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Possible Management Procedures for Increasing Production of Sockeye Salmon Smolts in the Naknek River System, Bristol Bay, Alaska

Robert J. Ellis and William J. McNeil

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U.S. DEPARTMENT OF COMMERCE
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Possible Management Procedures for Increasing Production of Sockeye Salmon Smolts in the Naknek River System, Bristol Bay, Alaska

ROBERT J. ELLIS and WILLIAM J. McNEIL[1]

ABSTRACT

About 35% of the Naknek River system is greatly underutilized by juvenile sockeye salmon, *Oncorhynchus nerka*. In two basins the cause seems to be a lack of spawning grounds, and in a third basin the cause may be too few spawners or poor quality spawning grounds. The annual yield of adult sockeye salmon to the fishery could probably be increased by about 200,000 to 300,000 fish by increasing the production of smolts. Artificial production of fry, along with improving or increasing the spawning environments, is recommended. The numbers of adult females, eggs, and fry required to fully seed the three underutilized basins are discussed. Attempts to increase the production of sockeye salmon in the Naknek River system must be accompanied by detailed biological studies to determine optimum seeding levels and establish cause-and-effect relations.

INTRODUCTION

The sockeye salmon, *Oncorhynchus nerka*, resources of Bristol Bay, Alaska, are large and valuable and have been heavily fished since about 1900 (Burgner et al. 1969). The National Marine Fisheries Service (under various names) began research on the freshwater and early marine life of the sockeye salmon in Bristol Bay before 1920, and since the early 1940's much of this work has been done in the Naknek River system.

The studies on sockeye salmon of the Naknek system have included most aspects of their freshwater biology, both biological and physical. Much is known about factors that appear to limit the number of young salmon produced by the system and the number of returning adults (Burgner et al. 1969). Within broad limits, the number of returning adults produced in seawater increases as the number of young leaving freshwater as smolts increases. In contrast, above a certain minimum, the number of smolts produced in freshwater appears to be independent of the number of parent spawners—smolt production is limited by freshwater spawning or nursery areas.

In this paper we briefly review information available in the literature on 1) physical aspects and relative productivity of the various lakes of the Naknek system, 2) abundance and distribution of spawning grounds and spawning adults, and 3) abundance, distribution, and growth of young sockeye salmon and associated species of fish. We then consider factors that appear to be limiting production of juvenile sockeye salmon in the Naknek system and suggest management procedures that might significantly increase the production of smolts (juveniles going to the ocean).

PHYSICAL ASPECTS AND PRODUCTIVITY OF LAKES

In freshwater, juvenile sockeye salmon typically occupy four successive habitats for varying periods: spawning gravels of streams or lake beaches for several months, littoral of lakes for a few weeks, open-water areas of the lakes for several months to 2 or 3 yr, and an outlet river through which the smolts travel for a few hours or days to reach the ocean. Two factors seem most likely to limit the production of smolts: the quantity and quality of spawning grounds, which may limit the number of fry produced, and the productivity of the pelagic waters of the lakes where juvenile salmon do most of their feeding and growing.

The Naknek system consists of four major lakes—Coville, Grosvenor, Naknek, and Brooks—and an outlet stream that connects these lakes to the ocean—Naknek River (Fig. 1). Naknek Lake differs from the others in that it consists of five regions which appear to be physically and biologically discrete. These regions are treated as separate basins in our research—Iliuk Arm, South Bay, West End, North Arm, and Northwest Basin. Because of their relative locations and to facilitate our discussion in this paper, we designate five of these lakes or basins as main-stem basins and three as external basins (Table 1). Two high mountain lakes, Hammersly and Murray, are tributary to Coville Lake and receive only a few adult sockeye salmon each year so they are not considered here. In general the lakes of the Naknek system are deep, have little littoral area, and are oligotrophic (Burgner et al. 1969). The portion of each lake

[1] Northwest and Alaska Fisheries Center Auke Bay Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 155, Auke Bay, AK 99821.

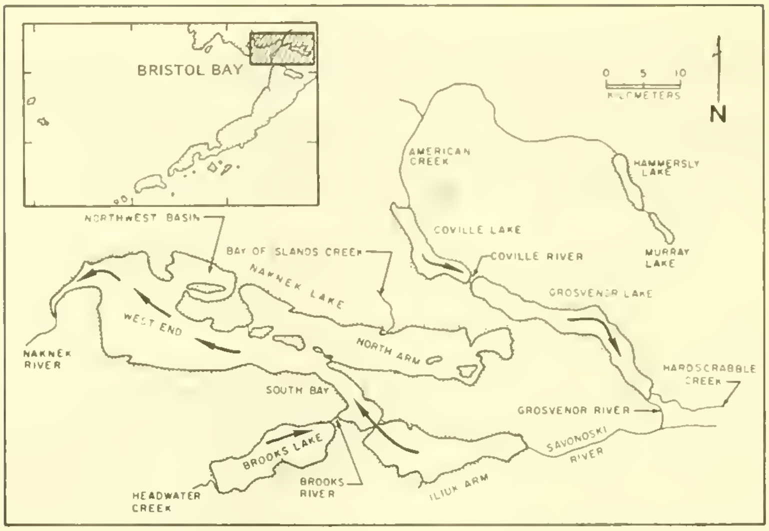

Figure 1.—Naknek River system, Alaska, showing the five main-stem lake basins (Coville and Grosvenor Lakes, Iliuk Arm, South Bay, and West End) and the three external lake basins (North Arm, Northwest Basin, and Brooks Lake).

Table 1.—Total surface area and percentage of each major basin of the Naknek River system shallower than 5 m.

Lake or basin	Surface area (km² or 100 ha)	Percent littoral area (<5 m deep)
Main stem basins		
Coville Lake	33	39
Grosvenor Lake	73	10
Iliuk Arm	94	4
South Bay	74	10
West End	218	26
External basins[1]		
North Arm	182	11
Northwest Basin	41	30
Brooks Lake	75	1
Total	790	

[1]The total surface area of the external basins composes 37.7% of the total surface area of all of the lakes.

<5 m deep ranges from about 39% in Coville Lake to about 1% in Brooks Lake.

Sockeye salmon spawn in tributaries of each lake, on some beaches, and in Naknek River; but the amount of spawning grounds and the numbers of spawners are not proportional to the size of the lakes (Table 2).

ABUNDANCE OF JUVENILE SOCKEYE SALMON AND ASSOCIATED SPECIES

The apparent abundance of juvenile sockeye salmon and associated species in the Naknek system from 1961 to 1964 has been reported in detail (Ellis 1974). Five species of fish predominated—sockeye salmon; threespine stickleback, *Gasterosteus aculeatus*; ninespine stickleback, *Pungitius pungitius*; pygmy whitefish, *Prosopium coulteri*; and pond smelt, *Hypomesus olidus*.

Table 2.—Distribution of spawning grounds of sockeye salmon and reported escapements of adult spawners in basins of the Naknek system.

		Potential spawning grounds		Range in spawners[1]	
Basin or lake	Surface area (km²)	Total (ha)	Relative to size of lake (ha spawning ground/ km² lake area)	Total (thousands)	Relative to size of lake (thousands/ km² lake area)
Main stem basin					
Coville Lake	33	111	3.32	80-1,000	2.4-30.3
Grosvenor Lake	73	30	0.40	35	0.5
Iliuk Arm	94	34	0.37	—	—
South Bay	74	6	0.07	4-150	<0.1-2.0
West End	218	148	0.68	75-200	0.3-0.9
External basin					
North Arm	182	8	0.04	6-[2]300	<0.1-1.6
Northwest Basin	41	1	0.02	<1-5	<0.1-0.1
Brooks Lake	75	18	0.24	8-27	0.1-0.5

[1]From Ellis (1974) except North Arm and Northwest Basin.

[2]About 300,000 fish were observed in North Arm in 1969. (R. D. Dewey, Northwest & Alaska Fisheries Center Auke Bay Fisheries Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821, pers. commun. June 1975.)

Sockeye salmon were widely distributed and relatively abundant throughout the system. The distribution of the two species of sticklebacks approximated that of juvenile sockeye salmon, and in some areas sticklebacks were more abundant than juvenile salmon. Pygmy whitefish and pond smelt were abundant in some basins but never abundant together—pond smelt were abundant in Coville Lake and pygmy whitefish in Brooks Lake and South Bay.

Our best measure of the actual abundance of juvenile sockeye salmon came from sampling with tow nets in the pelagic areas of each basin (Ellis 1974). The use of this gear to estimate abundance of juvenile salmon is documented by Johnson (1956), Ruggles (1966), and Pella (1968). Ellis found that the abundance of age 0 sockeye salmon decreased after midsummer in Coville and Grosvenor Lakes, increased in Iliuk Arm and South Bay, and was so low or erratic in Brooks Lake, Northwest Basin, West End, and North Arm that changes appear to have no meaning (Fig. 2). A decrease in abundance of age 0 sockeye salmon after midsummer would be expected because normally mortality would exceed recruitment from spawning grounds and littoral areas. Some basins, Coville and Grosvenor especially, had very few age I fish, although they were common to abundant in others (Fig. 3).

Water flows from one main-stem basin to the next (Coville Lake, Grosvenor Lake, Iliuk Arm, South Bay, and West End) and a summer migration of age 0 sockeye salmon results in migration of large numbers of fish from Coville Lake through the sequence of basins (Ellis 1974). By late August the abundance of age 0 sockeye salmon in Coville Lake had markedly declined and had increased in Iliuk Arm and South Bay (Fig. 2). The three external basins, North Arm, Northwest Basin, and Brooks Lake, are not included in this sequence of events but the role of West End in the summer migration is uncertain. Relatively few age 0 sockeye salmon migrate from Brooks Lake to South Bay in the fall.[2] The apparent abundance of age 0 fish in the external basins is relatively constant and so low during the summer that no great number could be migrating out of the external basins or in from South Bay or West End.

To determine relative numbers of the major species in the pelagic areas, we summarized the tow-net data for August 1961-63 (Table 3). The catches of species other than sockeye salmon were much more variable than the catches of salmon. (Pygmy whitefish were rarely taken in tow nets. Indication of their considerable abundance in Brooks Lake and South Bay comes from otter trawls and gill nets.)

A reduction in growth of juvenile sockeye salmon in some systems has been associated with large numbers of sockeye salmon, alone or with other species (Foerster 1944; Johnson 1958; Krogius 1961; Burgner 1964; Narver and Dahlberg 1964), but this association does not appear

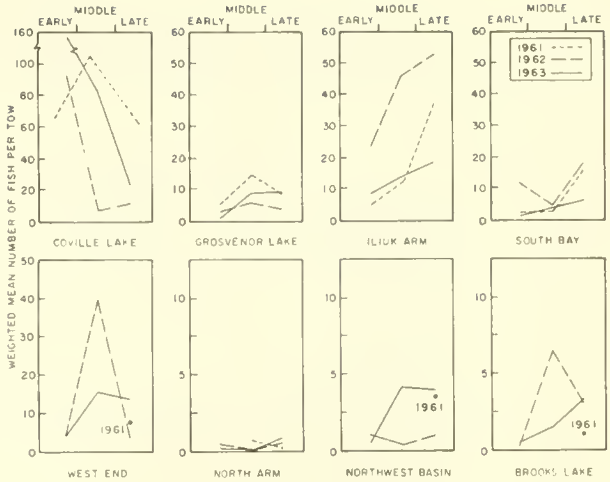

Figure 2.—Weighted mean number of age 0 sockeye salmon per standard tow by early (before 26 July), middle (26 July-10 August), and late (after 10 August) time periods in each lake of the Naknek River system, 1961-63. From Ellis (1974).

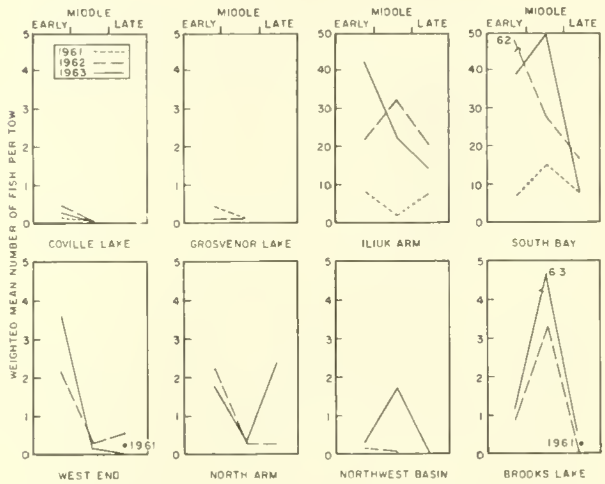

Figure 3.—Weighted mean number of age I sockeye salmon per standard tow by early (before 26 July), middle (26 July-10 August), and late (after 10 August) time periods in each lake of the Naknek River system, 1961-63. From Ellis (1974).

in the Naknek system (Ellis 1974). The three basins with the greatest numbers of all species of fish in the tow-net catches were those with age 0 sockeye salmon of average or greater than average length—Northwest Basin, West End, and Coville Lake (Table 3). It appears that competition for food or space did not result in a reduction in growth of juvenile sockeye salmon in the Naknek system. The mean fork lengths of age 0 sockeye salmon from the Naknek system on 1 September were generally equal to or greater than those of two other major river systems of Bristol Bay (Wood and Kvichak Rivers) for which we have comparable data (Burgner et al. 1969).

The rankings of abundance of age 0 sockeye salmon in the various basins in early summer relative to the rankings of area of potential spawning grounds (Table 4)

[2] Hartman, W. L., W. R. Heard, C. L. Strickland. 1962. Red salmon studies at Brooks Lake Biological Field Station, 1961. Unpubl. manuscr., 53 p. Northwest & Alaska Fisheries Center Auke Bay Fisheries Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821.

Table 3.—Mean surface water temperatures in August, mean number of age 0 and age I sockeye salmon and of pond smelt and threespine and ninespine sticklebacks, and mean fork lengths of age 0 sockeye salmon in seven lakes of the Naknek River system, 1961-63.

Lake or basin	Mean surface water temperature[1] (°C)	Number of fish per tow[2]: Mean for each species: Sockeye salmon Age 0	Sockeye salmon Age I	Pond smelt	Threespine sticklebacks	Ninespine sticklebacks	Four species combined	Mean fork length of age 0 sockeye salmon[3] (mm)
Northwest Basin	14.4	30	0	46	35	29	140	56
Grosvenor Lake	10.8	8	0	0.5	0.5	0.5	8	48
Iliuk Arm	10.2	37	10	0.5	6	1	54	52
South Bay	11.7	10	9	0.5	19	5	43	53
West End	12.5	8	0.5	0.5	108	6	192	59
North Arm	11.8	1	1	0.5	1	0.5	3	52
Northwest Basin	14.5	5	0.5	2	548	37	590	54
Brooks Lake	11.9	3	0.5	0	0.5	0.5	3	53

[1]Mean of all observations made in each lake during tow netting in August 1961-63.
[2]Mean for 16 August to 1 September 1961-63, for species other than sockeye salmon and after 11 August for sockeye salmon.
[3]Mean for 20 August 1962 and 1963.

Table 4.—Abundance of spawning grounds and average catch per unit effort of age 0 sockeye salmon in early July 1961-63 in lakes of the Naknek River system.

Lake or basin	Area of potential spawning grounds per unit lake area (ha/km²)	Age 0 sockeye salmon per tow
Coville Lake	3.32	96
West End	0.68	3
Grosvenor Lake	0.40	3
Iliuk Arm	0.37	13
Brooks Lake	0.24	1
South Bay	0.07	5
North Arm	0.04	1
Northwest Basin	0.02	2

within each basin were not correlated (at $P = 0.05$, Spearman rank correlation, Siegel 1956). However, Coville Lake had by far the highest ratio of spawning grounds to lake area and the greatest abundance of age 0 sockeye salmon in early July, and basins with the lowest proportions of spawning grounds had smallest catches of age 0 fish in the tow nets. The lack of significant correlation in all basins is likely due to many factors including: sampling error, annual variations in success of the various stocks, and incomplete knowledge of potential spawning grounds and their capacities to produce fry.

For the Naknek system, the abundance of age 0 sockeye salmon in late August between 1961 and 1964 was relatively constant. The mean number of fish per tow (weighted by surface area of each basin) varied by a factor of <3—from 8.8 to 23.0 (Table 5). In addition, the numbers of smolts produced by these age 0 fish (estimated in the Naknek River) were relatively constant. The parent escapements for the age 0 fish sampled from 1961 to 1964 ranged from 351,000 to 828,000 and for age I fish from 351,000 to 2,231,000 (Table 5).

From the foregoing discussion we see that the Naknek system has a relatively constant number of age 0 fish in the fall of each year and, similarly, a relatively constant number of smolts produced in the spring from 351,000 to 2.2 million parents (Table 5). It appears, however, that

Table 5.—The systemwide mean catch per tow (weighted by area of each lake) for age 0 and age I sockeye salmon in the Naknek River system in August 1961-64 and resulting numbers of smolts produced. Age 0 fish in August can become age I or age II smolts, but age I fish in August can become only age II smolts (rarely age III).

Age of fish and year of sampling	Fish in parent escapement (thousands)	Mean number of fish per tow-net catch	Smolts produced[1] (millions): Age I	Age II	Total
Age 0					
1961	828.4	11.9	8.0	8.7	16.7
1962	351.1	13.2	6.0	5.0	11.0
1963	723.1	8.8	2.2	9.9	12.1
1964	905.4	23.0	14.7	6.1	20.8
Age I					
1961	2,231.8	1.9	—	8.5	—
1962	828.4	4.7	—	8.7	—
1963	351.1	3.2	—	5.0	—
1964	723.1	5.4	—	9.9	—

[1]Stewart, Donald M. (editor). 1969. 1967 Bristol Bay red salmon smolt studies. Alaska Dep. Fish Game, Inf. Leafl. 134, p. 69.

the three external basins are not supporting the density of age 0 sockeye salmon that could be possible. Two of the external basins, North Arm and Northwest Basin, have by far the lowest spawning-area to lake-area ratios of the system which apparently results in too few fry to fully use the rearing areas. The third external basin, Brooks Lake (fifth ranking in the system in ratio of spawning area to lake area), may have enough spawning grounds in Headwater Creek where the lake's major stock is produced, but the true capacity of this stream is unknown.

PREDATION AS A LIMITING FACTOR

Predation has been considered both significant in limiting the number of sockeye salmon smolts produced (Foerster and Ricker 1942; Rounsefell 1958) and insignificant (DeLacy and Morton 1943; Roos 1959). Many species of fish and bird predators occur in the Naknek system but they appear to have little effect on the number of smolts. The best example of this little effect is the large number of smolts per spawner produced by the

1961 escapement. This escapement was relatively small (351,000), but about two-thirds of the spawners went to the uppermost spawning grounds of the system—American Creek. As a consequence most of the progeny of the escapement had to run the gamut of predators to reach the ocean. Even so, the number of smolts produced per adult in the parent escapement was about 32, the highest rate recorded between 1956 and 1963. Thus, a large rate of production can occur in this system despite maximum exposure to predation.

RATIONALE FOR INCREASING PRODUCTION OF SMOLTS

It appears that significantly more sockeye salmon smolts could be produced in the Naknek system if production of fry in the three external basins (Brooks Lake, North Arm, and Northwest Basin), which now support relatively few juveniles, could be increased. Brooks lake has an intermediate ratio of spawning ground to lake area, but the only way of increasing the escapement to Headwater Creek (the major spawning ground) is by selectively protecting its stock from the fishery. Since the run into Naknek River occurs over a short period (Straty 1966), it may not be feasible to protect one stock without a closure of the entire fishery. Even if selective protection of stocks were possible, increasing the escapement of spawners to North Arm and Northwest Basin would probably not increase their fry production because of limited spawning grounds. Therefore, the need for other methods of increasing production of juveniles seems obvious—i.e., a selective increase in survival of some stocks from egg to fry via a hatchery system or artificial spawning channels. Rationale for an enhancement program will now be developed.

Spawning Populations and Sex Ratios

Our best estimates of the capacities of the Naknek system and of the three external basins in particular to produce fry can be determined from past escapement data. The annual escapements of adult sockeye salmon to the Naknek system averaged about 994,000 fish for the years 1956-69 (Parker 1974). For Brooks Lake, unpublished observations by the National Marine Fisheries Service for the years 1957-67[3] reveal that an average of about 21,000 adults spawned annually in the lake or its tributaries (Table 6). For North Arm the average number of spawning adults is assumed to be about 2% of the total escapement to the Naknek system (an average of 20,000 fish), and for Northwest Basin the number is assumed to be about 0.2% (an average of 2,000 fish). These assumed percentages are based on the respective percentages of the total spawning area in each basin.

Table 6.—Number of adult sockeye salmon spawning[1] in Brooks Lake and tributaries and the percentage of females, 1957-67.

Year	Number of spawners	Percentage of females
1957	28,813	49.7
1958	13,418	26.5
1959	21,849	27.8
1960	12,361	28.0
1961	7,942	53.4
1962	27,204	39.7
1963	9,904	31.3
1964	19,068	29.8
1965	15,383	26.7
1966	35,953	35.4
1967	43,974	39.3
Mean	21,443	35.2

[1]Total count of adults passed into Brooks Lake at Brooks River weir less number counted back downstream (data derived from Dewey et al. see text footnote 3).

Although stocks of sockeye salmon spawning in the Naknek system exhibit variable sex ratios from year to year, males generally predominate. Some stocks, such as Brooks Lake, have a strong dominance of males in most years (Table 6), whereas others, as illustrated by American Creek (which flows into Coville Lake), exhibit a weak dominance of males (Table 7). On the basis of these data, we assumed a sex ratio of 40 females/100 spawners in estimating various factors related to the production of sockeye salmon in the Naknek system.

Table 7.—Number of adult sockeye salmon entering American Creek (Coville Lake) and the percentage of females, 1961-72. (Data from Dahlberg see text footnote 4).

Year	Number of adults	Percentage of females
1961	217,824	53.0
1962	84,332	46.1
1963	63,855	33.1
1964	50,385	30.1
1965	—	—
1966	99,712	34.6
1967	109,492	60.0
1968	121,324	32.4
1969	99,619	34.6
1970	77,468	24.1
1971	284,725	61.8
1972	99,562	43.1
Mean	118,936	47.8

Fecundity

The fecundity of sockeye salmon in the Naknek system appears to vary around an approximate average of 4,000 eggs/female. For example, Dewey et al. (see footnote 3) counted an average of 3,950 eggs/female (range 3,668-4,336 eggs) from Brooks Lake samples from 1957 through 1967. Dahlberg[4] reported an average of 4,651 eggs/fe-

[3]Dewey, R. D., S. Tsunoda, and W. L. Hartman. 1971. Naknek system red salmon investigations, 1966-67. Unpubl. manuscr., 44 p. Northwest & Alaska Fisheries Center Auke Bay Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821.

[4]Dahlberg, M. L. 1972. Studies of sockeye salmon in the Naknek River system, 1972. Unpubl. manuscr., 114 p. Northwest & Alaska Fisheries Center Auke Bay Fisheries Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821.

male at American Creek (Coville Lake) and 3,553 eggs/female at Miss 42 Creek (Northwest Basin) in 1972.

Egg-to-Fry Survival

Ten estimates of survival from potential egg deposition to fry emigration have been made in three streams in the Naknek system (Table 8). The number of fry entering nursery lakes averaged nearly 9% of potential egg deposition.

Table 8.—Estimated survival of sockeye salmon from potential egg deposition to fry emigration in three spawning streams in the Naknek River system.[1]

Stream	Number of observations	Percentage survival Mean	Range
Hidden Creek (Brooks Lake)	5	10.1	6.6-13.7
One Shot Creek (Brooks Lake)	1	8.5	—
American Creek (Coville Lake)	4	7.3	0.7-12.0
Mean		8.8	

[1] Michael L. Dahlberg, Fisheries Research Biologist, Northwest & Alaska Fisheries Center Auke Bay Fisheries Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 155, Auke Bay, AK 99821. Pers. commun. May 1976.

Fry-to-Smolt Survival

Assuming that the annual escapement was 994,000, 40% of the fish were females, and the average female carried 4,000 eggs into the system, the annual potential egg deposition averaged 1,590 million. The average number of sockeye salmon smolts emigrating from the Naknek River from 1956 to 1969, from which the average annual escapement was figured, was 12.2 million. From these assumptions we can calculate the average annual freshwater survival ($\hat{S}$) from potential egg deposition to outmigrating smolts as follows:

$$\hat{S} = \frac{12.2 \text{ (smolts)}}{1{,}590 \text{ (eggs)}} = 0.008.$$

Average fry-to-smolt survival can be approximated from the following relationship:

$$\hat{S} = \hat{S}_1 \times \hat{S}_2,$$

where $\hat{S}$ is the estimated total freshwater survival from potential egg deposition to smolt, $\hat{S}_1$ is the estimated egg-to-fry survival, and $\hat{S}_2$ is the estimated fry-to-smolt survival.

Using the values $\hat{S} = 0.008$, and $\hat{S}_1 = 0.09$, we calculate $\hat{S}_2$ to be

$$\hat{S}_2 = \frac{\hat{S}}{\hat{S}_1} = \frac{0.008}{0.09} = 0.09.$$

Thus, fry-to-smolt survival is estimated to average about 9%.

Desirable Fry Recruitment

There is no consensus on the level of sockeye salmon fry recruitment to a lake that produces the maximum outmigration of smolts. It is generally recognized that optimum fry recruitment will vary among lakes, depending on various biotic factors such as primary and secondary productivity and abiotic factors such as length of growing season. Data on primary productivity presented by Burgner et al. (1969) for 10 western Alaska sockeye salmon lake systems reveal that the Naknek system has intermediate rankings with regard to carbon fixation and standing crop of phytoplankton. However, the Naknek system ranks relatively low with regard to escapement of spawners per 100 ha of lake area. Information is not available to compare all basins within the Naknek system in regard to production of food for juvenile salmon and distribution of spawners.

The number of spawners, potential egg deposition, and resultant smolt production for the Naknek system for the 14 brood years 1956-69 are shown in Figure 4. The higher levels of smolt production appear to result from escapements of slightly more than 1 million adult sockeye salmon, but for our estimates we used 1 million. Ellis (1974) concluded that juveniles resulting from escapements of up to 1 million adults did not overburden the food supply.

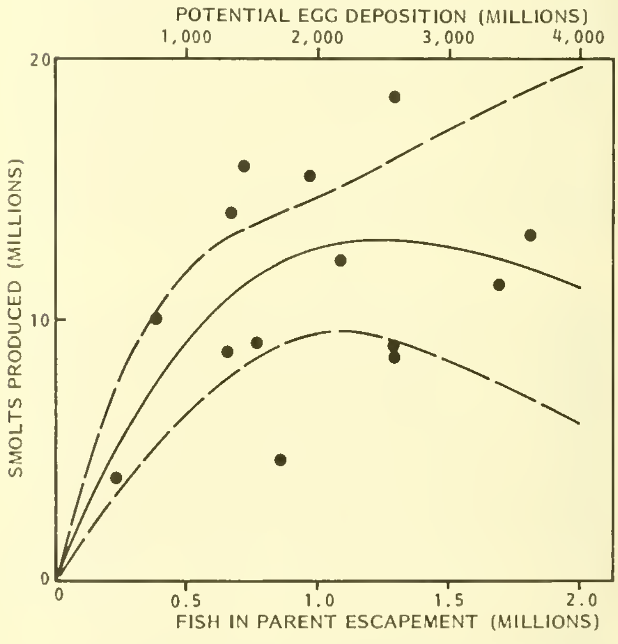

Figure 4.—Smolt production, parent escapement, and potential egg deposition in the Naknek system, 1956-69. Dashed line represents 95% confidence bounds of the expected smolt production. Modified from figure 35 of Pella and Jaenicke (see text footnote 6).

Estimates of Current Fry Recruitment

Our estimates of current levels of fry recruitment to the various lake basins are based on estimates of spawner escapement, sex ratio, fecundity, and egg-to-fry survival.

We calculated average annual fry recruitment per 100 ha of lake area by dividing estimates of annual fry recruitment (Table 9) by surface area (Table 1). The estimates for the combined main-stem lakes and for each of the external basins are:

Table 9.—Approximate number of fry recruited annually to lake basins in the Naknek River system, assuming that 40% of the spawners were females with an average of 4,000 eggs/female.

Basin	Assumed adult escapement	Assumed average fecundity (number)	Assumed egg-to-fry survival	Calculated average annual fry recruitment (millions)
Main stem lakes	951,000	1,600	0.09	136.9
North Arm	20,000	1,600	0.09	2.9
Northwest Basin	2,000	1,600	0.09	0.3
Brooks Lake	21,000	1,600	0.09	3.0

Main-stem lakes	278,000
North Arm	16,000
Northwest Basin	7,000
Brooks Lake	40,000.

A first approximation of the desirable number of additional fry that could be supported in the Naknek system is obtained by determining the number of fry needed to bring the average annual recruitment of fry in North Arm, Northwest Basin, and Brooks Lake up to the level estimated for the main-stem lakes, i.e., 278,000 fry/100 ha (Table 10).

Table 10.—Additional sockeye salmon fry that are desirable for lake basins in the Naknek River system.

Basin	Approximate fry recruitment (no./100 ha)	Target fry recruitment (no./100 ha)	Additional fry desired: Per 100 ha	Additional fry desired: For total basin (millions)
Main stem lakes	278,000	278,000	0	0.0
North Arm	16,000	278,000	262,000	47.7
Northwest Basin	7,000	278,000	271,000	11.1
Brooks Lake	40,000	278,000	238,000	17.8
Total				76.6

Additional Spawners Required

With natural spawning, approximately 532,000 additional adults would be required in the combined escapements to North Arm, Northwest Basin, and Brooks Lake to generate the potential for an additional 76.6 million fry recruits, i.e.,

North Arm	331,000
Northwest Basin	77,000
Brooks Lake	124,000
Total	532,000.

Adequacy of Natural Spawning Grounds

Up to 5,000 female sockeye salmon spawners can be accommodated on 1 ha of good quality spawning ground (Burgner et al. 1969). With a sex ratio of 40 females/100 spawners, 1 ha of spawning ground would accommodate up to 12,500 spawners (both sexes). Thus, at least 42.6 ha of spawning ground would be required for an additional 532,000 adults in the Naknek system. Under this assumption, the existing and required number of spawners and natural spawning areas in North Arm, Northwest Basin, and Brooks Lake (Table 11) lead us to conclude that:

1) The available natural spawning areas are inadequate for North Arm and Northwest Basin to meet the stated goals of fry recruitment, even if the desired spawner escapements could be provided.

2) The available natural spawning areas are adequate for Brooks Lake to meet the stated goals of fry recruitment. Factors which may now be limiting fry recruitment to Brooks Lake are underescapement of spawners and poor survival conditions in existing spawning areas or both.

Table 11.—Total existing and required number of spawners and spawning area for sockeye salmon in North Arm, Northwest Basin, and Brooks Lake.

Basin	Number of spawners: Existing	Number of spawners: Additional required	Spawning area (ha): Existing	Spawning area (ha): Total required
North Arm	20,000	331,000	7.5	28.1
Northwest Basin	2,000	77,000	0.7	6.3
Brooks Lake	21,000	124,000	18.0	11.4

RECOMMENDATIONS AND CONCLUSIONS

Any plan to increase recruitment of sockeye salmon fry to North Arm, Northwest Basin, and Brooks Lake must satisfy the requirements of sockeye salmon for reproduction and time of entry of juveniles into the lake nursery area. Furthermore, such a plan should be economically feasible and will have to be integrated with resource management programs of the U.S. Park Service and the Alaska Department of Fish and Game. We consider four currently used methods to increase fry production in each of the three external basins: 1) Increase the escapement of spawners into already accessible spawning grounds, 2) provide spawners access to presently inaccessible stream areas by laddering impassable waterfalls, 3) construct spawning channels, and 4) construct hatcheries. Because of probable need to revise any method undertaken, all attempts to enhance the present stocks in the Naknek system should be carefully documented and evaluated.

Spawning channels to supplement natural recruitment of sockeye salmon fry to lakes have shown promise in some instances in British Columbia, and should be considered in the Naknek system. Assuming a satisfactory egg-to-fry survival of 70% in spawning channels (versus 9% in natural spawning grounds), channels with a capacity of approximately 27,000 female spawners (or about 67,500 total spawners with a 40:60 sex ratio) would be required. This would mean about 5.4 ha of spawning surface.

A hatchery capable of producing 76.6 million fry would probably cost less to construct than a spawning channel and would require much less space. A building to house the required incubators would encompass about 1,300 m^2. Provision of about 1,800 m^2 of exposed raceways might be desirable to allow for short-term rearing of hatchery fry until physical and biological conditions in the lake nursery waters become suitable. Although some physical factors favor a hatchery system, spawning channels would obviate some of the biological problems of hatcheries—especially genetic selection (matings occur naturally in spawning channels) and reduction in spreading of diseases. For example, IHN (infectious hematopoietic necrosis) virus is present in most stocks of sockeye salmon in Bristol Bay and will be an important factor in the success or failure of artificial enhancement projects in the area (Grischkowsky and Amend 1976).

North Arm

About 90% of the natural spawning in North Arm occurs in Bay of Islands Creek (Fig. 1) which drains a high tundra lake (Idavain Lake) and runs 27 km to North Arm. Upstream migration of salmon in Bay of Islands Creek is blocked by a waterfall 14 km from North Arm.

Lack of suitable natural spawning area is most likely the principal factor limiting production of sockeye salmon in North Arm. Nevertheless the present available natural spawning area (7.5 ha) should support up to 100,000 spawners of both sexes or about 40,000 females—recent escapements have been only about 20% of this number.

Construction of a fish passage facility at the waterfall on Bay of Islands Creek would provide salmon access to an additional 13 km of stream and could increase the available spawning area[5] in North Arm by about 50%. The feasibility of laddering the waterfall should be investigated because of its potential for a significant low-cost increase in natural production of fry.

If the waterfall could be laddered and escapement of sockeye salmon spawners to Bay of Islands Creek increased to 150,000 adults, fry production should be about

$$150{,}000 \text{ spawners} \times 0.4 \frac{\text{female}}{\text{spawner}} \times 4{,}000 \frac{\text{eggs}}{\text{female}} \times 0.09 \frac{\text{fry}}{\text{egg}} = 21.6 \text{ million fry.}$$

The recruitment of fry to North Arm would be increased to 119,000 fry/100 ha, whereas the suggested target recruitment is 278,000 fry/100 ha (Table 10).

It seems doubtful, therefore, that Bay of Islands Creek has the potential to produce the additional fry needed to achieve the target density even with laddering of the waterfall. Therefore, consideration should be given to artificial propagation of fry. The minimum required capacity of either a spawning channel or a hatchery would be about 28.9 million fry annually.

A successful spawning channel or hatchery capable of producing 28.9 million fry could generate an additional 2.6 million smolts in the annual outmigration from North Arm. At least a 3 yr full-scale operation would be required to realize maximum smolt production from the lake. Should marine survival average 15% of the additional fish from North Arm leaving Naknek Lake as smolts (average survival of natural smolts from the Naknek system from 1956 to 1969 was about 19% and for the nearby Ugashik system 12%) (Pella and Jaenicke[6]), an additional 390,000 sockeye salmon adults would be recruited to the Bristol Bay fishing grounds. Three additional years would be needed after maximum smolt production is achieved before these artificially produced fish would become fully recruited to the fishery. It is likely that about 200,000 to 300,000 (50% to 70%) of the fish produced artificially in the Naknek system and returning to Bristol Bay would be caught in the fishery. This means that 117,000 or more of them would escape the fishery and return to Bay of Islands Creek, i.e., to the site of the incubation facility. However, <30,000 of these returning adults would be needed to restock a hatchery facility (more would be needed for a spawning channel because of lower efficiency), and the remainder could be allowed to spawn in Bay of Islands Creek. This would ensure almost full utilization of the natural spawning area in addition to the artificial facility.

Northwest Basin

Natural spawning areas are too limited in Northwest Basin to accommodate increased escapements of wild fish, and there are no opportunities to provide wild fish access to potential new spawning areas. The only obvious course of action for increasing recruitment of sockeye salmon fry to Northwest Basin is through hatchery propagation, because creeks entering Northwest Basin are too small to satisfy the water requirements of a spawning channel.

About 11 million hatchery-produced fry (see Table 10) would have to be added to the Northwest Basin to achieve a target recruitment of 278,000 fry/km^2 of lake nursery area. This would require a hatchery similar to the facility already described for North Arm but about one-third as large. However, costs of constructing and operating such a facility on Northwest Basin would be considerably more than one-third the cost of a larger hatchery for North Arm. It would probably be more economical to enlarge a hatchery at North Arm to raise 40 million fry instead of 30 million and to transplant 10 million fry annually to Northwest Basin. To reduce possible changes in genetic makeup of stocks of Northwest Basin, only adult fish randomly selected from Northwest Basin should be used to produce fry for that basin. Based on the same calculation used for North Arm, the 11 million hatchery fry could be expected to yield about 75,000 to

[5]Unpublished notes and stream survey data, Salmon Investigations (1961-1963). Unpaginated. Northwest & Alaska Fisheries Center Auke Bay Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821.

[6]Pella, J. J., and H. W. Jaenicke. 1975. Some observations on the biology and variations of populations of sockeye salmon of the Naknek and Ugashik systems of Bristol Bay, Alaska, 1956-69. Processed report, 133 p. Northwest & Alaska Fisheries Center Auke Bay Laboratory, Natl. Mar. Fish. Serv., NOAA, P.O. Box 155, Auke Bay, AK 99821.

100,000 adults to the fishery and about 45,000 to 75,000 spawners to Northwest Basin.

Brooks Lake

The known natural spawning area in tributaries to Brooks Lake appears to be more than adequate for the number of spawners required to fully stock the lake with sockeye salmon fry (Table 11). Inadequate fry recruitment in Brooks Lake appears to be the result of inadequate escapement of spawners to the system rather than a lack of sufficient spawning area.

The large terminal tributary to Brooks Lake, Headwater Creek, is 80 km long and provides at least 15 ha of spawning ground, all of which is accessible to salmon. Escapements of sockeye salmon adults are typically <10,000 fish (see footnote 5), even though the stream could easily accommodate 100,000 or more. Factors limiting the capacity of Headwater Creek to produce fry should be determined before plans are developed to increase stocks of sockeye salmon in Brooks Lake through artificial propagation.

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