Amant 1959). Young-of-year striped bass were seined from the San Joaquin River Delta and transported overland to the Colorado River near Blythe, California. All stocked striped bass were descendants of fish that were transported from the East Coast in 1879 and stocked in the delta near San Francisco Bay. Collaborative stocking efforts from 1962 to 1969 by state wildlife agencies in Arizona, California, and Nevada created thriving striped bass populations in Lake Mead, Lake Havasu, and the connecting river reaches (Edwards 1974). Popular striped bass sport fisheries developed, which included trophy-sized adults.

Striped bass were stocked by the Utah Division of Wildlife Resources in Lake Powell in 1974. It was initially thought that "reproduction would not be sufficient to maintain a sport fishery" (R. Stone, Utah Division of Wildlife Resources, personal communication). Hatchery rearing ponds were built near Lake Powell to meet the anticipated annual stocking requirement. The initial 1974 stocking in Lake Powell came from Virginia, California, and North Carolina genetic stock (May and Hepworth 1975). Over time, most of the fish stocked in Lake Powell came from North Carolina and the California Delta stock (Hepworth et al. 1976; Gustaveson et al. 1979).

Natural Reproduction

Based on the literature (Bailey 1975), biologists stocking Colorado River reservoirs believed that most reservoir striped bass populations were not self-sustaining. Most thought that fingerling introductions would be required to support a continuing sport fishery. However, in the late 1970s, reports from Arizona and Nevada suggested that evidence of striped bass natural reproduction had been found. Striped bass reproduction in Lake Mead was first noted in 1973 and in every year since (Allan and Roden 1978). Possible spawning sites included areas where river current could suspend eggs and larvae, as the literature suggested, but spawning sites were also suspected in reservoir locations with minimal current. The Lake Mead analysis by Allan and Roden (1978) referenced an important but overlooked hatchery experiment conducted by Bayless (1968) confirming that "suspension of striped bass eggs by water current is not necessary for a successful hatch provided eggs are not subjected to suffocation by silt or water quality."

Evidence of striped bass natural reproduction in Lake Powell was first discovered in 1979 and annually thereafter. Initially, it was thought that reproduction was confined to the Colorado River above the lake where river current could suspend eggs and larvae. The spawning site was in or below Cataract Canyon, a 19-km gorge containing 23 sets of rapids. Striped bass apparently used less than 20 km of river above the reservoir because ripe striped bass adults were collected below but not above Cataract Canyon during spawning season (Persons and Bulkley 1982).

During spring 1979, striped bass spawning was discovered in the lower reservoir near the dam. In spring of most years, prespawning striped bass aggregated near Glen Canyon Dam. These fish seemed attracted to the current created as water was drawn through the dam penstocks. With time and warming, the aggregation left the 165-m-deep dam forebay and moved to nearby coves where spawning occurred. Most fish left the prespawning staging area simultaneously during early May as water surface temperature reached 16–19°C, which is the generally accepted peak spawning temperature range (Setzler et al. 1980). Spawning sites were located near the dam where floating masses of dead (unfertilized) eggs were clearly visible. J. D. Bayless (South Carolina Wildlife and Marine Resources Department, personal communication) found that unfertilized eggs would float but that immediately after fertilization, eggs would sink 0.3 m in 27 s. Settling rate slowed with time, but eggs still descended 0.3 m every 60 s some 24 h after fertilization (Gustaveson et al. 1984).

An oxygen-temperature profile taken in spawning coves near the dam showed oxygen levels of 8.4 mg/L near the surface and 13.2 mg/L on the substrate in 9 m of water. Siltation was insignificant in these coves on the rock and sand substrate during the brief 48-h incubation period (Hardy 1978). Thus, eggs settling on the bottom of Lake Powell had adequate oxygen for normal development.

Collection of larval striped bass 18–22 mm total length (TL) with midwater trawl and meter tow net samples confirmed successful reproduction of striped bass near the dam. The collected larvae were determined not to be derived from the river upstream of the reservoir. Prolarvae are capable of swimming at 4 d of age and could be expected to travel great distances if assisted by strong mainstream reservoir currents. However, studies of density currents using total dissolved solids as an indicator showed a weak density current in the reservoir that could not have assisted in moving larvae from the inflow any closer to the dam than 190 km (D. Merritt, U.S. Bureau of Reclamation, personal communication). Instead, striped bass larvae were captured 295 km downstream from the inflow. If spawning occurred only at inflow areas and larval fish were distributed by reservoir currents, then larval fish should have been found throughout the reservoir. In contrast, there was a preponderance of young striped bass at two distinct locations, the inflow and again at the dam. It was evident from these analyses that these young striped bass found near the dam were the result of successful in-reservoir spawning (Gustaveson et al. 1984).

Over the years, it has been confirmed that striped bass spawning occurs annually in Lake Powell, Lake Mead, Lake Mohave (Liles 1985), and Lake Havasu. Eggs and larval striped bass also pass through the dams to provide additional recruits to downstream lakes and canals as water is delivered from the Colorado River to locations in California, Nevada and Arizona (Stewart and Burrell 2013).

Population Dynamics

Initial growth of Lake Powell and Lake Mohave striped bass was comparable to other fast growing cohorts in the United States (Liles 1985; Gustaveson 1999). Striped bass spawning was first discovered in Lake Powell in 1979, and stocking was terminated that same year. Threadfin shad *Dorosoma petenense* the only pelagic forage fish in Lake Powell, were well established before striped bass were introduced, having been stocked in 1968 and 1969 to provide forage for reservoir centrarchids and the anticipated introduction of striped bass (Gustaveson 1999). By 1982, threadfin shad stocks were reduced, likely by predation from the rapidly growing striped bass population. From 1982 to 1990, pelagic shad remained in low abundance and were often eliminated entirely from open water, presumably by striped bass predation (Figure 2). Shad persisted in warm

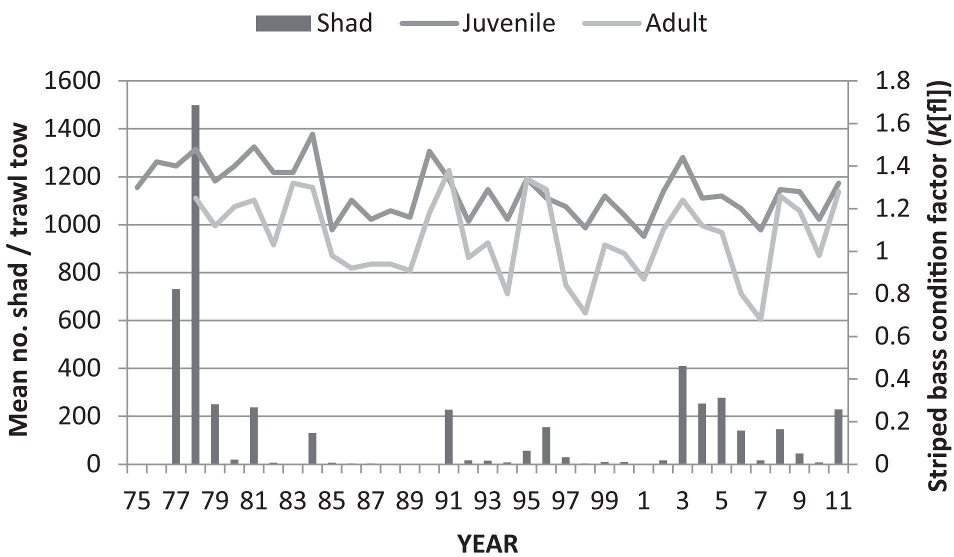

FIGURE 2. Pelagic shad abundance (vertical bars) compared to adult and juvenile striped bass condition, *K*(fl) (*K* factor based on fork length), 1976–2011, Lake Powell.

thermal refuges in turbid water in the backs of many canyons where striped bass foraging success was limited. Growth of striped bass decreased during periods of low forage (Gustaveson 1999). Adult striped bass suffered malnutrition while young striped bass maintained body condition on a zooplankton diet (Figure 2). As striped bass numbers peaked and forage fish abundance declined, back-calculated total length of each age-class declined 100–125 mm compared to lengths observed in the first 5 years of striped bass expansion. Striped bass were shorter and did not live as long, and some never gained sexual maturity. Most of the population was composed of immature fish 300–400 mm TL, which were as young as age 2 or as old as age 6 (Gustaveson 1999). When Lake Powell shad abundance increased in 2002, striped bass growth and condition immediately improved.

Striped bass condition (*K* factor based on fork length [*K*(fl)]) in Lake Powell (Gustaveson 1999) correlated with shad abundance (Figure 2). The initial expanding population (1975–1981) was consistently healthy, with *K*(fl) near 1.3 despite cyclical swings in shad abundance. Prior to striped bass establishment, shad exhibited a population peak every third year with two moderate production years in between. Shad population peaks in 1981 and 1984 resulted in high cohort survival, increased growth, and improved physical condition of striped bass. Condition of striped bass declined in 1982 and 1985–1989 to levels where adult fish were thin and juvenile fish smaller than expected.

Juvenile striped bass were able to maintain higher condition than adults partly because they occupied the same niche as shad in the warm epilimnion. When adult and juvenile striped bass competed for limited shad resources that were located in the pelagic epilimnion, smaller fish thrived while condition of adults declined. Adult striped bass preferred cooler temperatures and were forced into deeper, cooler water of the metalimnion and away from shad (Coutant 1985, 2013, this volume; Thompson and Rice 2013, this volume). Juvenile striped bass resided in and tolerated the warm surface layers. The ontogenetic separation of striped bass size-classes favored juvenile fish at the expense of adults.

Colorado River striped bass fisheries are thus characterized by a boom and bust cycle.

The initial stocked or naturally reproduced striped bass fed on abundant threadfin shad populations, grew rapidly with high condition factors, matured, and spawned. Shad populations then declined, and striped bass were less well fed. Spawning decreased when schooling adult striped bass with poor body condition probably were no longer able to produce viable eggs (similar to that observed by Coutant 1987 in Tennessee). Adult striped bass numbers declined in years of forage shortage, but a relatively small successful year-class was produced annually as a few females exceeding 10 kg spawned with young precocious males. These fast-growing females grew to larger size and were able to consume pelagic common carp *Cyprinus carpio* and sport fish of a size unavailable to the majority of schooling striped bass due to mouth gape limitations. Threadfin shad abundance eventually rebounded, allowing rapid growth, followed by spawning of the remaining striped bass.

Similar population swings were seen in each impoundment from Lake Powell to Lake Havasu. In most years, juvenile striped bass dominated the fish assemblage, with larger numbers of adults occurring on occasion. Lake Mohave has the best habitat conditions for a sustained population of larger adult fish in the upper lake, which is fed by the constantly cold oxygenated tailwater released from Hoover Dam (Stewart and Burrell 2013). Shad forage has been absent from Lake Mohave for the past decade, resulting in a striped bass population composed of fish less than 350 mm existing on plankton and trophy adults that forage on stocked rainbow trout and other fish species not available to smaller stripers. Fish size and condition fluctuates in Lakes Mead, Havasu, and Powell, depending on forage abundance during each particular year.

The unintentional introduction of gizzard shad *D. cepedianum* into Lake Powell in 2000 added an additional pelagic forage fish that may affect the boom and bust cycle. Gizzard shad were present in a load of largemouth bass from a federal fish hatchery in Texas, which were stocked into Morgan Lake, New Mexico. A thriving gizzard shad population was established and remains in Morgan Lake today (Knowles 2002). Some gizzard shad escaped into the San Juan River during flood events and moved downstream to Lake Powell. Gizzard shad apparently from Lake Powell were found in Lake Mead in 2008. This larger pelagic forage fish likely will pass through the dams and river system until it invades all Colorado River impoundments downstream from Lake Powell, which will in turn influence the predator–prey relationships for striped bass in each of these reservoirs. From the experience in Lake Powell, it appears that additional forage provided by gizzard shad will be advantageous to striped bass in forage-poor years and waters. Gizzard shad adults eat benthos and grow beyond the mouth gape of all but the largest stripers in the system. In 2009, for instance, gizzard shad added significantly to the forage base of Lake Powell. The ratio of gizzard shad to threadfin shad captured in midwater trawl samples was almost equal. How the boom-bust cycle will be affected in the Colorado River basin is unclear. Both threadfin and gizzard shad occupy many Southeast reservoirs where striped bass and striped bass hybrids currently thrive without such a boom and bust population cycle.

Management Implications

Striped bass were introduced into the Colorado River basin 50 years ago. Results differed from expectations of those who planned the introductions, both for population management via stocking and for development of a fishery for trophy-sized striped bass. Natural reproduction outpaced the planned stocking program. A few large trophy fish (20–27 kg) were taken shortly after the initial introductions but are now uncommon. Nonetheless, some striped bass exceeding 13 kg are still taken each year from the various impoundments.

More importantly, striped bass weighing from 1 to 2 kg are very abundant, depending on the lake and year, and provide a popular fishery. The trophy fish goal has been replaced by quality angling where many fish are caught. In Lake Powell, there is no striped bass creel limit, allowing those so inclined to harvest more than 100 fish per day (Figure 3). In Lake Mohave, there is no limit on striped bass less than 500 mm. Liberal creel limits exist in all Colorado River lakes. In years of low forage, creel survey catch rates exceeding two fish per hour are common. Management plans for such prolific populations that can overwhelm the forage base require maximizing harvest. Innovative plans to balance predator and prey numbers include liberal catch regulations combined with information dissemination to encourage more anglers to participate in harvesting striped bass.

There have been other inland locations where natural reproduction, either known in advance or unexpected, has dictated management plans for striped bass. The most well known are Lake Texoma (Texas and Oklahoma), John S. Kerr (Virginia and North Carolina), and the Santee–Cooper reservoirs (South Carolina) (Lamprecht et al. 2013, this volume). In each case, a fishery for young fish has predominated over a fishery for large, trophy-sized fish.

A Web page, www.wayneswords.com, is devoted to providing Lake Powell fishing and recreational information to the angling public. The goal is to provide detailed and timely information to Lake Powell fishers, allowing them to catch more fish, especially striped bass. As 3 million visitors come to Lake Powell each year, those that would not normally fish while enjoying a recreational trip are encouraged to try fishing. The Web site has been successful as evidenced by many fishers who have received fishing information and found it helpful. They are now submitting personal, successful fishing techniques and locations to the Web site, keeping the information current and broad-based. It is common for results of a successful fishing trip to be displayed on the Internet in a matter of hours. Arriving anglers with Internet or "smart phone" access can immediately use the

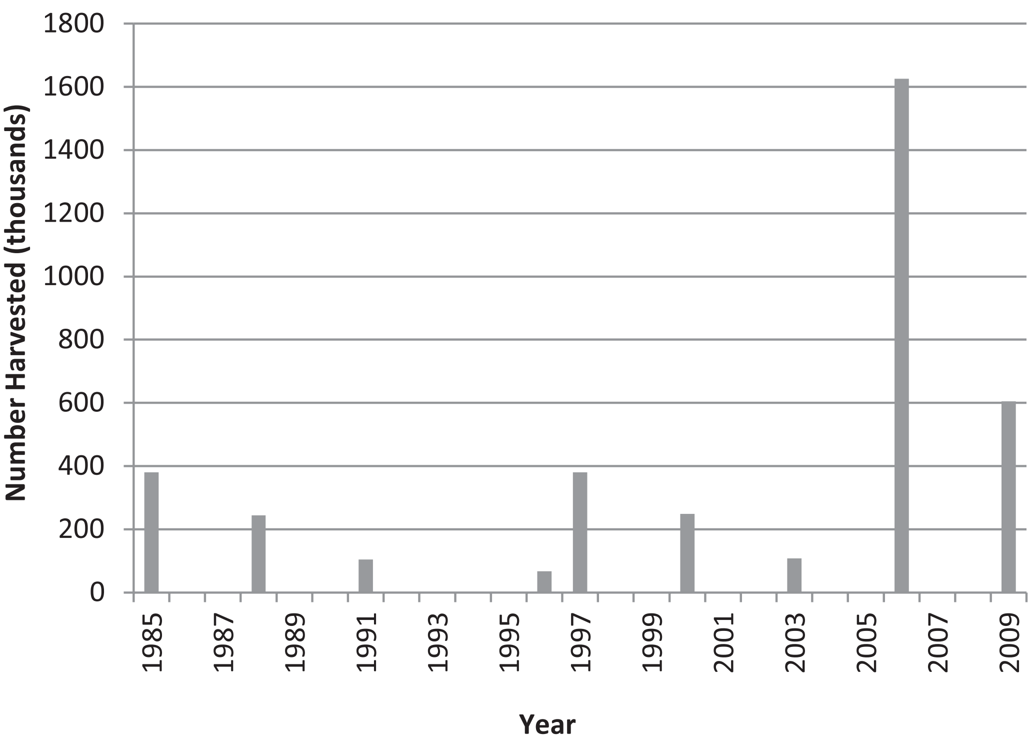

FIGURE 3. Angler harvest of striped bass in Lake Powell, Utah–Arizona, estimated by creel survey.

information about a hot fishing technique or location. In the age of catch and release elsewhere, the opportunity to "catch and keep" in Colorado River reservoirs is a bonus.

Anglers of all skill levels come from across the United States to harvest striped bass during times of high abundance. Colorado River reservoirs often have a mix of shad and striped bass schools in surface feeding events (striper boils) that are exciting to the fishing public and glamorous enough to entice nonfishers to join in the sport. The end result is increased harvest and license sales. At Lake Powell, harvest is limited only by the will of the angler to care for the number of fish caught. Since striped bass are often the largest fish ever caught by many anglers, the fishery is extremely popular. In 2006, 1.67 million striped bass were harvested (Blommer and Gustaveson 2007). Comparatively, in 2009, a high forage abundance year, harvest was estimated to be 700,000 striped bass at Lake Powell.

In summary, striped bass reproduce within the main stem reservoirs and the connecting Colorado River and its tributaries. Low nutrient loading provides adequate oxygen on the substrate for settling eggs to hatch. This makes striped bass populations within the Colorado River system nearly unique. Management of this prolific species must address adequate harvest to prevent stunting or death by starvation. Fisheries are cyclical with great population fluctuations. Predator populations periodically recover and rebound creating periods of low or high fish harvest, depending on prey population abundance. Fisheries vary but are generally classified as successful and highly sought after by those desiring a unique experience of fishing for a highly favored game fish in the incredibly beautiful red rock country of the desert Southwest.

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