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New England's Rivers and Atlantic Salmon

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The Atlantic salmon *(Salmo salar)* is an anadromous fish native to the north Atlantic region. Adults feed and grow in the Davis Straits between Labrador and Greenland (Mills 1989), and migrate to coastal rivers between about 40° and 70° north latitude for reproduction (Netboy 1974). In the United States of America, Atlantic salmon originally occurred in at least 28 rivers (Fig. 1), from the St. Croix on the Maine-New Brunswick border to at least the Housitonic in Connecticut, and probably as far as the Hudson River in New York (Dunfield 1985). Estimates of populations range from 300,000 (USFWS) 1984) to 1.1 million fish (Dunfield 1985).

Shortly after Europeans settled in North America, salmon stocks began to decline from a combination of overharvest, blockage of access to spawning areas by dams and other obstructions, and degradation of water quality resulting from logging and agricultural practices and municipal and industrial wastes (Dunfield 1985, Netboy 1974, Stolte 1981). By the late 1940s to the early 1950s, the Atlantic salmon population of the United States consisted of only a few hundred fish returning to five rivers in Maine (Beland 1984). The Anadromous Fish Conservation Act was passed in 1965 to preserve existing stocks and to reestablish salmon populations in rivers

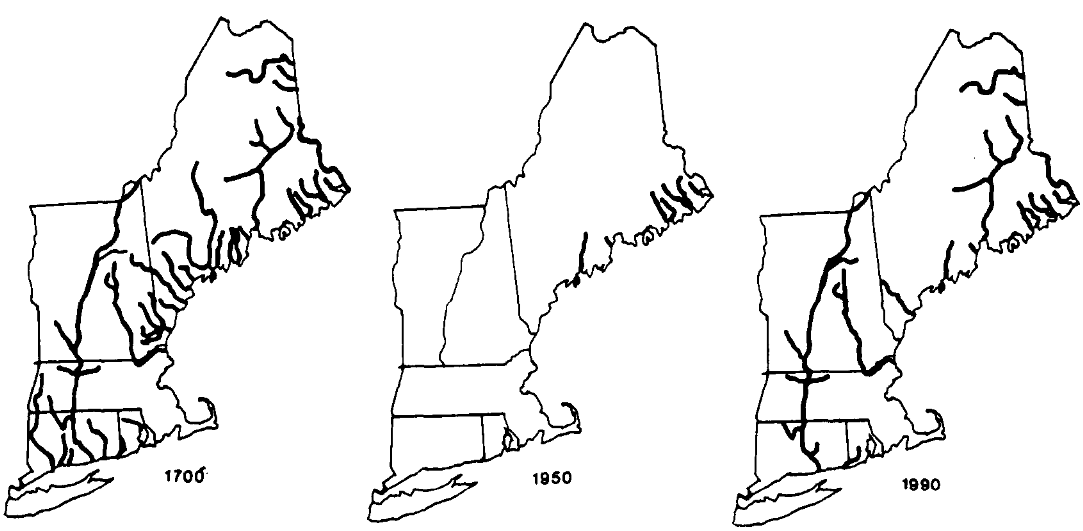

Figure 1. Atlantic salmon distribution in New England over time. Bold lines indicate rivers having populations of returning salmon. (sources: USFWS (1984), and A. Meister (personal communication).

where populations had been extirpated (USFWS 1984). After more than 25 years of recovery about 3,000 to 7,000 Atlantic salmon now return to 16 rivers in New England (Lewis 1991). Fewer than 1,000 of these are of wild origin and the remainder are from introductions of hatchery-reared parr or smolts (J. Marancik, U.S. Fish and Wildlife Service, personal communication). The continued recovery and existence of New England's Atlantic salmon population necessitates the presence of suitable environmental conditions for all life stages from returning adult to emigrating smolt. In this paper, I review the riverine habitat conditions Atlantic salmon require for survival and reproduction and the effects of human activities on these conditions.

Atlantic Salmon Life Cycle

The life history of Atlantic salmon was recently reviewed by Danie et al. (1983) and Mills (1989). After feeding and growing in the north Atlantic ocean for one to three years or more, most salmon (refer to Table 1 for terminology) return to their natal streams to reproduce. Salmon congregate in estuaries, bays, and river mouths in the early spring and then migrate up the rivers to the spawning areas, apparently following olfactory cues to locate these areas. Spawning takes place in mid-October to mid-November in gravel areas having moderate current. Individuals that survive spawning (kelts) either drop down stream immediately after spawning, or overwinter in the stream and migrate down stream the following spring.

Table 1. Terminology of Atlantic salmon life stages. Source: Allan and Ritter (1975).

Term	*Definition*
Embryo	From fertilization of egg to hatching
Alevin	From hatching to absorbance of yolk
Fry	From absorbance of yolk to dispersal from redd
Parr	From dispersal from redd to outmigration
Smolt	Fully-silvered juvenile migrating to the sea
Post-smolt	From departure from river to onset of wide annulus formation after first winter in the sea
Salmon	All fish from onset of wide annulus formation after first winter in the sea (grilse= one sea-winter salmon)
Kelt	Salmon from spawning until it re-enters the sea

Embryos develop in the gravel during winter and hatch in April to early May after 175 to 195 days of incubation. Alevins remain in the gravel for about six weeks after hatching and obtain nourishment from the yolk. Fry emerge from the gravel from mid-May to mid-June and disperse to nursery areas. After two to six years of stream residence, salmon parr undergo physiological transformation to the smolt stage, which is capable of survival in sea water. Smolts migrate down stream during spring and swim to the feeding grounds in the north Atlantic to continue the life cycle.

Mature Salmon

Once they have approached the freshwater environment, and possibly before, salmon are dependent on olfaction to find the proper migration route (Mills 1989). There is disagreement on the nature of the involved odors, but Stabell (1984) concluded that odors produced by the fish, themselves, pheromones, are most important. Pollution from copper and zinc mining halts upstream migration of salmon (Saunders and Sprague 1967), possibly by interference with odor reception. Experiments with Pacific salmon demonstrated that fish would home to the source of an organic chemical to which they had been exposed as smolts (Cooper et al. 1976). Whether this is true homing, the ability of artificial chemicals to modify homing behavior was demonstrated and raised the possibility that industrial and municipal wastes discharged into Atlantic salmon rivers could reduce homing and thus reproductive success.

Salmon are required to negotiate various obstacles along the length of the migration route and are capable of surmounting a vertical barrier of 2.5 to 3.5 m (8 to 12 ft) under favorable conditions. Fish ladders or lift facilities can allow fish passage around most dams, but fishway efficiency in passing Atlantic salmon varies widely. Efficiency has been estimated at 85 to 95% (mean 92%) for the Penobscot River, Maine, which is believed to be very significant for population status if the barrier is near the mouth of the river (J. Marancik, U.S. Fish and Wildlife Service, personal communication). Dams can also interfere with migration through reduction in water current. Adult salmon are rheotactic and require a minimum stream velocity of 0.3 to 0.6 m/sec (1 to 2 ft/sec) to continue movement up stream (Weaver 1963).

Another problem from dams and turbine operation is the supersaturation of water with atmospheric gases, primarily nitrogen, a phenomenon reviewed by Wolke et al. (1975). Briefly, air may be entrained in falling water or in water passing through a turbine and dissolved at concentrations in excess of atmospheric saturation. Gas emboli then form in blood and tissues of fish exposed to the gas-supersaturated water, resulting in death. Such an event killed 200 Atlantic salmon (10% of the run) in the St. Johns River, New Brunswick, in 1968 (MacDonald and Hyatt 1973).

Stream impoundment may also alter water temperature patterns, which are key factors in the delineation of the geographic range of Atlantic salmon (Danie et al. 1983). Salmon spawning streams are not found south of about 40° north latitude (in the northern hemisphere) because summer temperatures are too warm. Salmon generally enter rivers in late spring or early summer when temperatures exceed 5°C (40°F); migration ceases when temperatures exceed 25°C (76°F) (Elson 1975, McLaughlin and Knight 1987). If water discharged through a dam is drawn from the surface of the impoundment, stream temperature may increase rapidly in the spring and reach higher summer maxima. If water is drawn from deep in the impoundment, stream temperatures may be increased above normal during winter and decreased in summer. High summer stream temperatures may also result from cooling water discharge from steam electric generating stations and industrial facilities, reduced ground water inflow because of withdrawals for domestic use, and removal of bankside vegetation during timber harvesting. Restricted upstream passage, coupled with the absence of water currents, increased water temperature, and the possibility of gas bubble disease, make dams a major impediment to upstream migration of Atlantic salmon (USFWS 1984).

Atlantic salmon are capable of swimming at sustained speeds of 2.2 km/hr (1.5 mph) and can reach a maximum burst speed of 24 km/hr (15 mph) (Elson 1975). To make progress up most rivers, which may have current speeds greater than 4.5 km/hr (3 mph), salmon must have access to resting areas where current velocity is < 61 cm/s (2 ft/s) along the way. In addition, holding pools of similar current velocity, but larger and deeper than resting pools, are required in the vicinity of spawning areas. A holding pool surface area of 2.8 m^2 (3.4 yd^2) per adult is required (McLaughlin and Knight 1987). The ideal holding pool has a depth of 1.8-3.6 m (6-12 ft) at low flow (McLaughlin and Knight 1987). Channelization of river beds for drainage and flood control may destroy such habitat.

The mean temperature of the earth has increased 0.5°C (1°F) since the industrial revolution, perhaps as a result of the greenhouse effect, although natural variation cannot be absolutely ruled out (Kerr 1990). If emissions of greenhouse gases continue at the present rate, global temperatures may increase 1°C (2°F) above current temperatures by the year 2025, and 3°C (2.5°F) by 2100 (Houghton et al. 1990). All regions may not experience uniform temperature increases. Temperature increases are expected to be greater at higher than at lower latitudes (Smith 1990). Meisner (1990) predicted that a 4.1°C (7°F) increase in July and August air temperature will reduce brook trout *(Salvelinus fontinalis)* habit in two southern Ontario, Canada, streams by 30 to 42%. Thus, the amount of suitable stream habitat for Atlantic salmon may be reduced by global warming, and rivers in the southern part of the range may become too warm for parr survival (Power 1990).

In addition to changes in temperature, global climate change may alter annual and seasonal precipitation patterns and thus runoff and stream flow (Hengeveld 1990). Even if precipitation amount were unchanged, increased mean annual air temperature would result in decreased runoff and thus decreased flow (Regier and Meisner 1990). Frenette et al. (1984) showed that variability in the number of Atlantic salmon parr in a Quebec river was directly related to stream flow, and Havey and Davis (1970) found that the number of landlocked Atlantic salmon parr in a Maine stream was directly related to rainfall.

Embryo

Spawning occurs in the fall, generally from mid-October to early November, when water temperature has declined to 7-10°C (43-50°F). Eggs are deposited in depressions (redds) excavated and covered with gravel by females. Redds are usually constructed in areas where water velocity is increasing, especially at the tail of a pool or head of a riffle. Preferred areas are in average water depth of 38 cm (15 in) and with average current velocity of 53 cm/s (21 in/s) (Beland et al. 1982). Substrate particle size is usually 1.2 to 10 cm (0.5 to 4 in) in diameter.

Embryos develop in the gravel for 175 to 195 days (Danie et al. 1983). Permeability of the spawning substrate is critical for embryo survival. Water exchange must be sufficient to maintain adequate dissolved oxygen concentration. Standard water velocity, measured at 20 cm (8 in) depth in salmon redds, ranges between 74 and about 5,000 cm/h (28 to 1,900 in/h) (Jordan and Beland 1981), but embryos may fail to hatch in redds with velocity < 600 cm/h (235 in/h) (Peterson 1978). If the stream bed contains more than 20% sand (particle size 0.06 to 2.2 mm (0.002 to 0.09 in)), redd permeability is insufficient (Peterson 1978).

Human activity in the watershed may result in siltation of stream beds and reduced substrate permeability. Siltation often results from watershed activities such as agriculture, logging practices, construction of roads, pipelines, and buildings, and from streambank erosion (Holland 1975). Watt (1988) attributed the decline in Atlantic salmon catch at the head of the Bay of Fundy to intensive agricultural development that resulted in siltation of rivers in the area. Grant et al. (1986) found that stream crossings by timber harvesting vehicles reduced biomass of salmonid fishes in Canadian streams, most likely because of siltation of downstream reaches.

Dissolved oxygen levels for embryo incubation and hatching are optimal at or near saturation. The limiting level for early embryos is 1.14 mg/L (1.14 ppm), for mature embryos 5.9 mg/L, and for hatching eggs and alevins 8 mg/L (McLaughlin and Knight 1987). Putrescible organic matter from domestic or industrial waste discharge or from farm animal wastes may reduce stream dissolved oxygen content.

Stability of stream beds is important for survival of embryos to hatching. Hydraulic forces typically mold stream beds into alternating riffles and pools. Streambed materials may shift somewhat during floodwater flows, and may modify pool configuration occasionally, but the natural channel is relatively stable (Elson 1975, Jordan and Beland 1981). Channelization of streams and increased runoff from watershed alterations may increase flow, destabilize stream channels, disrupt redds, and kill salmon embryos.

Parr

Atlantic salmon embryos hatch typically in late April or early May, and fry emerge from the gravel a month later (Jordan and Beland 1981). The fish, now called parr, then disperse and occupy territories in riffles and runs (Gustafson-Greenwood and Moring 1990). Current velocity at the fish's nose (focal velocity) is considered the most important factor defining habitat use of salmon parr (deGraaf and Bain 1986). Parr select focal velocities of 5 to 35 cm/s (2 to 14 in/s), and larger fish select higher velocities (Morantz et al. 1987). McLaughlin and Knight (1987) and Elson (1975) reported that substrate particle size was important; small parr (4 to 7 cm (1.6 to 2.8 in) total length) preferred areas with particle size < 10 cm (3.9 in) diameter and large parr (total length > 7 cm (2.8 in) total length) preferred particle sizes from 7 cm up to 25 cm (2.8 to 10 in) or larger, depending on the length of the fish. Watershed activities that deposit silt in stream beds, or channelization that reduces riffle/pool distribution and removes coarser materials, reduce parr habitat.

Territoriality among fish allocates space and food resources to ensure adequate growth and to reduce predation (Symons 1974). Territory size is a function of the size of the fish, bottom roughness (visual isolation), and food availability (Kalleberg 1958, Symons 1971). Larger salmon parr will defend their territories against smaller parr, which may reduce salmon production in a stream (Symons and Heland 1978). Salmon parr feed on invertebrate drift (Danie et al. 1983), and thus may compete for food with other salmonid and non-salmonid fishes. Mac-

Crimmon et al. (1983) found that salmon parr growth was suppressed by the presence of brook trout, and Gibson and Dickson (1984) found that salmon parr growth increased when brook trout were removed from a stream. Symons (1976) reported that salmon parr would defend their territories against other species, but none of the species seemed to have a competitive advantage in obtaining food. Sayers (1990) found that the introduction of salmon parr into a stream with resident brook trout caused the trout to move to deeper, slower-flowing stream reaches, and that intra-specific competition for habitat among salmon was at least as important as inter-specific competition. Nevertheless, the introduction of other fish species that may compete with salmon parr for food may well reduce production of salmon in rivers.

Salmon parr are vulnerable to a variety of fish and avian predators. Fish predators include northern pike *(Esox lucius)*, chain pickerel *(Esox niger)*, burbot *(Lota lota)*, and brown trout *(Salmo trutta)* (Bley 1987, Mills 1989). Important avian predators are the belted kingfisher *(Megaceryle alcyon)* and common merganser *(Mergus merganser)* (Elson 1962). Human intervention in the introduction or protection and enhancement of predators may reduce survival of salmon parr.

The major causes of pollution in streams in the six New England states are silt, nutrient enrichment, and organic enrichment (Table 2). Industrial and municipal wastes have been greatly reduced through stringent enforcement of clean water legislation, so that many rivers in New England are again capable of supporting salmonid fishes (EPA 1990). Toxic pollutants may reach Atlantic salmon nursery streams from industrial and municipal waste discharge, aerial application and runoff of forest and cropland pesticides, runoff from croplands, mining activity, and atmospheric deposition of acids.

Organochlorine pesticides previously caused serious losses of Atlantic salmon (Elson 1967, Elson et al. 1973, Locke and Havey 1972); however, these pesticides have been banned from use and the replacement pesticides are much less toxic to fish (Haines 1981, Elson et al. 1973, Zitko et al. 1970). Metal mining has been a serious problem in New Brunswick and Newfoundland, Canada (Elson et al. 1973), but is not now a problem in New England. However, proposals are pending to open at least three metal mines in Maine, which could have adverse effects on Atlantic salmon.

Atmospheric deposition of strong acid (acid rain) has caused serious losses of Atlantic salmon in Norway, Sweden, and the United

Table 2. River miles not meeting water quality standards by state and cause. Source: EPA (1990).

State	Total Miles	Impaired Miles	Percent Impaired	Cause: Silt	Nutrients	Bacteria	Organic Enrichment
CT	8,400	298	3.5	12	163	176	156
ME	31,672	394	1.2	150	164	198	191
MA	10,704	933	8.7	—	386	879	394
NH	14,544	381	2.6	—	—	368	131
RI	724	92	12.7	—	20	53	35
VT	5,162	628	12.2	465	327	238	388
Total	71,206	2,726	3.8	627	1,060	1,912	1,295

State	Cause: Metals	Pesticides	Suspended Solids	Salinity	Flow Alteration	Habitat Modification	PH	Thermal
CT	98	—	11	—	—	111	—	—
ME	3	—	14	—	—	—	—	—
MA	169	20	41	18	—	—	5	—
NH	—	—	—	—	—	—	—	—
RI	74	—	—	—	—	—	—	—
VT	27	—	—	—	257	409	19	474
Total	371	20	66	18	257	520	24	474

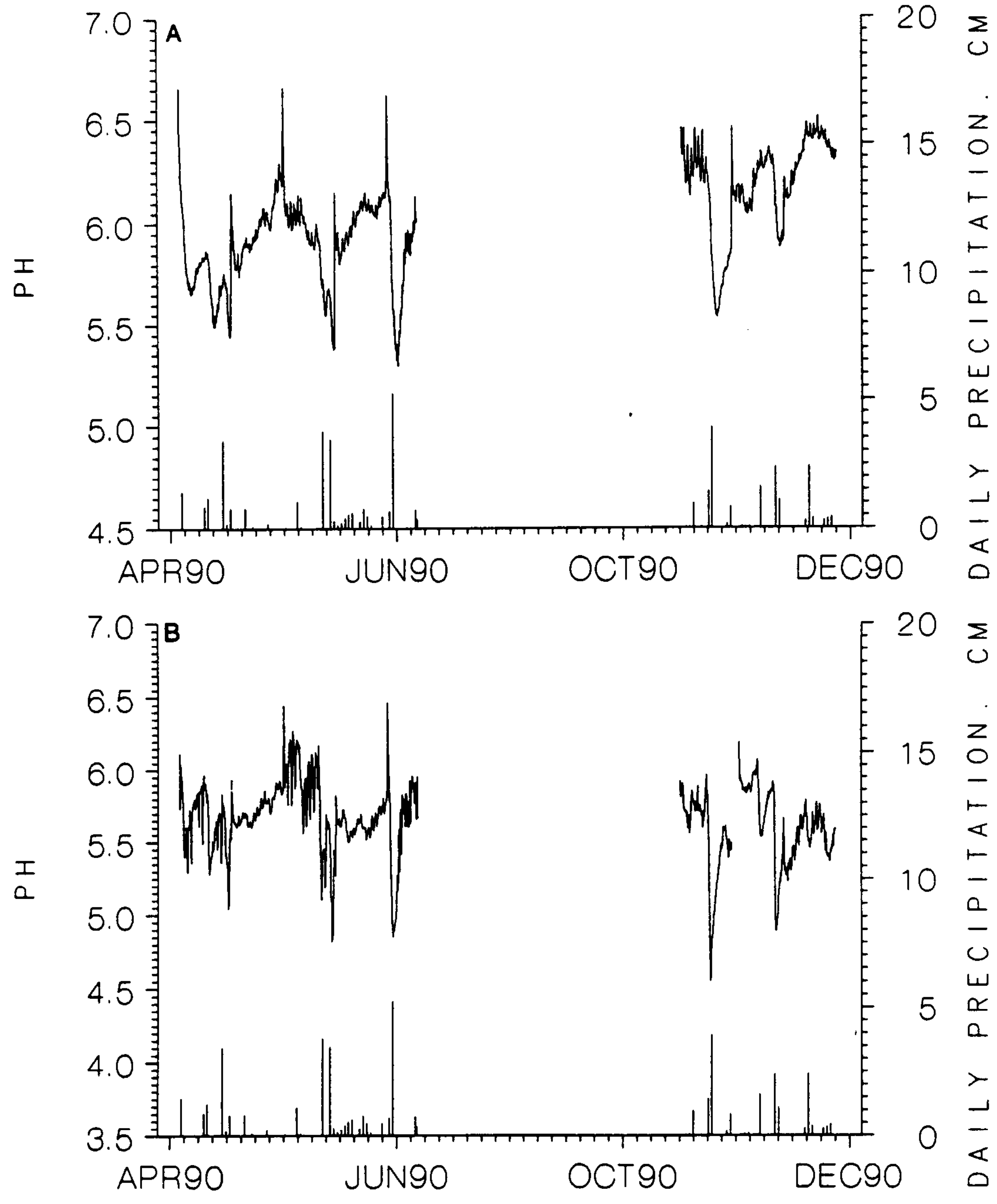

Figure 2. Temporal change in stream pH (solid line) and daily precipitation (vertical bars) in Sinclair Brook (A) and the upper Narraguagus River (B).

Kingdom (ICES 1989, Rosseland et al. 1986). In North America, acidification has caused the elimination of salmon runs in 13 rivers in Nova Scotia, Canada, and reductions in the runs in an additional 18 rivers (Watt 1986). Effects in the United States have not been so drastic. The New England region does receive acidic deposition (NADP 1990), but most accessible Atlantic salmon habitat is not chronically acidic (Haines 1980, 1987). Some streams tributary to mainstem salmon rivers do acidify episodically, depending on precipitation and climatic conditions, and salmon parr populations may occasionally be reduced in these streams (Haines et al. 1990). For example, in 1990 the Upper Narraguagus River reached pH levels as low as 5.3, whereas Sinclair Brook, a tributary stream, reached pH levels as low as 4.6 (Fig. 2). The passage of the new Clean Air Act in 1990 should greatly reduce the risk of serious future losses of Atlantic salmon in New England rivers.

Smolt

In New England, Atlantic salmon parr remain in freshwater for two to three years until they reach a size of 125 to 150 mm (5 to 6 in) total length (Bley 1987, Mills 1989). The transformation from the parr to smolt life stage involves a complex mix of biochemical, physiological, morphological, and behavioral changes that prepare the fish for life in the sea (Hoar 1976). Seaward migration occurs primarily at night and is triggered by rising water temperatures, reaching a peak at 9 to 10°C (46 to 50°F) (Bley 1987, Ruggles 1980). Predators of smolt, in addition to those listed for parr, include the eel *(Anguilla rostrata)*, double crested cormorant *(Phalacrocorax auritas)*, otter *(Lutra lutra)*, and mink *(Lutreola vison)* (Ruggles 1980).

The influence of dams on smolt emigration is similar to that already described for returning salmon. Because impoundments delay migration, they increase exposure of smolts to predation and possibly effect desmoltification (Saunders 1960). Passage of smolts over dam spillways has been studied extensively for Pacific salmon in the northwestern United States. Fish less than 20 cm (8 in) total length are seemingly able to withstand vertical drops up to 90 m (300 ft) with only 2-3% mortality (Ruggles 1980). Smolt passage through electric generating turbines, however, may cause mortality rates up to 40 or 50% (Ruggles 1980). Semple and McLeod (1975) cite a mortality of 16.5% for Atlantic salmon smolts at a hydroelectric facility in Nova Scotia.

Summary

As anadromous fish, Atlantic salmon require suitable freshwater habitat for all life stages from returning adult to emigrating smolt. The most significant habitat problems for salmon survival are dams, siltation of stream substrate, and water pollution. As progress is made in restoring access of salmon to historic habitat, other problems in survival of salmon or reproduction may become more important. Stream acidity from acidic deposition is not presently a serious problem in the United States, but it could reduce salmon survival in some tributary streams. Global climate change has the potential to affect Atlantic salmon survival seriously in fresh water by increasing stream temperatures and reducing flow.

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