Chapter 4

DIADROMOUS FISH

A State of Maine biologist cradles an American shad collected downstream of the Brunswick Dam fishway. While this fishway affords passage to other species, the design of the structure does not allow upstream migration of shad to historical spawning areas. Photo: J. Bartlett.

Before environmental alteration and overfishing reached peak levels, the Kennebec Estuary hosted annual diadromous fish migrations comprising millions of individuals. These runs fed local people, contributed to local economies, and provided nutrient and energy inputs into the estuary in ways that scientists are only beginning to understand. Despite notable advances in restoration and ongoing efforts toward that end, most fish runs persist only as fractions of their historical abundance. What factors have hindered recovery of collapsed migratory fish populations? How can our understanding of shifting environmental conditions and growing knowledge of ecosystem function contribute to a more complete restoration?

Introduction

The Kennebec and Androscoggin river complex was historically among the most important spawning and nursery habitats for diadromous fish in coastal New England (Taylor 1951; Squiers 1988; Bigelow and Schroeder 1953). Shortnose sturgeon (*Acipenser brevirostrum*), Atlantic sturgeon, American eel (*Anguilla rostrata*), blueback herring, alewife, American shad, rainbow smelt, Atlantic salmon (*Salmo salar*), and striped bass were known to migrate through the system in great abundance (Lichter et al. 2006; Saunders et al. 2006). Sea lamprey (*Petromyzon marinus*), Atlantic tomcod (*Microgadus tomcod*), and sea-run brook trout (*Salvelinus fontinalis*) are lesser-known members of the Kennebec's diadromous fauna. Historical spawning runs would have transported large quantities of nutrients and energy of marine origin far into the Kennebec and Androscoggin Rivers and their tributaries, possibly influencing complex food web processes (Durbin et al. 1979; Naiman et al. 2002). Consequently these runs, especially those of the river herring (i.e., blueback herring and alewife), may have had considerable influence on ecosystem function and services; however, with environmental alteration and overfishing, most diadromous fish populations in the Kennebec Estuary and across New England collapsed. Even with recent restoration successes, which include the removal of major dams such as the Edwards in Augusta, the functional role of affected fish populations probably remains much diminished and in some cases entirely inconsequential. In the sections that follow we discuss species that represent the primary targets of restoration efforts, challenges to those efforts, and the implications of choosing restoration targets that may fall short of full recovery.

Species Accounts

The Sturgeons

Sturgeon were among the first fish species to be commercially harvested in the lower Kennebec. In 1628 Thomas Purchase, one of the first settlers of the region, began harvesting sturgeon and salmon at the base of Pejepscot Falls in Brunswick for sale in foreign markets (Wheeler and Wheeler 1878). Declining sturgeon populations in the Kennebec Estuary preceded the general pattern of decline observed along the northeastern seaboard (described in Gilbert 1989), perhaps as a result of patterns in this region of early settlement, commercial fishing, and industry reliant on water power.

Atlantic sturgeon was thought to historically spawn in the Kennebec River between Augusta and Waterville (Squiers 1988), but construction of the dam on the Kennebec River at Augusta in 1837 blocked access to this spawning habitat. In 1849 approximately 160 tons of sturgeon were caught; two years later the fishery had largely collapsed (Atkins 1887). The delayed, but precipitous response to loss of spawning grounds and overexploitation was probably a result of sturgeon's protracted sexual maturation, which in the North Atlantic can take up to 34 years (reviewed in Gilbert [1989]). Attempts to revive the commercial fishery in the 1870s failed after some limited initial "success" that probably drove the remnant population to commercial and functional extinction (Lichter et al. 2006). Increasingly poor water quality in the Kennebec probably hindered sturgeon recovery, particularly Atlantic sturgeon, until improvements allowed the remnant population to rebound (ASSRT 2007; L. Flagg, personal communication).

Shortnose Sturgeon

Shortnose sturgeon is a federally listed Endangered species that occurs throughout the estuarine complex formed by the Kennebec, Androscoggin, and Sheepscot Rivers (NMFS 1998). The species was first

Maine DMR Biologists haul a catch of shortnose sturgeon on tidal flats of the lower Kennebec Estuary. Photo: J. Bartlett.

granted federal protection by the USFWS in 1967 under the Endangered Species Preservation Act (32 FR 4001) and was later protected under the Federal Endangered Species Act in 1973 (Squiers and Smith 1979). Shortnose sturgeon from the Kennebec Estuary complex are recognized by the National Marine Fisheries Service (NMFS) as one of 19 distinct population segments (DPS) from 25 river systems located along the east coast of North America ranging from the Saint John River in New Brunswick, Canada, to the St. Johns River in Florida, U.S.A. (NMFS 1998).

Relatively long-lived (> 60 years), shortnose sturgeon are slow to reach sexual maturity (8–11 years), particularly in northern portions of their range (Dadswell et al. 1984; Bain et al. 2007). In the Androscoggin River, adult shortnose sturgeon migrate from the lower estuary into fresh waters to spawn when water temperatures reach 6–8 ºC (42.8–46.4 ºF), usually in May (Dadswell et al. 1984). Spawning grounds include on the Androscoggin River below the dam at Brunswick, on the Kennebec River near Gardiner, and possibly in the Cathance River (NMFS 2003*a*). Eggs are laid in areas with high flows over gravel or rubble bottoms (Dadswell et al. 1984; NMFS 1998). In most rivers juvenile shortnose sturgeon are often found near the saltwater–freshwater interface, generally moving upstream during the spring and summer and downstream in the fall and winter (NMFS 1998). Adults have been observed foraging at the entrance to the Sasanoa River and in the Kennebec River below Bath (NMFS 2003*a*). Nearby, they also forage in the tidal mud flats of Montsweag Bay (18–25 ppt salinity) (McCleave et al. 1977) and use tidal channels of varying depths, vegetation characteristics, and salinities (0–21 ppt) (Squiers and Smith 1979; Squiers et al. 1981). Overwintering areas have been identified in the Kennebec River above Bath near Day's Ferry and in the channel east of Swan Island (NMFS 2003*a*).

Shortnose sturgeon have been thought to remain in their natal estuaries throughout their lives and have not been observed to make the long offshore migrations required for genetic flow among estuaries

(Dadswell et al. 1984; Kynard 1997; Bain et al. 2007). Based on analysis of mitochondrial DNA, shortnose sturgeon from the Kennebec River appear to be genetically distinct from sturgeon in 10 other river systems along the east coast of North America (Walsch et al. 2001; Wirgin et al. 2005). These findings suggest that there may be little gene flow among adjacent populations of shortnose sturgeon, although capture of Penobscot-tagged sturgeon in the Kennebec demonstrates some recruitment from systems outside of the Kennebec Estuary (Fernandes 2008). If immigration of individuals from other systems is only incidental, management of the species may require the maintenance or enhancement of populations within individual watersheds.

The Kennebec Estuary's shortnose sturgeon population is thought to be the largest in Maine and appears to be among the healthiest over its geographic range (Squiers et al. 1982; Dadswell et al. 1984; NMFS 1998; Bain et al. 2007). Population estimates made by MDMR in the late 1970s and early 1980s suggested that between 5,000 and 11,000 (mean 7,222) sturgeon inhabited the estuary (Squiers et al. 1982). Early 1990s capture rates of shortnose sturgeon below the dam at Brunswick were the highest recorded for this sampling area, suggesting that the Androscoggin River population may have increased since it was last surveyed over a decade earlier (Squiers et al. 1993; NMFS 1998).

Based on mid-19th century landings, estimates of sturgeon numbers (not distinguished by species) suggest that a total of over 10,000 individuals of all age classes used the Kennebec Estuary (KRRMP 1993), a value close to the 1980s population estimate for shortnose sturgeon alone. Apparent increases in shortnose sturgeon abundance in the Kennebec Estuary may reflect improvements in water quality over the past 20 years (Lichter et al. 2006) and, to a lesser extent, federal protection under the U.S. Endangered Species Act that prompted heightened management attention (L. Flagg, personal communication). Hudson River shortnose sturgeon populations have increased more than 400% in the last 30 years, apparently in response to improved water quality and protection measures afforded by the Endangered Species Act (Bain et al. 2007). The shortnose sturgeon is currently undergoing an NMFS status review slate for completion this year.

In the northeastern United States, dams are believed to have restricted upstream movements of shortnose sturgeon in most rivers inhabited by the species (Kynard 1997). The location of dams in the Kennebec Estuary potentially facilitated recovery of shortnose sturgeon in this system. The first dam on the Androscoggin River at Brunswick was built in 1753 and since 1815 there has been a permanent dam at that site (Lichter et al. 2006). Before the dams were constructed, however, a series of falls already restricted upstream movement of shortnose sturgeon. The first dam on the Kennebec River was built at Augusta in 1837 (Lichter et al. 2006), but spawning downstream of that site has been observed. Consequently, relatively uninterrupted access to some spawning grounds has preserved persistent native populations and apparently benefited shortnose sturgeon recovery efforts.

Atlantic Sturgeon

In contrast to shortnose sturgeon, adult Atlantic sturgeon spend most of their lives in the ocean, returning to freshwaters every 1–5 years to spawn (Dadswell 2006; ASSRT 2007). Spawning migrations for northern populations typically begin in the late spring and early summer (Bigelow and Schroeder 1953; Squiers et al. 1981; ASSRT 2007) and spawning is thought to occur between the head-of-tide and fall line of large coastal rivers in relatively deep water (> 10 m or 33 ft) over hard substrates (Gilbert 1989; ASSRT 2007). After hatching, larvae move downstream toward more saline portions of the estuary. Juvenile Atlantic sturgeon typically remain in the mesohaline (5–25 ppt salinity) region of an estuary for 1–12 years (Dadswell 2006; ASSRT 2007). Subadults ultimately move to coastal waters where they often undertake long migrations, mixing with sturgeon from other rivers before returning as adults to their natal estuaries to spawn (Dadswell 2006; ASSRT 2007). Atlantic sturgeon in northern populations typically take from 18–34 years to become reproductively mature, significantly longer than the shortnose sturgeon (reviewed in Gilbert 1989).

The Atlantic sturgeon is currently considered a candidate species for listing as threatened or endangered under the Endangered Species Act and is listed as a species of concern by the NMFS (NOAA 2008*b*). Atlantic sturgeon from the Kennebec Estuary have recently been recommended for inclusion in a Gulf of Maine DPS by the NMFS Atlantic Sturgeon Status Review Team (ASSRT 2007). The proposed Gulf of Maine Atlantic sturgeon DPS extends from the Merrimack River in Massachusetts to the Penobscot River. Most subpopulations associated with distinct rivers within each DPS also appear to be genetically isolated, suggesting strong breeding-site fidelity among reproductive adults (ASSRT 2007). Currently all states and the NMFS have enacted bans on the harvest and possession of Atlantic sturgeon (ASPRT 2006). In 1998 the Atlantic States Marine Fisheries Commission (ASMFC) enacted a 20–40 year ban on the harvest of Atlantic sturgeon in order to promote the recovery of depleted stocks (ASMFC 1998).

By the mid-19th century, at which time estimates put sturgeon of both species combined at 10,000 individuals (KRRMP 1993), sturgeon populations in the Kennebec Estuary had already been harvested commercially for over 200 years (Wheeler and Wheeler 1878). While no eggs, larvae, or young of the year Atlantic sturgeon have been found in the Kennebec Estuary within the last 15 years, the presence of ripe adult male and female sturgeon near the head-of-tide and the presence of subadults in the lower estuary and the tributaries of Merrymeeting Bay suggest that a spawning population persists (ASSRT 2007). Access to historical Atlantic sturgeon spawning areas does not appear to be restricted in the Kennebec, Androscoggin, and Sheepscot Rivers, but whether spawning occurs at all of these sites is unknown (ASSRT 2007).

Current threats to both Atlantic and shortnose sturgeon conservation in the Kennebec Estuary include habitat disturbance and uptake of persistent toxic contaminants (ASSRT 2007). Given the long life-

Survivors of a perilous journey that began in the Sargasso Sea, juvenile eels mass at the base of a derelict dam in an attempt to gain upstream access. Photo: T. Watts.

span of sturgeon, and the amount of time required to achieve reproductive maturity, these species are particularly vulnerable to accumulation of toxic contaminants associated with reproductive-developmental impairment. Sturgeon in the Kennebec Estuary may also experience habitat alteration and direct mortality associated with dredging operations (NMFS 2003*a*; NMFS 2003*b*; ASSRT 2007). Detailed studies focusing on seasonal movements, resource-use patterns, and habitat requisites of sturgeon are required to more fully characterize their sensitivity to habitat alterations (ASSRT 2007). Likewise, toxicological studies would help assess whether exposure to persistent bioaccumulative contaminants represents an important hindrance to recovery efforts.

American Eel

American eels have a broad geographic range (southern Greenland to northern South America) in addition to a unique life history (USFWS 2007). Adult eels spawn in the Sargasso Sea of the North Atlantic Ocean during the winter and early spring (MDMR 1996), after which they presumably die, though this has never been documented (USFWS 2007). Fertilized eggs hatch and develop into larval eels called leptocephali that are carried along ocean currents until they reach waters near the continental shelf . Once at the shelf, larval eels undergo a metamorphosis, their bodies transforming into the characteristic eel-like shape (Bigelow and Schroeder 1953). Commonly referred to as "glass eels" because they are initially very transparent, these juvenile eels arrive in coastal waters during the winter and spring (MDMR 1996) in great numbers, though densities can vary widely from year to year (USFWS 2007). With some growth and pigmentation, glass eels progress to the elver stage. These juveniles use a wide variety of habitats depending on how far upstream their movements extend (Bigelow and Schroeder 1953; USFWS 2007). American eels may spend 30 or more years in their juvenile habitats (Jessop 1987) during which time subadults are locally referred to as yellow eels. The sex of juvenile eels is not determined until they are somewhere between 3 and 24 years of age (Oliveira and McCleave 2000), during which a second metamorphosis called "silvering" occurs during the summer-fall period, which prepares the eels for their long migration to the Sargasso Sea to spawn (USFWS 2007).

An important food for Native Americans and early European settlers (Atkins 1887; MDMR 1996), eels were historically caught using weirs and pots during the autumnal seaward migration (MDMR 1996). Winter harvests relied on spearing eels through holes in the ice to capture eels that burrowed into muddy substrates (MDMR 1996). The eel fishery in Maine traditionally targeted silver stage and younger (yellow) eels (MDMR 1996). In

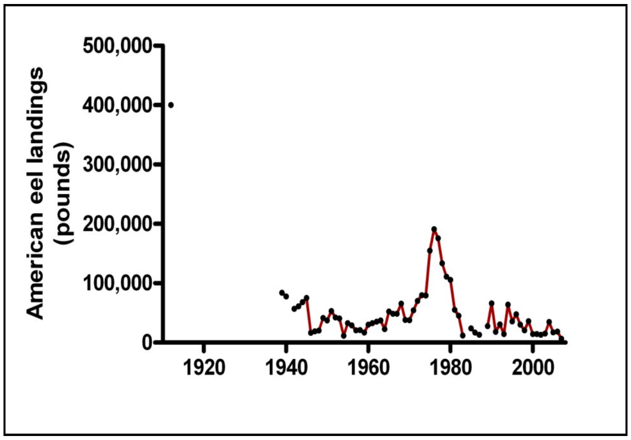

Figure 4-1. American eel landings for the state of Maine, 1914–2007. Gaps in the graph represent years for which no landings data were available. Data are from MDMR (1996, 2008*a*, 2008*b*).

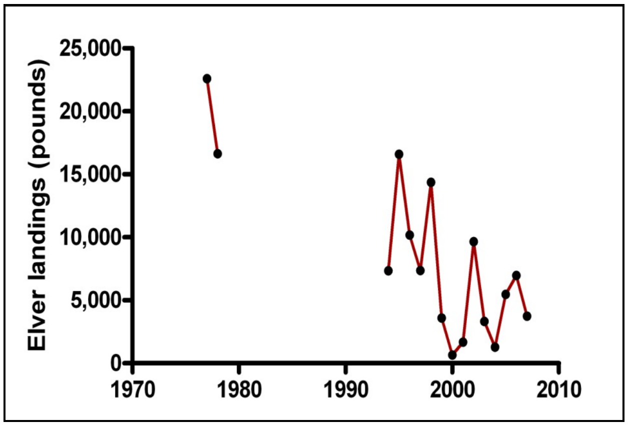

Figure 4-2. Maine elver landings, 1977–2007. Data from 1977 and 1978 are estimates compiled by the National Marine Fisheries Service and MDMR before formal data were collected for elver landings in 1994. Restrictions were placed on elver harvest beginning in 1999 (USFWS 2007). Adapted from MDMR (1996) and MDMR (2008*a*).

1912, 181.4 mt (400,000 lbs) of eels at the yellow and silver stages were harvested in Maine (MDMR 1996). In more recent decades the harvest of yellow and silver stage eels (Fig. 4-1) peaked in 1976 at 86.6 mt (191,025 lbs) (MDMR 2008*a*). In 2007, preliminary data suggest that 3.0 mt (6,532 lbs) of yellow and silver eels, valued at roughly $20,000 ($7.76/kg or $3.53/lb), were harvested in the state of Maine (MDMR 2008*b*).

During the 1970s (Fig. 4-2) and again in the early 1990s large numbers of elvers were harvested in Maine to provide the raw product for a lucrative Asian market that relies on the purchase of early juvenile eels for grow-out to adult size classes (MDMR 1996). Total elver harvests for the state in 1977 and 1978 were estimated to be 10.3 mt (22,600 lbs) and 7.6 mt (16,645 lbs), respectively (MDMR 1996). In 1995, 7.5 mt (16,599 lbs) of elvers valued at $3.82 million ($506.55/kg or $230.25/lb) were harvested in Maine (MDMR 1996). Some 20 years after the initial boom in the elver fishery, the state of Maine enacted legislation to limit harvests of glass eels and elvers by reducing the length of the fishing season and placing restrictions on fishing gear, fishing locations, and entry into the fishery (USFWS 2007). Preliminary data suggest that in 2007 1.7 mt (3,739 lbs) of elvers valued at about $1.3 million ($757.59/kg or $344.36/lb) were harvested in Maine (MDMR 2008*b*). Ecological concerns associated with this fishery include the potential for unsustainable bycatch of other species (smelt, alewife, trout, and salmon) that use the same small tributaries as elvers. Of course, the short-term incentive for overharvest is also a concern, given the landed value of elvers.

Some fraction of the juvenile eel population remains entirely in estuarine environments (USFWS 2007), where high primary productivity allows eels to grow faster and reproduce at younger ages (USFWS 2007). Apart from the experience of harvesters, little is known about American eel habitat use in the Kennebec Estuary. In surveys of the Kennebec and Androscoggin Rivers above Merrymeeting Bay, Yoder and colleagues (2006) found that American eels were most numerous on the Androscoggin River below the dam at Brunswick (175 individuals per km, or 282 per mi) and on the Kennebec River between Waterville and Augusta. In the Kennebec River upstream of the Lockwood Dam the abundance of American eels decreased to less than 100 per km, or 161 per mi (Yoder et al. 2006). On the Androscoggin River few American eels were collected above Lewiston-Auburn and none were collected above the Gulf Island Dam (Yoder et al. 2006). On the Kennebec River, American eels have been found as far upstream as Wyman Dam near Bingham (USFWS 2007).

Elvers have some ability to scale obstacles and can also exchange oxygen across their moistened skin, which facilitates climbing over or around barriers (USFWS 2007). Thus, unlike the case of other migratory fish, dams without formal fish passage do not always represent insurmountable barriers to upstream eel migrations (Yoder et al. 2006; USFWS 2007), and despite the presence of apparent barriers, eels often remain widely distributed throughout watersheds (Jacobs et al. 2004). Some barriers represent more of an impediment to upstream migration than others. On the Androscoggin River there are 12 dams between Merrymeeting Bay and Rumford Falls, which was believed to be the upstream limit of American eels in the Androscoggin watershed (MDMR and MDEP 2008). Although there is no specific design provision for upstream eel passage at the most seaward dam on the Androscoggin (Brunswick), some limited elver migration may yet occur (Yoder et al. 2006). Purpose-built changes to the Brunswick Dam allowing eel passage would require reopening the Federal Energy Regulatory Commission (FERC) license for the dam, which currently expires in 2026 (MDMR and MDEP 2008). On the Little Androscoggin River there are an additional five licensed hydropower projects that block access to traditional diadromous fish habitats. In the Kennebec River prior to 1999 there were 23 dams within the historical range of the American eel in the watershed (MDMR and MDEP 2008). The Edwards Dam at Augusta, the Madison Electric Works Dam, and the Fort Halifax Dam have since been removed (Hickey 2008; MDMR and MDEP 2008). As of 2007, upstream eel passage had been installed on 9 of the remaining 20 dams (MDMR and MDEP 2008).

Within hours of reaching their spawning grounds, river herring negotiate the last few miles of tea-colored waters in this shallow tributary to the Kennebec Estuary. Photo: Slade Moore.

Alewife and Blueback Herring

Alewife and blueback herring, often referred to collectively as river herring, co-occur in the coastal waters of eastern North America. Historically, alewife ranged from South Carolina to Labrador, Nova Scotia and Northeastern Newfoundland (ASMFC 2008). Blueback herring range from Nova Scotia and New Brunswick to Florida (ASMFC 2008). In Maine, both adult alewife and blueback herring enter coastal rivers between May and early June to spawn (MDMR 2008*d*). Although both species migrate upstream to spawn, alewife tend to reproduce in ponds, lakes, and slow-moving rivers, whereas blueback herring typically spawn in rivers and streams with more current (MDMR 2008*c*; ASMFC 2008). Adults of these species often spawn multiple times, with some individuals making spawning migrations as many as seven to eight times during a lifetime (Jessop et al. 1983; Richkus and DiNardo 1984). Both alewife and blueback herring eggs hatch in a matter of days after fertilization (ASMFC 2008) and most juveniles begin migrating downstream during their first summer and fall for their offshore movement (ASMFC 2008). However, in northern populations, some juveniles spend their first winters close to the mouth of their natal rivers (Marcy 1969). Females may take up to 5 years to mature, whereas males often mature earlier (3–4 years), though at a smaller size (ASMFC 2008; MDMR 2008*c*).

Maine rivers historically supported blueback and alewife spawning runs of impressive magnitude (Saunders et al. 2006). In the lower Kennebec and Androscoggin Rivers, these species were captured in fishing weirs (Foster and Atkins 1869), dip nets, seines, drift nets and set nets (MDMR 2008*c*). In the early 19th century on the Kennebec River near Clinton, up to 1.2 million individuals were harvested annually (Foster and Atkins 1869). Harvested primarily for human consumption in the 19th century (MDMR 2008*c*), alewife and blueback herring were either consumed fresh or preserved by smoking, salting or pickling (ASMFC 2008). During the 20th century, food markets for river herring declined, though demand grew for its use as fish meal, as a pet food ingredient, and as bait for commercial and sport fishing (Fay et al. 1983; MDMR 2008*c*).

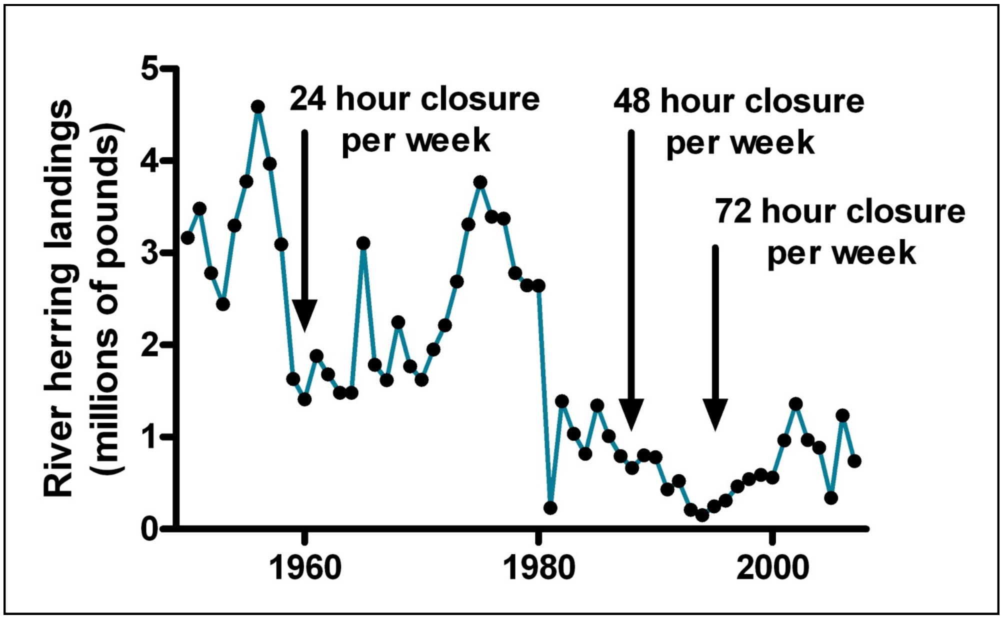

Figure 4-3. Maine alewife and blueback herring landings, 1950–2007. As landings continued to decline, progressively more stringent closure periods were implemented to allow passage to spawning habitats (MDMR 2008*c*).

Before the widespread construction of dams, blueback and alewife migrated as far as 191 km (119 mi) up the Kennebec River (Atkins 1887). The construction of dams during the 19th century on the Kennebec River at Augusta and on the Androscoggin River at Brunswick probably restricted access to much of the upstream spawning habitat. However, there was apparently adequate spawning habitat below these dams in the vicinity of Merrymeeting Bay to allow Kennebec Estuary fisheries to persist (Foster and Atkins 1869). Increasing industrial and municipal pollution in the early to mid-19th century caused these runs to become commercially extinct, but water pollution abatement in the mid 1970s, coupled with trap-and-truck stocking and improved fish passage, greatly enhanced these runs (L. Flagg, personal communication).

In recent years, commercial landings of blueback and alewife have fallen at both local and regional scales. Massachusetts, Rhode Island, Connecticut, Virginia, and North Carolina have closed their fisheries, presumably in response to declining stocks (ASMFC 2008). Maine harvests contributed an average of up to 61% of the total U.S. landings between 2003 and 2007 (ASMFC 2008). Total Maine landings in 2007 were 336.1 mt (740,900 lbs), a notable decline from the 1950s, when landings peaked at 2086.5 mt (4.6 million lbs) (Fig. 4-3; ASMFC 2008; MDMR 2008*b*; MDMR 2008*c*). Maine's fishery is managed by the MDMR and municipalities that have been granted harvesting rights (MDMR 2008*c*). Beginning in the 1960s, local fisheries were closed during the run for one to three days each week to allow passage of fish to spawning habitats; since 1995 fisheries have been closed for 72 hours each week of the run (MDMR 2008*c*).

Currently, MDMR restoration efforts for blueback herring and alewife in the Kennebec River watershed are focused on re-establishing access to traditional spawning grounds and on attaining annual production in the river segment above Augusta of 6 million individuals (MDMR 2004). Much progress has been made toward providing upstream access in the Sebasticook River basin, one of the major tributaries of the Kennebec River (MDMR 2007). In 2006, upstream anadromous fish passage was added to the Benton Falls and Burnham hydroelectric projects on the Sebasticook River. Combined with the removal of the Fort Halifax Dam in 2008, this means that anadromous fish have access to nearly 100% of the riverine and 43% of lacustrine habitat historically available in this drainage, creating the largest spawning and nurs-

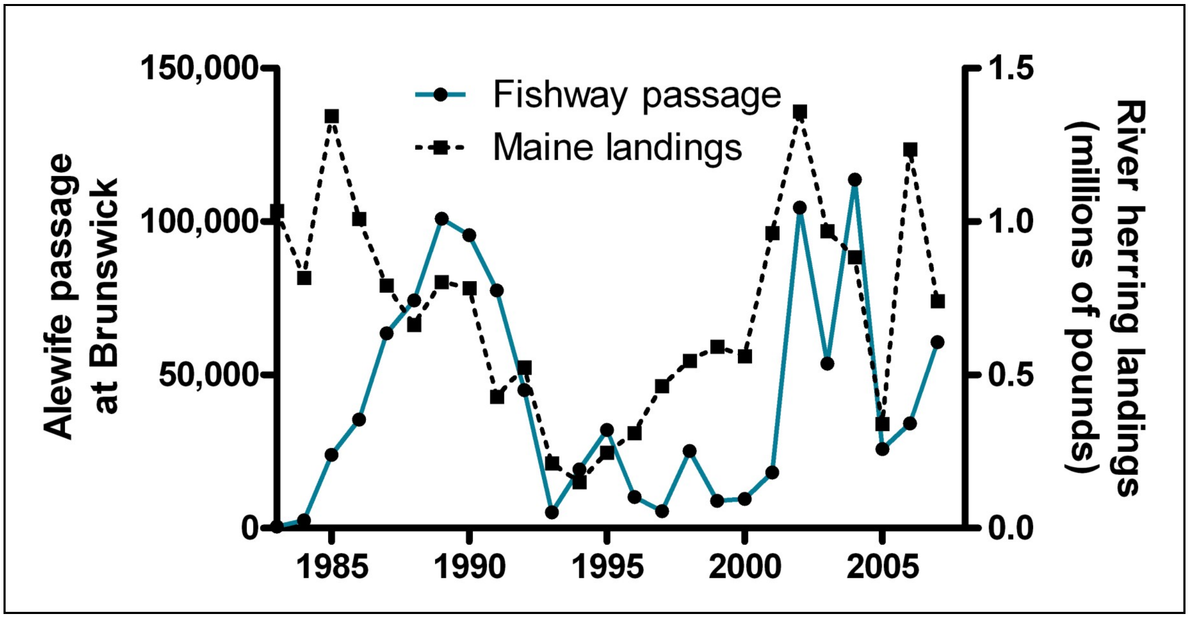

Figure 4-4. Alewife and blueback herring passage at the Brunswick Dam on the Androscoggin River, 1983–2007, and statewide landings during the same period. Data are compiled from Rushton et al. (1990); Brown (2003, 2004); Brown and Valliere (2005); Brown et al. (2006); MDMR (2008*c*).

ery habitat for alewife in the state (MDMR 2007). On the mainstem of the Kennebec River, a trap-and-truck project for blueback and alewife became operational at the Lockwood Dam in 2006 (MDMR 2007). In 2007, 3,448 adult individuals were captured and trucked upstream to stock Wesserunsett Lake and the Kennebec River at Fairfield (MDMR 2007). Between 4 May and 14 June 2008, 93,775 adult river herring were captured at the Lockwood facility (MDMR 2008*d*).

Some degree of fish passage on the Androscoggin River at Brunswick was reestablished in 1983 when a fish ladder was installed during construction of a new hydroelectric project at that site (Flagg 1988; Rushton et al. 1990). Between 1983 and 2007, 1,046,053 blueback and alewife passed through that facility. The number of fish using the fish ladder has varied considerably in the last 24 years with passage peaking at 100,895 individuals in 1989 and 113,686 in 2004 (Fig. 4-4). Between 1993 and 2001 passage was generally low, averaging 14,866 (range 5,202–32,002) fish per year (Rushton et al. 1990; Brown 2003, 2004; Brown and Valliere 2005; Brown et al. 2006; MDMR 2008*e*). Alewife that ascend the Brunswick fishway are trapped and distributed into otherwise inaccessible habitats blocked by upstream dams (Brown et al. 2006). The decline in passage at the Brunswick Dam during the 1990s is thought to have been related to the loss of landowner permission to access most upstream alewife stocking habitat (Fig 4-4) (M. Brown, MDMR, personal communication). Currently, only about 35% of the available upstream alewife habitat in the Androscoggin River basin is stocked (M. Brown, personal communication). However, young of the year alewife have been observed below the town of Durham suggesting that the trap-and-truck process at the Brunswick Dam is resulting in some upstream recruitment (Yoder et al. 2006). The notably sharp decline in passage in 2005 was thought to have been related to high river flows that prevented alewife from climbing or finding the downstream access to the fish ladder (Fig. 4-4) (M. Brown, personal communication).

American Shad

The Kennebec River formerly supported the largest shad fishery north of the Hudson River (Stevenson 1898; Taylor 1951). American shad traditionally migrated up the Kennebec River to Norridgewock Falls and up the Androscoggin River to the falls below Lewiston (Allen 1849; Taylor 1951; Brown et al. 2007). As with other species, much of what is known about past abundance of American shad is based on harvester accounts. Foster and Atkins (1869) recounted a story in which shad were so plentiful that a group of four men harvested about 6,400 large individuals below the falls at Waterville in one day. A single fishing weir at Abagadasset Point in Merrymeeting Bay caught between 3,000 and 10,000 shad annually in the 1820s (Stevenson 1898). Between 1826 and 1835 another weir operating in Merrymeeting Bay caught 6,000 shad annually (Stevenson 1898). Coarse population estimates based on shad harvests suggest there were as many as 2.25 million adult fish in the waters of Maine at the beginning of the 20th century (Flagg et al. 1976) and possibly 1.5 million in the Kennebec River (T. Squiers, MDMR, personal communication). This is probably a very conservative estimate of the historical abundance of American shad because by that time the widespread construction of dams throughout the state had already blocked access to many of their traditional spawning grounds for over 100 years (Taylor 1951; Flagg et al. 1987*a;* Brown et al. 2007).

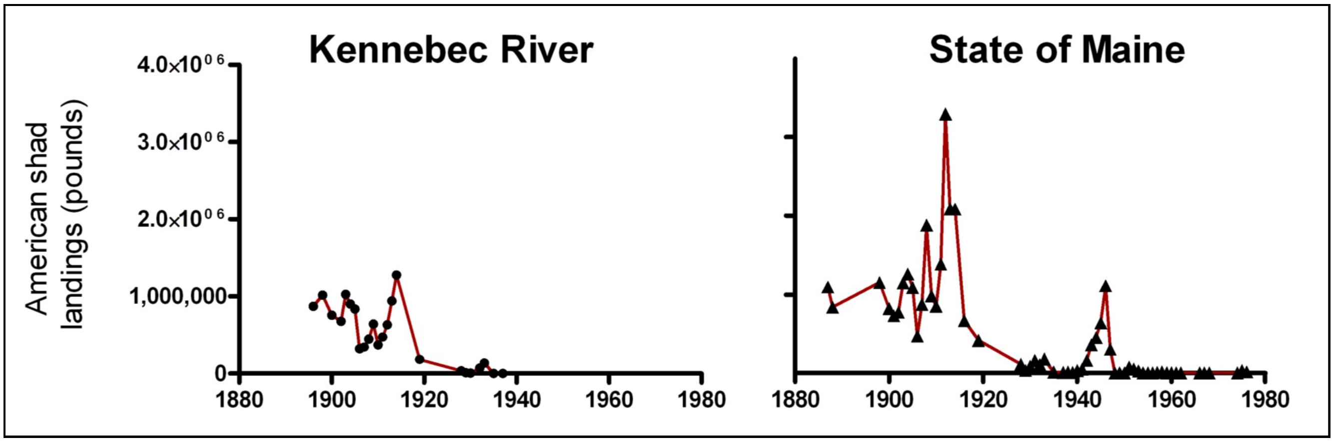

Figure 4-5. American shad landings in Kennebec, Lincoln, and Sagadahoc counties along the Kennebec River, 1896–1937, and in the entire state of Maine, 1887–1976. Adapted from Taylor (1951) and Flagg et al. (1976).

The dramatic impact of dams on local shad fisheries was nearly immediate and quickly recognized by harvesters. For instance, several years after a dam was built on the Sebasticook River near Benton in 1809, town selectmen dismantled the structure because "it had so impoverished the fisheries" there (Foster and Atkins 1869). In 1837, completion of the dam on the Kennebec River at Augusta blocked access to nearly half of the American shad spawning habitat in the river (Flagg et al. 1976). At various times fishways were constructed around this dam to facilitate shad passage, but none were particularly effective (Taylor 1951; Brown et al. 2007). A decline in the Augusta shad fishery was observed soon after the construction of this dam and by 1867 the fishery failed entirely (Atkins 1887; Foster and Atkins 1869). Despite the loss in spawning habitat above the Augusta dam, a shad fishery managed to persist in the lower Kennebec River into the 1920s (Taylor 1951), most likely because that river contained suitable spawning habitat (Stevenson 1898; Taylor 1951). During the late 1800s the most productive shad fishing grounds in the Kennebec were in the vicinity of Merrymeeting Bay where 77% of the estimated 140,000 American shad harvested in the Kennebec system were caught (Atkins 1887). During the mid-1800s the Eastern River fishery was particularly robust, with catches estimated at 100,000 shad annually (Stevenson 1898). By 1896 the total catch of American shad in the Kennebec River was 251,329 fish, with 81.7% of the catch made in weirs and the remaining 18.2% with drift nets (Stevenson 1898). On the Androscoggin River below Brunswick, 13,410 shad were harvested in 1896 (Stevenson 1898). At the turn of the century, the local economic impacts of this fishery must have been considerable, as the vast majority (84.3%) of harvesters were residents of Lincoln and Sagadahoc counties (Flagg et al. 1976).

A small fishery persisted in the Kennebec River into the early 1900s, but by 1920 most of the American shad harvest occurred offshore (Flagg et al. 1976). Statewide shad landings peaked in 1912 at 1492.3 mt (3.29 million lbs) and two years later the Kennebec River fishery reached its apex at 576 mt (1.27 million lbs) (Fig. 4-5). Overfishing and water pollution are thought to have precipitated the long-term decline of the Merrymeeting Bay shad fishery after 1914 (Taylor 1951; Brown et al. 2007). Between 1933 and 1940, American shad were commercially extinct in Maine, but landings temporarily increased during the mid-1940s to a high of over 499 mt (1.1 million lbs), after which they crashed (Taylor 1951; Brown et al. 2007). The commercial harvest of American shad was not officially suspended until 1995, by which time landings for the entire state were less than 0.9 mt (1,991 lbs) (Brown et al. 2007).

American shad restoration in the Kennebec and Androscoggin Rivers currently focuses on providing improved upstream and downstream fish passage at dams, restricting recreational and commercial harvest, and stocking pre-spawn adults and fry into historically inhabited waters (Brown et al. 2007). In the Kennebec River basin, MDMR's goal is to restore shad in the mainstem as far north as Madison and in tributaries including the Sebasticook River, Sandy River, Seven Mile Stream, and Wesserunsett Stream (Brown et al. 2007). Assuming a 10% mortality rate during the downstream migration at each hydropower plant, these waters have the collective potential of supporting 519,759 adult shad, or 34% of estimates for the early 20th century population (Brown et al. 2007; T. Squiers, personal communication). In 2007, roughly 8 million shad larvae reared at the Waldoboro shad hatchery were released into the Kennebec River below the Shawmut Dam; an additional 422,518 were released in the Sebasticook River in the Burnham head pond (MDMR 2007). That same year, a fish lift at Lockwood dam on Kennebec River near Winslow captured and passed 18 adult American shad (MDMR 2007). In 2008, no American shad had passed through the Lockwood facility (MDMR 2008*d*).

The American shad recovery goal for the Androscoggin River is to restore the species as far upstream as Lewiston Falls and to Biscoe Falls on the Little Androscoggin River (Brown et al. 2007). Estimates suggest that the Androscoggin drainage could support 235,000 adult shad annually (Lary 1999), but stocks are currently very low in the Androscoggin (Brown et al. 2007) because shad passage at the Brunswick dam is so poor. Video surveillance and radio telemetry studies conducted at and near the dam suggest that shad congregate in the river below the fishway, but most do not move into it (Brown et al. 2007), and those that do rarely accomplish passage (Brown et al. 2007). Between 1983 and 2006, fewer than 100 American shad successfully passed through the Brunswick facility; in 2007, 6 shad accomplished passage (Brown et al. 2007; MDMR 2008*e*).

Some limited shad reproduction occurs below the first barrier to upstream migration in Brunswick, as evidenced by eggs that were collected in 2005 and 2006 (Brown et al. 2007; J. Reblin, personal observation). Because so few spawning adults gain unaided access to river reaches above Brunswick Dam, MDMR initiated a stocking program for that portion of former shad habitat. In 2007, 201 adult shad from the Merrimack River and approximately 722,000 shad fry from the Waldoboro shad hatchery were released into the Androscoggin River (MDMR 2007).

Rainbow Smelt

Anadromous populations of rainbow smelt range in eastern North America from eastern Labrador and the Gulf of St. Lawrence to the Delaware River (NOAA 2008*c*). Adult smelt typically remain in shallow coastal waters or estuaries throughout the summer months and move upstream or into estuaries to overwinter

(Buckley 1989; Collette and Klein-MacPhee 2002). During the early spring, adult smelt migrate upriver to spawn in shallow habitats, often near the head-of-tide over coarse substrates (Bigelow and Schroeder 1953). In coastal populations most smelt, particularly females, move diurnally between spawning habitats at night and the estuary during the day (Buckley 1989). Individual smelt can spawn in several different streams during a spawning season (Rupp 1968; Murawski et al. 1980). After eggs hatch, larval smelt are transported throughout the estuary by tidal currents (Buckley 1989). As juveniles grow, they move into the lower estuary and nearshore coastal areas until fall, when they join adults in the upper estuary to overwinter (Buckley 1989). Juvenile smelt typically mature after two years (Bigelow and Schroeder 1953).

The widespread construction of dams and the pollution of coastal river systems probably had less effect on rainbow smelt than on other anadromous species (Dow 1972; KRC 1987). By spawning in early spring coincident with periods of high runoff, smelt temporally avoid the freshwater reaches of rivers during the summer months when water quality is poorest (Dow 1972; MDEP 1979). By early summer, adult and young of the year smelt are in or moving toward the lower estuary (Buckley 1989) where water quality is typically better owing to dilution with cleaner marine waters. Dams built above the head-of-tide would probably have had little impact on smelt because they typically do not spawn much farther upstream than those reaches (Buckley 1989). In the Kennebec, smelt were thought to have historically migrated up the Kennebec River only as far as Ticonic Falls in Waterville (KRC 1987). While the construction of the dam at Augusta in 1837 would have blocked access to some habitat in the Kennebec River, there was still a significant amount of spawning habitat in the river below Augusta and in the tributaries of Merrymeeting Bay to support breeding requirements. On the Androscoggin River the site of the first upstream dam was at Pejepscot Falls at Brunswick, which would probably have barred access to migrating smelt.

At the beginning of the 1800s, the smelt fishery in Maine and associated markets was small (Squiers 1988). In the latter half of the century the fishery expanded and supplied markets as far away as New York City (KRC 1987). In 1887 and 1888, over 544 mt (1.2 million lbs) of smelt were harvested in Maine (Bigelow and Schroeder 1953). In the Kennebec River, three smelt fishing areas alone produced over 52.6 mt (116,000 lbs) in one season during the late 1880s (Atkins 1887). The Kennebec River fishery used hook and line, small gill nets, bag nets, and weirs (KRC 1987). During the winter of 1879–1880, harvesters used 114 of these bag nets between Bath and Richmond (KRC 1987). Hook and line methods were used in Hallowell, Gardiner, in the tributaries of Merrymeeting Bay, and in the Sasanoa River (Squiers 1988). By the late 1880s, the smelt fishery had become the most valuable fishery in the Kennebec (Atkins 1887). As late as 1945, smelt landings for the state approached 453.6 mt (1 million lbs) (Bigelow and Schroeder 1953). Currently the lower Kennebec and Androscoggin Rivers support a winter recreational fishery for rainbow smelt, and between Randolph and Merrymeeting Bay nine commercial smelt camp operators provide ice-shack rentals for winter hook and line fishing (MDMR 2008*f*). Despite the apparent resilience of smelt to human-induced habitat changes, the dearth of information necessary to adequately assess their populations has in recent years led the NMFS to the precautionary action of listing smelt as a species of concern (NOAA 2008*c*).

Atlantic Salmon

Estimates suggest that during their spawning runs hundreds of thousands of Atlantic salmon once migrated up U.S. coastal rivers from Long Island Sound to the Canadian border (NRC 2004; Fay et al. 2006). The Connecticut, Merrimack, Androscoggin, Kennebec, and Penobscot Rivers all traditionally supported large populations of Atlantic salmon (Baum 1983; NRC 2004; Fay et al. 2006). Rough estimates by early fishery managers indicate that upwards of 200,000 salmon were harvested yearly in the Kennebec River during the early 19th century (Foster and Atkins 1869). However, over the last 150 years Atlantic salmon populations have experienced catastrophic declines (NRC 2004), to the extent that once-mighty runs have been reduced to a few fish each year.

The construction of dams has long been implicated in the decline of Atlantic salmon populations throughout New England (Foster and Atkins 1869; Fay et al. 2006; NRC 2004). Atlantic salmon historically migrated up the mainstem of the Kennebec River as far as the Kennebec Gorge below Moosehead Lake (Atkins 1887; Foster and Atkins 1869) and up the Androscoggin River to the falls at Rumford (Foster and Atkins 1869). Unlike American shad, which had some amount of suitable spawning habitat downstream of the Brunswick and Augusta dams, virtually the entirety of the Atlantic salmon spawning habitat in the Kennebec and Androscoggin Rivers was rendered inaccessible by dam construction except for short periods during which the dams were breeched (Foster and Atkins 1869). Damming of the Kennebec in

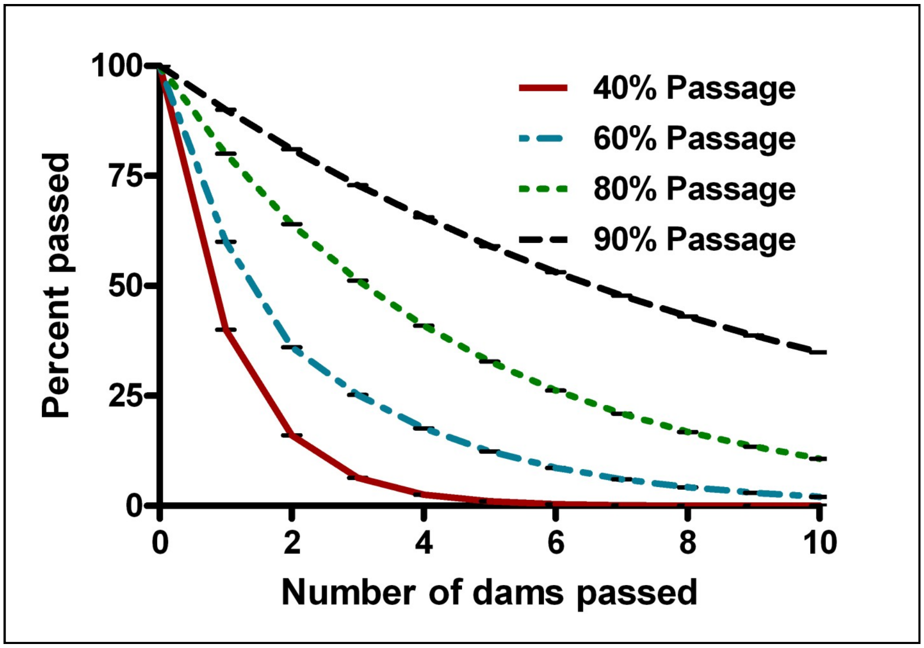

Figure 4-6. Model of the cumulative effects of upstream fish passage through a series of hypothetical dams with fish passage efficiencies between 40 and 90%. In the Kennebec River, 50% of the available salmon habitat lies above six dams.

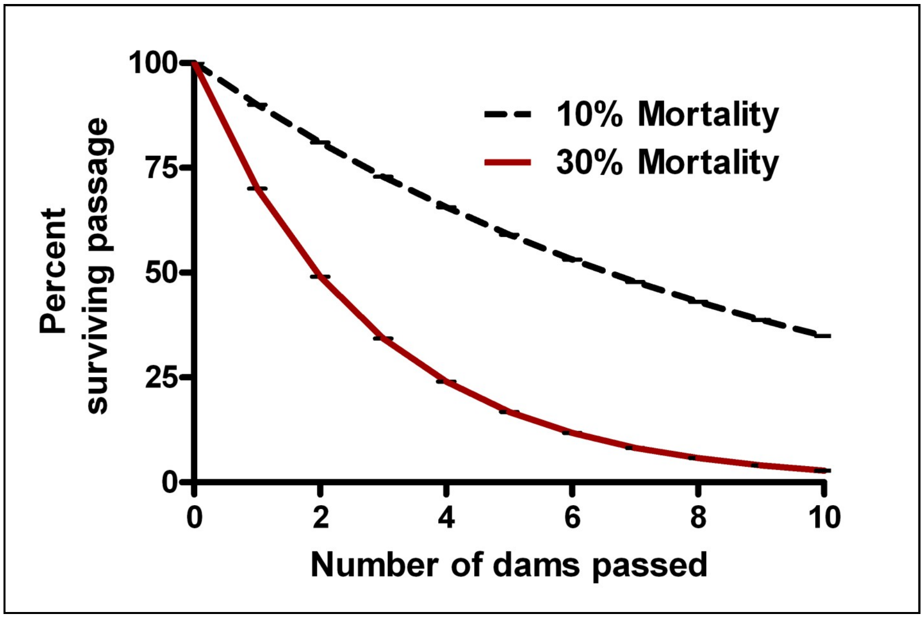

Figure 4-7. Model of the cumulative mortality of fish during downstream passage through dam turbines, assuming survival rates or 70% and 90%, according to EPRI (1992).

Augusta had immediate impacts on Atlantic salmon populations (Taylor 1951; Lichter et al. 2006). In the year following construction, fishermen reported paltry harvests that degraded precipitously over the next few decades (Foster and Atkins 1869). At Rumford Falls on the Androscoggin River, no Atlantic salmon were observed in the years following downstream construction of the dam at Brunswick (Foster and Atkins 1869). Upstream of these dams, many others were subsequently constructed on tributaries of the Kennebec and Androscoggin Rivers to facilitate log drives (NRC 2004). By the middle of the 20th century, nearly all of the significant salmon rivers in Maine had at least one impassible dam (Fay et al. 2006).

During the same period when dams were being installed on the Kennebec and Androscoggin Rivers, Maine was subject to widespread deforestation (NRC 2004). Land clearance practices during this period caused increased sedimentation, nutrient loading, elevated stream water temperatures, and altered stream flow regimes (NRC 2004). It is also likely that spring log drives had devastating effects on stream ecosystems (NRC 2004). Lumber mills along the rivers discarded their wastes, including sawdust and bark, directly into the rivers, which reduced water quality (Foster and Atkins 1869; Taylor 1951) and caused "drifts" so great that they filled fishing weirs to a depth of several feet (Stevenson 1898).

Overfishing also contributed to the decline of salmon during the 19th century (Fay et al. 2006). However, the earliest concerns about overfishing in the lower Kennebec and Androscoggin Rivers date to the late 18th century (Lichter et al. 2006) when residents of Brunswick petitioned the Commonwealth of Massachusetts to outlaw the use of seines, weirs, and dip nets in Merrymeeting Bay and its tributaries (Baxter 1916). Nevertheless, by the early 19th century, the lower Kennebec fishery employed at least 60 weirs, and 82 drift nets were counted in one day (Foster and Atkins 1869).

Today, dams are still implicated in Atlantic salmon declines worldwide (NRC 2004). Prior to 1999 there were 23 dams within historical Atlantic salmon range in the Kennebec River (MDMR and MDEP 2008). Removal of the Edwards Dam in 1999 made the Lockwood Dam at Winslow the first barrier to upstream salmon migration in the Kennebec River, blocking access to over 90% of habitat in the Kennebec's mainstem (Fay et al. 2006). By the spring of 2006, a fish lift, trap-and-truck process was initiated to facilitate salmon passage at the Lockwood Dam. A little over a year later, 16 migratory Atlantic salmon were captured at this facility (MDMR 2007). By virtue of this passage system, the Lockwood Dam became the only one of eight dams on the Kennebec's mainstem that allows upstream salmon passage (MDMR and MDEP 2008). In addition to passage at Lockwood, passage would also need to be established at five additional upstream dams (Hydro-Kennebec, Shawmut, Weston, Abenaki, and Anson) to achieve salmon access to more than 50% of the available habitat in the Kennebec River. Over 33% of the Atlantic salmon habitat in the Kennebec lies between the two uppermost dams on the mainstem (Fay et al. 2006). In the Androscoggin River, the three seaward-most dams have both upstream and downstream fish passage facilities, but nearly 90% of all suitable Atlantic salmon habitat is above the dam at Lewiston Falls, which does not allow fish passage (Fay et al. 2006).

It bears mention that installation of fish passage structures at dams does not ensure efficient passage of fish. On the Penobscot River, upstream fish passage efficiency for Atlantic salmon ranged from 44% to 90% for individual dams (reviewed in Fay et al. 2006). Suboptimal efficiency of passage at multiple dams can have significant cumulative effects on the number of salmon that ultimately reach upstream spawning habitats. For example, if in a series of three dams each dam had a passage efficiency of 80%, just over 51% of upstream migrating salmon would be expected to successfully pass all three dams in the series (Fig. 4-6). If the passage efficiency of those dams fell to 40%, less than 7% of the population would be expected to pass the same series of dams. On the Kennebec River 50% of the available salmon-rearing habitat is upstream of six dams (Fay et al. 2006). If each of those six dams had a fish passage efficiency of 90%, less than 60% of migrating Atlantic salmon would be expected to migrate past the most upstream dam (Fig. 4-6). Even if passage at the next five upstream dams were possible, with only 16 fish captured at

Lockwood in 2007, the outlook is bleak for salmon access to historical spawning habitat in meaningful numbers.

In addition to losses in fish passage efficiency during upstream migration, the downstream passage of salmon and other species through (and over) hydroelectric dams can result in significant mortality, with fish subject to grievous injuries from interactions with turbines or other equipment (Fay et al. 2006). Mortality associated with turbine entrainment for salmonids typically ranges between 10–30% of the population that passes through the turbines at each dam (EPRI 1992). Assuming a 10% mortality rate, if 100% of the total fish population passed through the turbines, just over 49% of a migrating population would be expected to survive passing through the turbines of 7 dams. However, with a 30% mortality rate, ~50% of the population would be killed after passing downstream through the turbines of just two dams (Fig. 4-7). For adult salmon migrating back to sea, rates of mortality passing through turbines may be higher because of their larger sizes (FERC 1997); however, Maine adult salmon tend to migrate downstream during the early spring when high flow conditions flood dam spillways and provide an alternate route of passage (Fay et al. 2006). Currently none of the hydroelectric dams on the Kennebec River have permanent, dedicated downstream passage facilities to circumvent fish interactions with turbines (Fay et al. 2006). By contrast, the three seaward-most dams on the Androscoggin River do have downstream fish passage facilities (Fay et al. 2006); however, passage at the Brunswick facility may be inadequate (Brown et al. 2007).

Concern over the impact of dam impoundments on the downstream migration of salmon smolts to the ocean has also increased in recent years (Fay et al. 2006; NRC 2004). Compared to water in free-flowing rivers, the water in these impoundments is generally slower moving, has altered water chemistries, and can become thermally stratified, disorienting smolts during migration (NRC 2004). These slow-moving waters can also increase the energetic costs of downstream migration and provide habitat for salmon

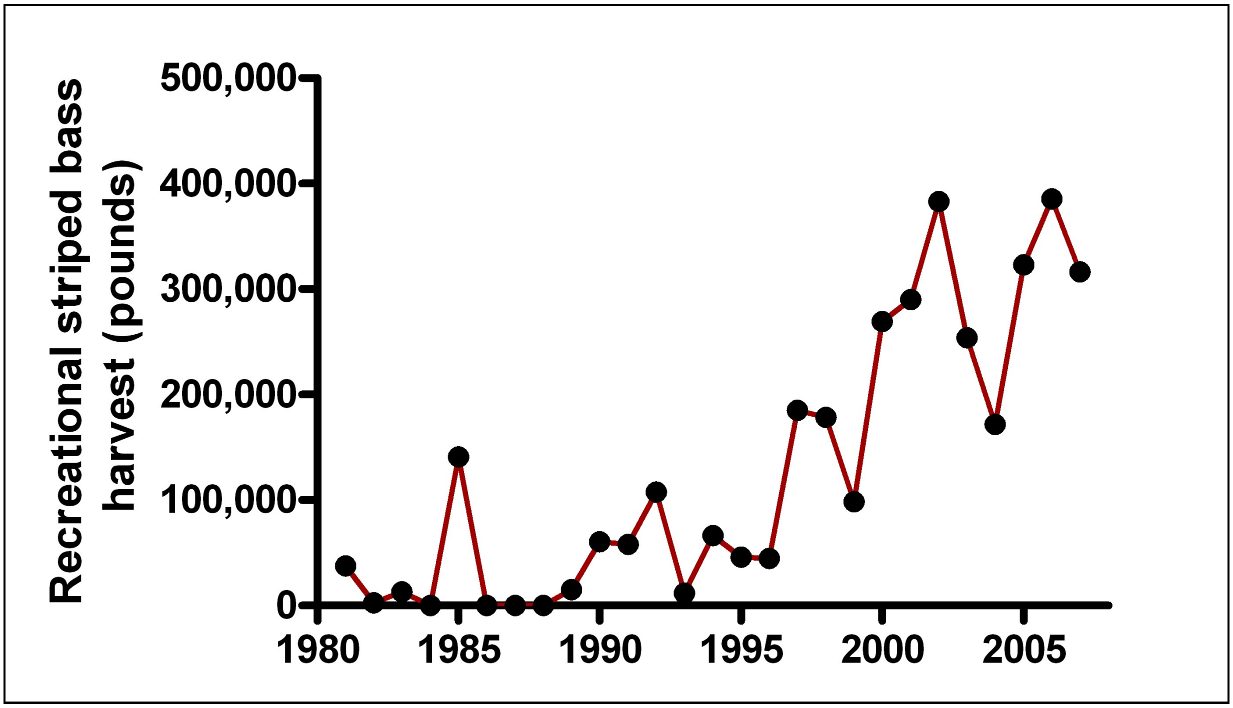

Figure 4-8. Estimated recreational harvest of Maine striped bass, 1981–2007. Adapted from NOAA Fisheries Statistics Division data reported in Meserve (2008).

predators and competitors (NRC 2004). Furthermore, migratory delays caused by increased passage time through impoundments can reduce the preparedness of smolts to enter the marine environment (Budy et al. 2002; McCormick et al. 1999).

Atlantic salmon is also one of several species in Maine waters that may be relatively sensitive to climate change. Among other factors, impacts to several life history stages as a result of increased water temperatures and seasonally lower base flows in streams have generated concern and in some cases have been demonstrated (Friedland et al. 2003; Hayhoe et al. 2007; Walsh and Kilsby 2007). This research emphasizes the need to assess the life history traits of salmon and other species in the context of vulnerability to projected climate-change-induced environmental shifts.

Striped Bass

Strong salinity gradients caused by high tidal ranges generally restrict the availability of spawning habitat for striped bass in most Maine estuaries, but low salinities north of the Chops in the Kennebec Estuary provided favorable spawning habitat for the species (Flagg et al. 1987). As a result, the Kennebec Estuary was historically the major production area for striped bass in the state of Maine (Squiers and Flagg 1991; Flagg and Squiers 1992). In the early 1800s, the striped bass harvest in Merrymeeting Bay often exceeded market demand for the species (Flagg et al. 1987; Flagg and Squiers 1992), with weirs capturing 0.5 mt (1,000 lbs) of striped bass in a single tide (Squiers and Flagg 1991). Young striped bass were routinely caught during the winter smelt and tomcod fisheries on the bay (Foster and Atkins 1869; Squiers and Flagg 1991), and in the Eastern River near Dresden so many striped bass were harvested as to "sink the ice on which they were deposited" during some winters (Foster and Atkins 1869). "Tons and tons" of striped bass were caught in one winter during this period on Winnegance Creek near Bath (Flagg et al. 1987*b*). The incidental catch of juvenile striped bass and the targeted winter fishery for adults suggests that the Kennebec Estuary historically provided overwintering habitat for a resident population (Foster and Atkins 1869; Atkins 1887; Squiers and Flagg 1991).

Striped bass were once found in the Kennebec River as far upstream as Waterville and into the lower reaches of the Sebasticook River (Foster and Atkins 1869), but the construction of the dam at Augusta in 1837 reduced the Kennebec River's available striped bass spawning habitat by about 50% (Flagg and Squiers 1992). Within a few decades, populations began to decline. By 1867, no striped bass had been caught for several years, leading fishery managers to surmise that the magnitude of the decline exceeded that of American shad and alewife (Foster and Atkins 1869). Despite the striped bass population collapse, a small winter fishery persisted in the Eastern River and in the nearby Sheepscot River into the 1920s (Flagg and Squiers 1992) until heavy industrial and municipal pollution was thought to have extirpated the native spawning population (Squiers and Flagg 1991). By the 1960s, surveys of the estuary failed to observe any striped bass (Flagg and Squiers 1992).

Exceedingly poor water quality persisted in the Kennebec River through the 20th century until implementation of the Clean Water Act in the 1970s (MDEP 1979; Lichter et al. 2006). In the early 1980s, after several years of sustained water quality improvements, the MDMR began efforts to restore striped bass populations in the river (Flagg and Squiers 1992). Between 1982 and 1991, a total of 263,735 juvenile striped bass were stocked in the Kennebec Estuary (Flagg and Squiers 1992) and in 1987, for the first time in nearly 50 years, young of the year striped bass were caught, demonstrating that natural reproduction was once again occurring in the estuary (Flagg and Squiers 1992).

Commercial landings of striped bass in the state peaked in 1909 at 50.7 mt (111,673 lbs) (Flagg et al. 1987*b*). Currently, there is no commercial striped bass fishery in Maine (Meserve 2008), but in the last 20 years a significant sport fishery for the species has developed. Since the late 1980s, the estimated recreational harvest of striped bass in Maine (Fig. 4-8) increased from 6.9 mt (15,221 lbs) in 1989 to 174.9

mt (385,598 lbs) in 2006 (Meserve 2008), representing 1.3% of the total recreational harvest of 13,314.8 mt (29,354,099 lbs) along the Atlantic coast that year (Meserve 2008).

With successful stocking efforts and much or all of the Kennebec's historical striped bass spawning habitat once again available to migrating fish, most work related to striped bass restoration focuses on monitoring the relative abundance of juveniles in the Kennebec River between the Sebasticook River and Phippsburg and in the Androscoggin River between the dam at Brunswick and Merrymeeting Bay (G. Wippelhauser, MDMR, personal communication). There are also plans to use telemetry to track the movements of tagged fish in the estuary (G. Wippelhauser, personal communication).

Ecosystem Implications

The spectacle of diadromous fish runs in the Kennebec less than 200 years ago can scarcely be imagined, for in our lifetimes there are few biological phenomena of such magnitude in the Gulf of Maine. In some ways, our unfamiliarity with historically superabundant fish runs prompts a lack of appreciation for their significance, leading us to perceive them as a surplus that contemporary ecosystems can do without. Yet emerging estuarine and aquatic science suggests that far from being an expendable overabundance, the huge size of these runs was probably integral to ecosystem function. Recent research in the mid-Atlantic indicates that anadromous fish runs currently influence ecosystems in numerous ways. Nutrients assimilated by anadromous fish in marine ecosystems contribute to the nutrient budgets of freshwater systems through excretion, gamete release, and the decay of fish carcasses (Garman and Macko 1998; MacAvoy et al. 2002).

In freshwater tidal systems of the mid-Atlantic, the timing of alewife runs and concurrent increases of marine-derived carbon in alewife predators (MacAvoy et al. 2002) suggests that diadromous fish are at least a seasonally important source of nutrition for predaceous fish. Research elsewhere suggests that other high-level piscivores, including terrestrial and avian predators, derive a similar benefit from annual fish migrations (Cederholm et al. 1999). The timing of these fish runs, which facilitated concurrent use of streams by different migratory species, may have allowed high densities of lower trophic forage species such as alewife to buffer the population-level effects of predation on young salmon (Saunders et al. 2006). It has also been suggested that restoration of inshore groundfish, once the backbone of the Gulf of Maine's commercial fishing industry and maritime culture, requires the recovery of forage species, particularly river herring (Ames 2004).

Conclusions

Achieving an integrated understanding of the complex history of human-induced environmental alteration, responses of diadromous fish species to those changes, and the co-evolved nature of aquatic and terrestrial communities represents a significant challenge to diadromous fish restoration efforts in the Kennebec and in Maine's other rivers. Since the late 20th century efforts to improve water quality, establish populations from transplanted stock, and promote increased access to spawning habitat have facilitated notable progress toward re-establishing historical fish runs. Yet success remains uneven across species. Where numbers are concerned, most runs still pale in comparison with those of the past.

In the absence of overfishing and water pollution, sturgeon populations have increased to levels apparently approaching those of the 19th century, by which time they had already been commercially exploited. Under current conditions, sturgeon may benefit most from research that identifies the species' seasonal movements and resource-use patterns to assess their sensitivity to environmental alterations such as those associated with dredging (ASSRT 2007). Given their relatively long lifespan and advanced age at onset of reproductive maturity, toxicological studies could provide indications of whether exposure to persistent bioaccumulative contaminants represents a significant hindrance to sturgeon conservation. Fishing mortality associated with bycatch of Atlantic sturgeon in ocean fisheries is also an area of concern (L. Flagg, personal communication).

Also benefiting from restoration efforts, striped bass have responded dramatically to a combination of water quality improvements, stocking programs, dam removal, and harvest regulations. The recreation striped bass fishery in the Kennebec currently supports landings >3 times more than those observed during the historical peak of commercial harvests. Most striped bass are thought to represent fish on feeding migrations (T. Squiers, personal communication), although there is some recent evidence of spawning in the estuary. Though greatly improved since mid-20th-century levels, breeding populations in the Kennebec have not apparently achieved historical abundances, which may be more a result of factors operating outside the estuary (T. Squiers, personal communication).

American shad present a somewhat different suite of challenges. Until about 1914, overfishing and water pollution probably led to the decline of the shad fishery in Merrymeeting Bay, shad's last stronghold in the Kennebec River (Taylor 1951; Brown et al. 2007), although dam construction was responsible for greatly limiting their upstream range and productivity. Early 1900s shad numbers may have been close to 1.5 million fish in the Kennebec River watershed (T. Squiers, personal communication). The population restoration goal for shad in the watershed above Augusta is currently 750,000 individuals, or about half of the estimated population using the entire Kennebec in the early 1900s (MDMR 2004). However, when habitat alteration (primarily blocked passage) and 10% downstream mortality are considered, the potential maximum shad production estimate for that portion of the watershed is ~480,000, or about a third of the estimated population size during the early 20th century (MDMR 2004). Under the Lower Kennebec River Comprehensive Hydropower Settlement Accord, permanent upstream passage is required no earlier than 2010 and can be triggered only by passage of 8,000 American shad in the interim trap, lift, and sort facility at Lockwood Dam (MDMR 2004). Currently, only several thousand shad use the Kennebec River each year and migrate only as far upstream as Lockwood, which few individuals successfully pass. There is little indication that shad numbers will grow sufficiently to trigger actions to improve passage without, among other factors, access to historical breeding habitat upstream of Lockwood. Shad in the Androscoggin above Brunswick have fared even worse. Despite an estimated annual habitat production potential of over 200,000 fish, few gain access to historical spawning habitat upstream of the Brunswick facility.

For alewife and blueback herring, the state's annual production goal is 6 million fish above Augusta. The Sebasticook watershed, which supports the most spawning habitat, is thought capable of producing an estimated 4.5 million fish annually. While recent annual runs to the Sebasticook drainage have exceeded two million fish (L. Flagg, personal communication), both river herring species require significantly improved access to large portions of their historical spawning habitat to achieve production goals.

More than 200,000 salmon were harvested each year on the Kennebec during the early 1800s. Despite a history of overfishing and benthic habitat degradation, it was 19th-century dam construction that eventually caused salmon populations to collapse. Today only a handful of fish migrate upstream through the first dams on the Kennebec and the Androscoggin Rivers, and lack of fish passage at upstream dams blocks access to the greater share of historical spawning habitat. Downstream mortality associated with dam turbines and other structures presents an added risk of salmon population erosion, and impoundments may hinder downstream migration of smolts.

Few data are available to put current American eel numbers in the context of historical populations. However, given the landed value of elvers, eel conservation may be threatened by the potential for overharvest if fishery control measures do not adequately restrict biomass removal. Additionally, several anadromous species (smelt, alewife, trout, and salmon) are vulnerable to unsustainable bycatch associated with the elver fishery. Concerns associated with turbine-induced mortality of out-migrating adult eels warrant close coordination between managers and dam operators. Also, the propensity of eels to carry high body burdens of persistent bioaccumulative toxic contaminants suggests the need to determine if these compounds are capable of inducing population-level effects.

The Kennebec River is currently rated as MDMR's highest fish passage restoration priority (MDMR and MDEP 2008). Yet several common challenges hinder restoration and conservation of most diadromous species native to the Kennebec Estuary, the most notable being the availability of unimpeded access to historical upstream spawning areas. Among other consequences, such as stream flow alteration, dams present a major impediment to upstream access, especially those with no provisions for fish passage. Of the licensed dams within the historical migratory range of diadromous fish in the Kennebec watershed, 12 lack upstream passage for eels, 7 lack upstream passage for the alewife-blueback complex, and 11 lack upstream passage for salmon (MDMR and MDEP 2008). These numbers do not include other barriers to passage such as improperly installed or designed road crossings over streams. Yet even with passage structures at dams, the ever-eroding fraction of the migrating population that successfully passes upstream suggests that design inefficiency may represent a persistent obstacle to restoration. Some species simply do not use fish passage structures (e.g., sturgeon, rainbow smelt, striped bass) and others cannot use some structures that are in place. Likewise, mortality of seaward-migrating diadromous species due to interactions with dam infrastructure (e.g., turbines) also represents an ongoing hindrance to passage.

On the Androscoggin, no special provisions for eel passage were made during relicensing of the Brunswick project. Although shad were a targeted species for passage at that site, they do not use the fish ladder in sufficient numbers to achieve a self-sustaining spawning population above the Brunswick dam (MDMR and MDEP 2008). Restoring fish passage on the Androscoggin is currently rated as only a "moderately-high" priority by MDMR in part because obtaining full passage at the Brunswick facility would require re-opening the license for that dam, which is not due for relicensing until 2026 (MDMR and MDEP 2008). Additional upstream dams in the Androscoggin mainstem that do not currently provide passage are not scheduled for relicensing until 2026–2048; those in the Little Androscoggin are scheduled for relicensing between 2019 and 2037 (MDMR and MDEP 2008). An anti-alewife sentiment among recreational anglers and conflicting objectives of the MDIFW have both been cited as hindering MDMR's alewife restoration efforts in the Androscoggin River.

Given the magnitude of resources expended on re-establishing diadromous fish runs in the Kennebec, the sensitivity of these species to climate change also warrants attention if conservation priorities and investments are to successfully reflect shifting environmental conditions. Overall restoration goals may also require reassessment in light of recent developments in estuarine science. The demonstrated nutrient and energy linkages within and between aquatic and terrestrial communities indicate that the superabundance of historical diadromous fish runs may have conferred manifold benefits to ecosystem function. The magnitude of these runs was also key to their support of fisheries that had considerable economic and food provisioning value.

Of course, it must be asked whether diadromous fish can be restored to their former abundance, and if so, would they contribute to ecosystem functioning in ways that mirror their likely historical role? Or, even with dramatic improvements in fish passage, would other system-wide environmental alterations—

including those associated with water quality, physical habitat changes, and aquatic community structure—hinder full recovery of stocks or ecosystem function? These questions and others can be answered most confidently through transparent and rigorous assessments necessary to unambiguously inform the policy decisions required to drive meaningful restoration progress. The involvement, cooperation, and stewardship of resource users also constitute critical components of equitable restoration efforts as evidenced by the success of the Penobscot Restoration Trust. Ensuring a focus on both ecosystem services and function requires the adoption of management principles that acknowledge the complexity of these systems. Ecosystem-based approaches can integrate adjustments to existing resource management systems by developing, implementing, and when necessary reevaluating multiple compatible objectives that address functional linkages between different aquatic taxa, their contributions to estuary-wide processes, their relationships to terrestrial systems, and the desires and needs of resource users, all within the context of the most appropriate geographic scale.