ESCAPEMENT LEVELS AND PRODUCTIVITY OF THE NUSHAGAK SOCKEYE SALMON RUN FROM 1908 TO 1966[1]

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ABSTRACT

Since the inception of a commercial fishery for sockeye salmon in the Nushagak District, Bristol Bay, Alaska, the annual yields have followed a definite pattern. Catches increased during a relatively short development phase of the fishery, then stabilized for some years and then declined in two steps separated by periods of relative stability.

For years the cause of the decline had been thought to be overfishing, and various measures of curtailment had been placed upon the fishing industry.

Evidence is presented in this paper that the average escapement or the potential egg deposition remained about the same during each of three periods (1908-1919, 1925-1945, and 1946-1966); hence the diminution in the runs was due not to lack of spawners but to a decline in the rate of return per spawner.

So that the cause or causes of the present low reproductive potential can be ascertained, the effects of fishing on the stocks of salmon must be examined. Besides removing part of the run, the yearly commercial fishing operation may have altered either the age composition or the distribution of the escapement.

Available historical records were examined for evidence of these types of changes but largely with a negative result; therefore, the hypothesis was advanced that the observed declining rate of return per spawner is caused by a declining basic productivity of the nursery areas. The latter is then ascribable to the cumulative effect of relatively little enrichment of bioenergetic elements from salmon carcasses since the instigation of commercial fishing operations in comparison with the prefishing era when the entire virgin run escaped to the spawning grounds.

Suggestions are made for future field testing of this hypothesis.

In the development of the salmon fishery along the eastern perimeter of the Pacific Ocean, the most southern stocks were utilized first. As demand increased and certain stocks declined, the fishery shifted northward until the runs of the entire southeastern Alaska and soon thereafter those of the western districts were exploited. The rapidity of growth of the salmon fishing industry in Alaska is astonishing. The first cannery was built in southeastern Alaska at Klawak in 1878 (Rich and Ball, 1928), and only 6 years later exploratory fishing was conducted in Bristol Bay.

The early Bristol Bay catch records show that, from 1884 to 1891, fishing was conducted only in Nushagak Bay (Figure 1). Four years later, salmon was harvested in the other watersheds of Bristol Bay, the Kvichak-Naknek, the Egegik, and the Ugashik Districts. The patterns were initially alike, with a continuous and steady rise in production for at least 10 years in the smaller districts of Egegik and Ugashik and 20 years or more in the Nushagak District and even longer in the Kvichak District where on the average more than 60% of the Bristol Bay harvest is made annually.

As these four fisheries developed, annual variations became more and more apparent, but the overall production was fairly stable until 1919, when it declined drastically all over Bristol Bay in spite of no decline in fishing effort. The catches in Ugashik, Egegik, and Kvichak Districts soon thereafter rebounded to their former production level, but the catches in the Nushagak District did not. From this point on, the pattern of development in Nushagak differed from that of the other fishing areas in Bristol Bay, primarily in a more severe and persistent decline of the stocks making up the entire run.

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In an effort to reverse this downward trend by providing for larger escapements, fishing effort was reduced by restrictions on fishing time, gear, and location. The effect of these measures can be gauged from three principal sources of information: (1) A counting weir was operated in the Wood River of the Nushagak District, the principal trunk stream, during the years 1908-1919. (2) Biological studies were conducted in subsequent years that provided data on the age, length, and size composition of the catch and in part of the escapement. (3) The salmon canning industry itself has kept meticulous records on daily catches, number of fishing units, and type of gear operated.

The various sources of data indicated above were utilized to reconstruct the levels of escapements in the Nushagak District during the last 50 years in an effort to determine whether the magnitude of the yearly escapements is correlated with the declining salmon production in Nushagak Bay. If this were not the case, the fishery may have changed the age and size composition of the stock or the distribution of the various stocks in time and space. These factors will be examined in a search for a logical explanation of the decline of the Nushagak fishery.

NUSHAGAK BAY AND WATERSHED

Nushagak Bay includes the waters between a line drawn from Nichol's Spit to Etolin Point and the confluence of the Wood and Nushagak Rivers (Figure 1). These streams serve as the trunk streams of the Wood River lakes and the Tikchik lakes, respectively. Two other trunk streams drain into Nushagak Bay, namely, the Snake River and the Igushik River. The entire watershed comprises a drainage basin of 10,207 km^2. The morphometric parameters of some of the more important salmon-producing lakes are given by Gadau (1966).

Although sockeye salmon occur in more northerly latitudes, the Nushagak River system represents the northern boundaries of large sockeye salmon runs. The reason may be the absence of large lakes in more northern stream systems, which would provide sufficient nursery grounds. Thus, in the Tikchik system there are six lakes with five accessible to the salmon, but only the three lower ones, indicated on Figure 1, are important for sockeye salmon production.

NUSHAGAK SOCKEYE CATCHES, 1884-1966

The commercial fishery for sockeye salmon in Bristol Bay began in Nushagak Bay in 1884 after the schooner *Neptune* made an exploratory salting expedition (Moser, 1902). Prior to that time, some salting, from 800 to 1200 barrels each year, was done by fishermen operating a simple trap in the Wood River.

The most recent account of catch data was published by Kasahara (1963). His figures differ in some years from those given in Tables 1 and 2 of this paper, compiled in part from original sources, but the discrepancies are mostly minor in nature, and they do not change the overall picture in catch level and trend. Derivation of the Nushagak catch figures used in this report is given in the footnotes and comments to the mentioned tables.

When the Nushagak catches are plotted, they exhibit strong annual variations, as in most sockeye salmon runs (Figure 2). A small part of the variability can be explained by differences in fishing effort, which reflected economic conditions or inaccurate predictions by the cannery superintendents as to the actual size of the run. Viewed over longer time periods, however, there can be no doubt that the annual catches reflect changes in stock strength. This conclusion is amply brought out by the construction of a trend line by a moving average of 5's because of 5-year cycle.

Three distinct periods are discernible. The first period spans the years 1900-1918, the second one covers the years 1921-1945, and the last period includes the years 1946-1966. The average annual catches during these periods were 5,134,156; 2,888,726; and 1,183,485 salmon, respectively.[3]

Transition from one level to the next took

[3] If the estimated foreign catches made since 1956 were included with the domestic catches for the third period, the average annual catch would be raised about 25%.

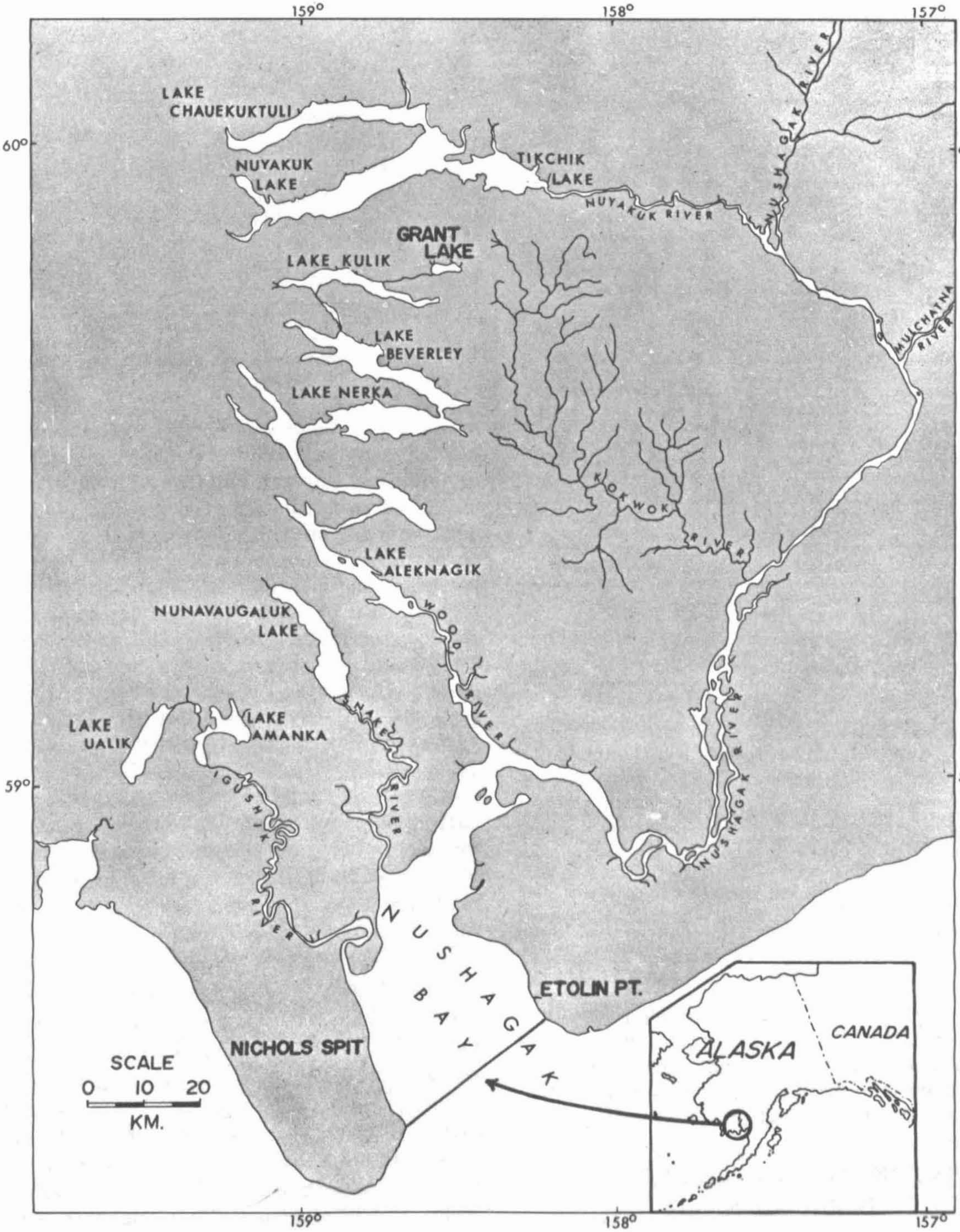

FIGURE 1.—The Nushagak District of Alaska showing (from north to south) the Tikchik, Wood River, Snake River, and Igushik River lake systems.

TABLE 1.—Commercial catches of sockeye salmon, Nushagak Bay, 1893-1945.

Year	Number of fish	Year	Number of fish
1893	640,000	1921	3,717,284
1894	860,000	1922	3,408,358
1895	938,946	1923	1,921,874
1896	1,262,690	1924	2,168,154
1897	1,240,080	1925	3,903,125
1898	1,890,092	1926	4,022,328
1899	2,517,436	1927	657,467
1900	4,234,533	1928	4,957,096
1901	5,401,051	1929	3,851,479
1902	4,725,715	1930	1,610,568
1903	6,319,189	1931	2,260,541
1904	5,345,659	1932	3,083,615
1905	7,387,935	1933	3,753,230
1906	5,427,512	1934	4,575,049
1907	2,627,351	1935	649,093
1908	6,092,031	1936	1,560,138
1909	4,906,635	1937	4,561,298
1910	4,469,755	1938	2,322,704
1911	2,957,073	1939	4,169,121
1912	3,993,428	1940	1,519,082
1913	5,409,933	1941	1,897,869
1914	6,457,815	1942	2,465,779
1915	5,904,862	1943	3,373,643
1916	3,744,551	1944	3,513,241
1917	5,847,239	1945	2,296,019
1918	6,296,702		
1919	1,477,336		
1920	2,682,056		

Sources:
1884-1927 — Rich and Ball (1928).
1929-1945 — Annual District Management Reports, District Agents. Bureau of Fisheries and Fish and Wildlife Service.

Comments:
The catches for 1884-1892 are only given in cases and therefore are not included.
For the years 1925-1946, Alaska Salmon Industry gathered data on the catch, the pack, and expended effort by the major fishing companies.
The number of fish per case is computed from the information collected by Alaska Salmon Industry. It was used for conversion of the case pack into number of fish for the years 1929, 1930, 1931, 1932, and 1941, since only the case pack is recorded for these years in the Reports of the Management Agencies.
One 200-lb. barrel of salted salmon has been set equal to 54 fish and one 350-lb. barrel equal to 95 salmon.
The official records for the year 1928 list only canneries that operated in Nushagak in this year. The catch figure used is based on records submitted to Alaska Salmon Industry from all but two canneries. The catch in the latter case was extracted from the sworn reports submitted by the fishing industry to the tax authorities.

place within 2 to 3 years. Although the other districts in the Bristol Bay region have experienced a decline in production, this decline has been neither so distinct nor so drastic in nature as in the Nushagak District.

FISHING GEAR AND AREAS IN NUSHAGAK BAY

Three types of fishing gear have been utilized in Nushagak Bay—traps, drift gill nets, and

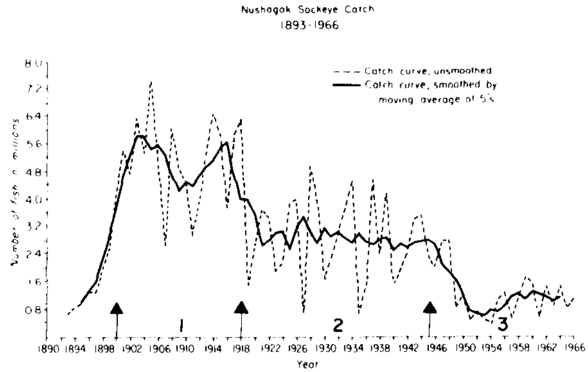

FIGURE 2.—Catches of sockeye salmon in the Nushagak fishery, 1893-1966.

stationary gill nets (set nets). Traps were not used to any great extent in the Nushagak fishery or in Bristol Bay as compared with other areas of Alaska, in which they were in widespread use. The main factor which discouraged the use of traps undoubtedly was the strong tidal currents in Bristol Bay, where tidal differences reach as high as 25 ft or more and peak water velocities reach 4 to 5 knots. These conditions permitted trap operations only in a restricted number of places. Since gear records became available in 1904 and until traps were outlawed in 1923, their number in Nushagak Bay varied from 3 to 11 (Rich and Ball, 1928).

Apparently set nets were not commonly used during the period when traps were legal. The first documented set net catches were taken in 1924, and set nets are mentioned in the 1926 regulations. A maximum length of 75 fm was set in 1926, but in 1931 maximum length was reduced to 50 fm, as is the case today. Since the advent of yearly reports by the management agent in 1929, accurate records have existed as to the distribution of effort between these two types of gear.

Up to and including 1922, no restrictions were placed on mesh size and length of the drift gill nets. In 1924, the maximum length of drift nets was set at 200 fm and mesh size of at least 5¾ inches, stretched measure, between knots. After the 1925 season, minimum size was set at 5½ inches. No other changes in mesh regulations

TABLE 2.—Catches and escapements of sockeye salmon in Nushagak District, 1946-1966.

Year	Catch	Escapement by river system			Estimated total run	Escapement as percent of total run
		Wood River	Other streams	Total		
1946	2,028,144	3,717,000	1,002,000	4,719,000	6,747,144	70.0
1947	2,767,287	1,782,000	725,000	2,507,000	5,274,287	47.5
1948	2,805,793	1,483,250	608,000	2,091,250	4,897,043	42.7
1949	800,123	101,025	37,000	138,025	938,148	14.7
1950	1,212,091	451,600	121,000	572,600	1,784,691	32.1
1951	436,950	457,600	82,000	539,600	976,550	55.3
1952	698.071	226,800	207,000	433,800	1,131,871	38.3
1953	449,341	515,542	313,000	828,542	1,277,883	64.8
1954	315,357	570,624	121,000	691,624	1,006,981	68.7
1955	1,054,978	1,382,755	551,000	1,933,755	2,988,733	64.7
1956	1,263,186	773,101	439,000	1,212,101	2,475,287	49.0
1957	491,498	288,727	210,000	498,727	990,225	50.4
1958	1,092,156	960,455	317,478	1,277,933	2,370,089	53.9
1959	1,719,687	2,209,266	832,619	3,041,885	4,761,572	63.9
1960	1,517,988	1,016,073	657,185	1,673,258	3,191,246	52.4
1961	511,483	460,737	398,896	859,633	1,371,116	62.7
1962	1,461,766	873,888	63,810	937,698	2,399,464	39.1
1963	842,744	721,404	342,452	1,063,856	1,906,600	55.8
1964	1,420,941	1,076,112	262,892	1,339,004	2,759,945	48.5
1965	793,323	675,156	424,110	1,099,266	1,892,589	58.1
1966	1,170,271	1,208,682	422,044	1,630,726	2,800,997	58.2
Total	24,853,178	20,951,797	8,137,486	29,089,283	53,942,421	--
Average 1946-1966	1,183,485	997,705	387,499	1,385,204	2,568,689	51.9

Sources:
1946-1959 — Mathisen, Burgner, and Koo (1963).
1960-1966 — Alaska Department of Fish and Game, Division of Commercial Fisheries, Bristol Bay Area, Annual Management Report 1966, 59 p.

were made until 1961, when 5⅜-inch nets were permitted.

The length of drift nets was reduced to 150 fm per boat in 1929 and has remained unchanged. However, the industry did not necessarily always feel compelled to observe these maximum and minimum limits. The gill net fishery developed before such regulations were introduced and enforced. The necessity of observing a correspondence between the pull of the boat and the drag of the gill net had more or less standardized the gear. Length of the drift net and mesh size as actually used can be studied from two other sources (Table 3).

For the period 1902-1925, the mesh sizes and lengths of the drift nets used were given in the yearly reports of two canneries belonging to Alaska Packers Association in Nushagak.

Since 1926 reports have been submitted by the operators to the Federal government concerning their canning activities. These sworn statements give the lengths of nets used by the different companies. Since the advent of statehood, gear regulations have been published annually.

There has been a gradual but steady decline of the mesh size to 5⅜ inches, stretched mesh. In contrast, the length of the drift nets has been remarkably constant. Even when an upper limit of 200 fm was introduced in 1924, many opertors used nets half this size or 100 fm. Since 1928, all drift nets have measured 150 fm long,

TABLE 3.—Mesh sizes and lengths of drift gill nets used in the Nushagak sockeye salmon fishery, 1902-1966.[a]

Year	Stretched mesh size	Length of drift net
	inches	*fathoms*
1902	6⅛-6¼	--
1903	6⅛	120
1904	6-6⅛	150
1905	6⅛	150
1906	6-6⅛	150
1907	6¹⁄₁₆-6¼	160
1908-1912	6	160
1913-1925	5¾	150[b]
1926-1927	5½-5¾	100-200[c]
1928-1960	5½	150[d], [e]
1961-1966	5⅜	150

[a] Information prior to 1925 taken from records of the Alaska Packers Association and for subsequent years from announced regulations of the Federal Authorities.
[b] A maximum legal length of 200 fm and minimum mesh size of 5¾ inches specified for 1924 and 1925.
[c] A minimum mesh size of 5½ inches set for new nets.
[d] A maximum length 150 fm set in 1929.
[e] A maximum length of 100 fm set for 1937 only.

except for the year 1937, when the maximum size was reduced to 100 fm for 1 year and only for Nushagak Bay.

Powered fishing boats were outlawed in 1922 and not permitted again until 1951. However, in the 30's the canning companies started to use small tug boats to tow the fish boats from one place to another, or most commonly to assist in bringing a boat to the delivery scow. Consequently, the efficiency of one boat increased with this added mobility. In part, it was offset by the movement of fishing boundaries over the years farther and farther out from the river mouth and thereby reduction in efficiency of the fishing gear.

In 1899, fishing above tidewater was prohibited in streams less than 500 ft in width. In the tidewater of smaller streams, gear could only cover one-third of the stream width.

In 1907, fishing in the Wood and Nushagak Rivers was prohibited within 500 yards of the mouth of Wood River. Over the years, gradually, restrictions of fishing area have been imposed, which resulted in a transfer of fishing operations away from the river and river mouth and into the open Nushagak Bay. In Figure 3 are indicated locations of canneries in operation shortly after the turn of the century. Only three plants remain actively canning in Nushagak Bay today.

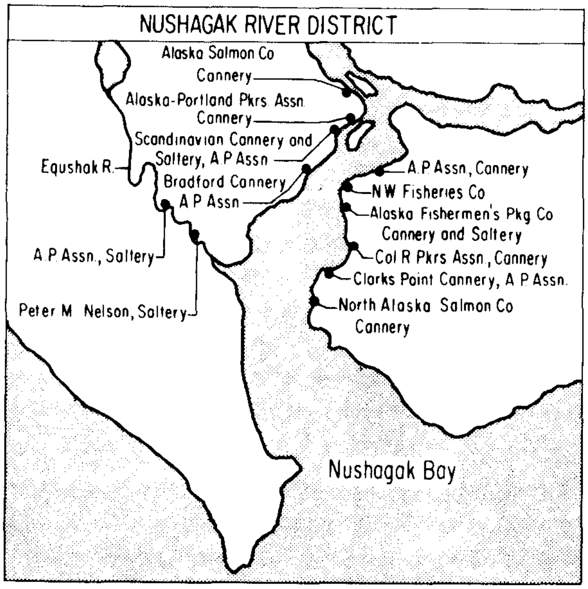

FIGURE 3.—Copy of an old map (probable date 1907) with the locations of canneries and salteries in Nushagak Bay. Canneries in operation today are the Columbia-Wards Cannery at the site of North Alaska Salmon Company Cannery, a Queen Fisheries plant near Columbia River Packers Association plant, and Pacific Alaska Fisheries Dillingham plant at the site of Alaska-Portland Packers Association.

THE NATURE OF THE SOCKEYE SALMON RUNS

All sockeye salmon runs to Bristol Bay have a very distinct and regular time schedule. Historically, the period from June 25 to July 25 has been considered as the time when the salmon are present in Nushagak Bay in catchable quantities. Records accumulated since 1955 indicate that, on the average, peak catches in Nushagak Bay were made on July 5 (Royce, 1965).

The entry is of a pulse type with exponential declining departure curves for the trunk streams and the spawning grounds (Mathisen, 1969). Bi- or trimodal catch curves, especially in earlier years, undoubtedly were created by changes in frequency or relative strength of the individual pulses. We do not know the racial composition of the individual pulses, but some tagging data (Straty, 1969) point to a fairly random mixing of individual races.

Basically, the juvenile salmon spend 1 or 2 years after emergence in the nursery areas of the freshwater lakes. They return from ocean feeding after 2 or 3 years. Thus, four different age groups will make up a year's run, namely, 1.2, 1.3, 2.2, and 2.3 (after Koo's [1962] notation). The number of fish in other age groups is insignificant and can be disregarded. The Nushagak District differs from other districts in Bristol Bay in having a preponderance of 1-freshwater check salmon.

ESCAPEMENT LEVELS IN THE NUSHAGAK DISTRICT

The history of the Nushagak fishery was divided earlier into three periods. Within each of these periods data exist in regard to escapement levels, although they differ in completeness. Naturally the best records have been assembled during the last period, while the most incomplete records exist from the middle period. The escapement records are discussed in order of completeness.

THE PERIOD 1946-1966

The records for this period are complete in the sense that escapement estimates were made for all streams draining into Nushagak Bay (Table 2). Estimates were based originally on ground or aerial surveys. In 1953, the Wood River escapement was estimated from tower counts in the trunk stream. In 1958, this technique was adopted for assessment of the Igushik escapement, and in 1959 for that of the Nuyakuk River. From 1960 to 1964, tower counting was conducted in the Snake River system and inaugurated in the Nushagak-Mulchatna River in 1966. Otherwise, escapement estimates were made by the less reliable aerial survey. The earlier estimates based on ground surveys all have in common a much larger variance, but they gain in consistency because of the fact that largely the same personnel conducted spawning surveys in all years, even after introduction of tower counts (Gilbert, 1968).

In the present context, we are not primarily interested in the year-by-year changes in catch and escapement level, rather in the overall ratio of catch to escapement over the entire period. The average catch amounted to 1,183,485 sockeye salmon and the average escapement to 1,385,204 spawners. The ratio is almost one to one; or on the average, a pair of spawners produced a progeny of four fish. In terms of fishing mortality, the rate of exploitation has averaged 48.1%.

THE PERIOD 1908-1919

No total escapement estimates exist for this period, except for the Wood River system where a counting weir was operated from 1908 to 1919 with the exception of the 1914 season. Daily counts and comments on weir building and maintenance are found in Reports of the Commissioner of Fisheries for the years in question (Table 4).

On the assumption that the ratio of the Wood River escapement to the total Nushagak escapement was the same for the years 1908-1919 as was observed during the period 1946-1966, when estimates were available of the Wood River escapement as well as of the total Nushagak escapement, then this ratio can be used to estimate the total Nushagak escapement for the years 1908-1919 from the weir counts.

The ratio of the total Nushagak escapement to the Wood River escapement has been computed in two ways from data in Table 2. The first ratio

TABLE 4.—Total Nushagak escapement 1908-1919.

Year	Wood River weir count	Estimated Nushagak escapement	Catch	Estimated total run	Escapement as percent of total run
1908	2,603,655	3,758,636	6,092,031	9,850,667	38.2
1909	893,244	1,289,487	4,906,635	6,196,122	20.8
1910	670,104	967,362	4,469,755	5,437,117	17.8
1911	354,299	511,466	2,957,073	3,468,539	14.7
1912	325,264	469,551	3,993,428	4,462,979	10.5
1913	753,109	1,087,188	5,409,933	6,497,121	16.7
1914	No count	--	6,457,815	--	--
1915	259,341	374,385	5,904,862	6,279,247	6.0
1916	551,959	796,808	3,744,551	4,541,359	17.5
1917	1,081,508	1,561,265	5,847,239	7,408,504	21.1
1918	943,202	1,361,606	6,296,702	7,658,308	17.8
1919	145,114	209,487	1,477,336	1,686,823	12.4
Total	8,580,799	12,387,241	57,557,360	63,486,786	--
Average 1908-1919	780,073	1,126,113	4,796,447	5,771,526	19.5

Sources: Reports of the Commissioner of Fisheries for the fiscal years 1908 through 1919 and special papers. Government Printing Office, Washington, D.C., 1910-1921.

is based on the data for the years 1946-1957, when the escapement estimates were made largely from ground and aerial surveys. Presumably this estimate is less reliable than the second estimate based on the years 1958-1966, when the escapement estimates were based largely on very reliable tower counts. The two ratios are 1.4438 and 1.4433.

Thus the average Wood River escapement has formed a remarkably constant proportion of the total Nushagak escapement regardless of which years are used for calculation. Consequently, the ratio 1.4436, based on data for all the years 1946-1966, has been used to enlarge the early Wood River weir counts from 1908 to 1919 to reflect the Nushagak escapement for the same years.

Estimated in this manner, the annual Nushagak escapement for the period 1908-1919 averaged 1,126,113 spawners, and the total Nushagak sockeye run averaged 5,771,526 salmon, or a rate of exploitation of 80.5%.

THE PERIOD 1925-1945

No weir counts exist for these years, and quantitative stream surveys were not conducted. However, escapement estimates can be made from available data on the catch, size distribution of the fish, sex ratio, and expended effort.

From 1926 on, the legal minimum mesh size was 5½ inches, and from 1927 the maximum length of the drift gill nets remained unaltered at 150 fm. An exception must be made for 1937, when the maximum length was reduced to 100 fm for this one year in the Nushagak fishery. Therefore, given a measure of the catch and the instantaneous rate of fishing for each centimeter group by the 5½-inch gill nets and an estimate of expended fishing effort, the escapement can be calculated by centimeter groups from the formula for competitive fishing units and summed over the size range observed in a year to give the total escapement:

$$E = \sum_{j=a}^{b} C_j \frac{1}{e^{fq_j} - 1},$$

where E = the unknown total escapement,
C_j = the known catch for size group j,
q_j = the coefficient of catchability for size group j,
f = the number of standardized fishing units, and
a and b = lower and upper bounds of the size range.

No natural mortality has been assumed during the fishing season.

Because of the different selection curves for males and females by 5½-inch mesh size, these calculations must be done separately for each sex. The necessary data for this calculation follow.

Sex Ratios

It has been assumed that no selection for sex was exerted in the collection of samples for size and age composition. Consequently, the numbers of males and females measured in a day provide an estimate of the sex ratio in the catch for that particular day. This procedure was necessitated by the absence of specific sex ratio samples.

Size Composition of the Catch

During the years considered here, the Bureau of Fisheries stationed biologists at selected canneries for collection of scale samples and length measurements. At other times, resident people were hired for the same purpose and paid a fixed amount for each scale book collected.

Generally the type of length measurements made is not indicated in the records; but it has been assumed that the procedure was to measure length from the tip of the snout to the fork of the tail. This assumption was verified by a comparison of the resulting length-frequency curves with the mean lengths of 2- and 3-ocean fish in postwar years.

Since 1946, the common procedure has been to measure the length of the sockeye salmon taken in the fishery from the middle of the eye to the fork of the tail. The Fisheries Research Institute took a series of double measurements in 1946 to provide a basis for constructing a regression line between the two types of measurements, and a conversion can be made from one measurement to the other by means of the two following equations:

$$\male : \text{ME-TF} = 536.772 + 0.8279 [(\text{snout-TF}) - 592.340]$$

$$\female : \text{ME-TF} = 527.481 + 0.8946 [(\text{snout-TF}) - 569.724]$$

Commonly, length measurements were collected throughout the fishing season. These measurements were grouped by fishing periods or by time periods for which catch records exist. Finally, a seasonal weighted length-frequency distribution was computed by the use of the period catches as weighting factors.

Expended Fishing Effort

Batts and Fischler (1967) have summarized the fishing regulations promulgated during the years 1924-1945. A summary of the allowable fishing time is given in Table 5, without consideration for the stage of the tide in relation to closed and open periods. Although the largest or smallest tides generally are inferior fishing periods compared with the medium-sized ones, no correction was attempted on the premise that the plus and minus deviations tended to cancel each other over the entire season.

The number of fishing boats that operated each year for the period 1929-1945 is recorded by the management agents in their annual reports and copied in Table 5. The size of the Nushagak fishing fleet in 1925-1928 was estimated from the data collected by the Alaska Salmon Industry. More than 60% of the total Nushagak catches during these 4 years were made by the reporting canneries, which also submitted records on the number of boats employed. By direct proportionality an estimate was derived for the total number of fishing boats and set nets that operated from 1925 to 1929 (Table 5).

So that a common unit of effort could be derived, the fishing power of set nets was expressed in terms of that for drift nets according to a method by Robson (1961).[4] The conversion was made separately for each year by consideration

[4] Robson, D. S. 1961. Estimation of the relative fishing power of individual ships. Cornell Univ., Biometrics Unit, Plant Breeding Dep., BU-133-M. (Unpublished manuscript.)

TABLE 5.—Registered fishing effort in Nushagak Bay, Bristol Bay, Alaska, 1925-1950.

Year	Total fishing time in days	Total number boats (drift nets)	Total boat day units	Total number set nets	Total set net day units	Relative efficiency set nets/boats	Set net units converted to boat units	Total effort in boat days
1925	22.000	337	7,414	66	1,452	.0717	104.0	7,518
1926	21.000	256	5,376	44	924	.1153	106.5	5,483
1927	19.500	292	5,694	68	1,326	.2796	370.7	6,065
1928	22.500	264	5,940	39	878	.3288	288.7	6,229
1929	21.000	311	6,531	115	2,415	.3613	872.5	7,404
1930	15.250	335	5,109	112	1,708	.1640	280.1	5,389
1931	13.500	351	4,739	152	2,052	.3264	669.8	5,409
1932	18.333	276	5,060	208	3,813	.1151	438.9	5,499
1933	18.688	280	5,233	167	3,121	.1617	504.7	5,738
1934	19.666	279	5,487	221	4,346	.0833	362.0	5,849
1935	9.000	65	585	154	1,386	.2981	413.2	998
1936	17.750	298	5,290	263	4,668	.5129	2,394.2	7,684
1937	19.500	236	4,602	173	3,374	.1594	537.8	5,140
1938	19.500	99	1,931	96	1,872	.2426	454.1	2,385
1939	19.000	235	4,465	144	2,736	.3217	880.2	5,345
1940	14.000	129	1,806	128	1,792	.5773	1,034.5	2,841
1941	19.000	125	2,375	116	2,204	.1803	397.4	2,772
1942	27.500	96	2,640	53	1,458	.2827	412.2	3,052
1943	21.500	119	2,559	98	2,107	.3850	811.2	3,370
1944	24.000	118	2,832	103	2,472	.2889	714.2	3,546
1945	20.000	82	1,640	164	3,280	.2134	700.0	2,340
1946	16.500	198	3,267	119	1,964	.3077	604.3	3,871
1947	21.000	181	3,801	190	3,990	.2650	1,057.4	4,858
1948	16.000	198	3,168	216	3,456	.4709	1,627.4	4,795
1949	10.400	192	1,997	272	2,829	.2255	637.9	2,635
1950	13.500	108	1,458	270	3,645	.1728	629.9	2,088

of 5 days during the peak of the fishing season. This procedure eliminated some of the variability present at the beginning or the end of the fishing season due to irregular entries or departures of the salmon. The choice of 5 days was made in order to avoid too complicated a scheme, and often more than half of the total Nushagak catch was taken during the time period considered.

In this two-way classification with two rows corresponding to drift net and set net and five columns corresponding to the time periods, the catch in 1 day and by a given type of gear is:

$$C_{ij} = f_{ij} \cdot r_i \cdot N_j \cdot \epsilon_{ij} ,$$

where f_{ij} = the number of fishing units of type i operated on day j,
r_i = the coefficient of catchability of gear type i for all size groups,
N_j = the average stock of salmon encountered by the gear on day j, and
ϵ_{ij} = error term.

If $r_{..}$ is the coefficient of catchability of a unit of a theoretical average of all types of gear, one can write $\alpha_i = r_i/r_{..}$. Similarly, if the average stock size encountered by the gear during the entire period is defined as $N_{..}$, one has $\beta_j = N_j/N_{..}$. Finally, the error term was considered log-normal (Beverton and Holt, 1957).

The random variable $Y_{ij} = \log\ (C_{ij}/f_{ij})$ can be written then as

$$Y_{ij} = m + a_i + b_j + e_{ij}.$$

Since we have only two types of gear, $\log r_2 - \log r_1 = a_2 - a_1$. An estimate of a_1 can be obtained directly from a linear hypothesis program, such as BMD 05V (Dixon, 1965), under the constraint $a_1 + a_2 = 0$. The results expressed as arithmetic ratios are listed in Table 5.

Fishing Power of 5½-Inch Gill Nets

Two size groups of fish predominate in all Bristol Bay sockeye salmon fisheries (Mathisen, Burgner, and Koo, 1963). The 3-ocean fish measure on the average from 5 to 6 cm longer than the 2-ocean fish, and the males of both size groups are between 2 and 3 cm larger than the females.

Between years there are pronounced differences in the proportion of 2- and 3-ocean fish and, to a much smaller extent, in the sex ratio of the total runs. Since during the middle part of the Nushagak fishery considered here, the mesh size of the gill nets remained stable at 5½ inches, the total fishing mortality generated by one unit of gear changed from year to year primarily with changes in the relative proportion of 2- and 3-ocean fish and males and females. Consequently, the coefficient of catchability must be determined by length or age groups, and separately for males and females. There are only 5 years, 1946-1950, with records of catch and escapement when sailboats were used together with linen gill nets. Conversion to powered fishing boats was largely accomplished by 1954, although a shift in boat types continued. At the same time nylon gill nets came into universal use. Added to these changes were modifications of boundary lines of the fishing districts. Therefore, the rate of the present-day fishing of the gear in Bristol Bay is not comparable with that which prevailed during the middle period of the Nushagak fishery.

Data on catch and escapement and the corresponding length-frequency distributions for Nushagak from 1946-1950 are available (Mathisen et al., 1963). The escapements were estimated visually and may not be too accurate. But in 1 year, 1946, when an independent estimate could be made from a tagging experiment, the correspondence was remarkably great (Mathisen, 1969). Effort during the same years is listed in Table 5. On the assumption that set net effort can be converted into drift net effort and that all units of gear were fishing simultaneously on the same stock, it is a straightforward matter of computing the coefficient of catchability for each centimeter group and separately for males and females from the expression on page 754 used in reverse.

There were rather large year-to-year variations; therefore the following smoothing process has been applied to the data. An arithmetic mean value for each centimeter group was found for the 5 years considered. A moving average of 5's of these arithmetic means provided the final values in the selection curves in Figure 4. The dip in the selection curve for males is con-

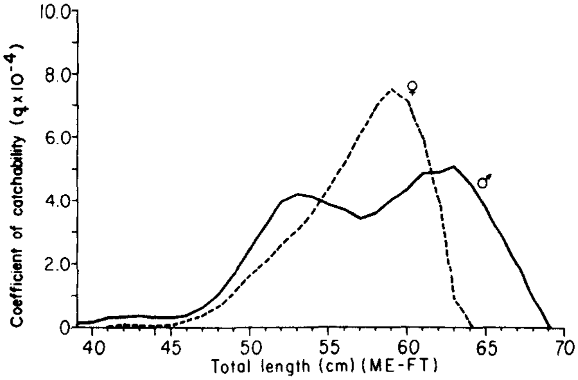

FIGURE 4.—Instantaneous rate of fishing by centimeter groups.

sidered due to statistical variability introduced by the rather small escapements in 1949 and 1950. It was further demonstrated by similar calculations for recent years with exact catch and escapement data that once the males become vulnerable to the gear, the coefficient of catchability increases only slightly from 2- to 3-ocean fish. Whereas in the lower part of the selection range, the curves are fairly similar for males and females, the rate of fishing on 3-ocean females was several times that of 2-ocean females based on the average lengths of these two groups given by Mathisen et al. (1963). As a result, in years when 2-ocean fish predominated in the run, a large preponderance of females was present in the escapement as in 1946, when there were 68% males in the catch and only 35% males in the escapement. In 1948, when there was a predominance of 3-ocean fish, the corresponding figures were 44% and 49%.

The selective action of the gill nets on the 3-ocean fish can be demonstrated further by comparison of age composition of gill net and trap catches made in the same year (Table 6). The traps can be considered nonselective and were placed close to the upper boundary line of the fishing area (Moser, 1902). Therefore, the age composition of the trap catches can be used as an estimate of the age composition of the escapement. Whereas the 2- and 3-ocean fish were present in about the same numbers, the catch by 5¾-inch gill nets contained more than five times as many 3-ocean fish as 2-ocean fish.

TABLE 6.—Age composition in trap and gill net catches in Nushagak, July 1 and 5, 1919.

Age group	Traps		Gill nets	
	Number of fish	Percent	Number of fish	Percent
1.2	65		14	
2.2	33		15	
2-ocean	98	51.9	29	15.5
1.3	83		150	
2.3	8		8	
3-ocean	91	48.1	158	84.5
Total	189		187	

Source: Clark, Frances N. 1933. Red salmon in the Nushagak District of Bristol Bay Alaska. (U.S. Bureau of Fisheries) Natl. Mar. Fish. Serv., Biol. Lab., Auke Bay, Alaska. (Unpublished manuscript.)

ESTIMATED ESCAPEMENTS, 1925-1945

When the calculations outlined above are executed, an estimated escapement for each of the years from 1925 to 1945 is obtained (Table 7). Two years, 1932 and 1938, were not included in the computation of an average escapement level since no length measurements were taken in these years. No measurements were taken in the fishery in 1931; instead, scales and measurements were collected in the Wood River, and this length-frequency distribution has been

TABLE 7.—Calculated escapements and total runs in Nushagak District, 1925-1945.

Year	Total catch	Total escapement	Estimated total run	Escapement as percent of total run
1925	3,903,120	285,081	4,188,201	6.8
1926	4,022,333	697,730	4,720,063	14.8
1927	657,468	803,643	1,461,111	55.0
1928	4,957,072	1,383,130	6,340,202	21.8
1929	3,851,482	754,125	4,605,607	16.4
1930	1,610,568	3,158,751	4,769,319	66.2
1931	2,260,539	491,877	2,752,416	17.9
1932	3,083,165	--	--	--
1933	3,753,230	1,995,688	5,748,918	34.7
1934	4,575,043	1,791,481	6,366,524	28.1
1935	649,093	2,277,858	2,926,951	77.8
1936	1,560,135	1,816,382	3,376,517	53.8
1937	4,561,297	10,118,033	14,679,330	68.9
1938	2,322,704	--	--	--
1939	4,169,122	361,356	4,530,478	8.0
1940	1,519,082	990,237	2,509,319	39.5
1941	1,897,870	1,197,981	3,095,851	38.7
1942	2,465,779	1,586,861	4,052,640	39.2
1943	3,373,650	1,762,232	5,135,882	34.3
1944	3,513,236	1,335,734	4,848,970	27.6
1945	2,296,020	1,614,470	3,910,490	41.3
Total	61,002,458	34,422,650	90,018,789	--
Average 1925-1945	2,904,879	1,811,718	4,737,831	38.2

used. Since the fish in the escapement average smaller than in the catch, it will result in an overestimate of the total run for this year.

Unquestionably, the computed escapements are subject to many sources of error, and they reflect only the general magnitude of the escapements. In general there are some measurements from each fishing period that can be weighted by the corresponding catches, and any unrepresentativeness of the sampling was in part corrected. It therefore appears that the greatest bias arises from the way in which fish were selected and measured. In 1930, for example, there were few measurements taken, and they included a rather high proportion of suspiciously small 2-ocean females, which resulted in the rather large estimated total escapement. Almost 12,000 measurements were made in 1937, but largely of fish from the resident set net fishery near the upper fishing boundary. The result is an underestimate of the mean average length in the commercial catches, since the run at this point had been subjected to the selection of the drift net fishery; the calculated escapement is substantially inflated. In 1939 no 2-ocean fish were measured in drift net catches, and therefore the low rate of escapement may be substantially correct.

The International North Pacific Fisheries Commission (1962) has published estimates of Nushagak escapements for the period considered here. A fishing rate common for all size groups, and with no distinction between males and females, was computed from Bristol Bay catch and escapement data for 1955-1957. Furthermore, nylon gill nets were used and were operated from power boats. Because of the selective action of the gill nets for males and females, and for 2- and 3-ocean fish, it is easy to understand that these estimates are entirely different from those presented here.

SUMMARY OF RESULTS

On the previous pages, escapement levels were calculated for the three distinct periods of the Nushagak fishery shown by the catches on Figure 2. These results have been summarized in Table 8.

TABLE 8.—Rate of exploitation in three periods of the Nushagak fishery.

Period	Average escapement	Average catch	Exploitation
	Thousands	*Thousands*	%
1908-1919	1,126	4,796	81
1925-1945	1,812	2,905	62
1946-1966	1,385	1,183	48

During the early period of the fishery, the runs sustained a fishing mortality of more than 80% until 1919 when all runs to Bristol Bay suffered a drastic decline. The universality of this decline in many sockeye salmon systems suggests that the causes must be sought in changes in the environment and not in the mode of fishing operation. The Nushagak runs never returned to their former level, in contrast to those of the other systems in Bristol Bay, notably those to the Kvichak River.

During the middle period, here defined as the time from 1925 to 1945, the amplitude of the year-to-year oscillation increased (Figure 2).

Following the last World War, not only did the Nushagak and other Bristol Bay sockeye salmon runs decline, but many of the Kamchatka salmon runs did too (Krogius and Krokhin, 1956). The widespread decline suggests again that environmental and probably oceanographic conditions not related to fishing depressed the survival. In the third period of the Nushagak fishery the runs remained at a very low level, compared with levels of the two previous periods.

Concomitant with this stepwise decline in average yield, there has been a decrease of the reproductive potential of the Nushagak sockeye salmon runs. Whereas during the early period of the Nushagak fishery, the runs were exposed to an exploitation rate of nearly 80%, during the middle period of the Nushagak fishery, the runs were exposed to an exploitation rate of around 60%. During the last period, the exploitation rate was around 50%, largely set by the regulation. The runs are maintaining themselves, but so far no substantial increase is apparent.

Thus the rate of return per spawner has fallen from five to less than three and finally to two mature fish. As a result, there has been no increase to former run levels in spite of the reduced exploitation rates. This situation is in contrast to the situation in the Fraser River, where the removal of the Hell's Gate blockade and increased escapements initiated almost an immediate increase in the returns in some river systems.

Therefore, it remains for us to explore if any changes have occurred in the Nushagak runs that can explain the described reduction in reproductive potential.

DISCUSSION

No visible changes have taken place in the Nushagak environment since fishing commenced there before the turn of the century. Even today there are no dams or any other obstruction to the migrating salmon. The resident population still remains so low that pollution problems or any form of industrial waste are nonexistent. Neither has the subsistence fishery increased in volume and an estimated 30,000 or more of all species are harvested today. Other freshwater fishes were not or were lightly harvested until recent years, when a recreational fishery for trout and char has developed.

A sockeye salmon run to a watershed such as the Nushagak District is made up of a great number of races that differ in morphological features, age structure, time and place of spawning, and reproductive rate. The most direct effect of overfishing would be the disappearance of certain races, or at least a reduction in their numerical size to the point where they cease to be important contributors to the commercial catches. If this were true, it could manifest itself on the spawning grounds after the various races have segregated. The number of spawners per unit of nursery area reflects the stock strength on a spatial basis.

There are some river systems within the Nushagak District with low spawning density relative to that of others. For 1955-1962 the average number of spawners per square kilometer of lake rearing area in the Tikchik Lakes was 280 and in Lake Nunavaugaluk 290. In contrast, the spawning density in the Wood River lakes was 2,340 fish per square kilometer of lake rearing area and 4,360 fish in the Igushik system (Burgner et al., 1969). There is no evidence available to indicate that this was different in the early history of the Nushagak fishery. While there are relatively more 3-ocean fish in the Tikchik runs than elsewhere in the Nushagak system and hence a higher fishing mortality, the scarcity of spawning beaches and streams precludes both here and in the Nunavagaluk system the possibility of a large population prior to commercial exploitation.

The possibility still remains that the individual races may pass through the fishery at different times and thereby be exposed to different fishing rates. If this were so, one might expect to see some shift in time when peak abundance occurred. This was studied by plotting the dates when 10, 50, and 90% of the commercial catches were made (Figure 5). From 1895 to 1947, the two first points were reached at the same time aside from simultaneous year-to-year variations. There are some indications in Figure 5 that salmon were present longer in Nushagak Bay in years prior to 1920, but when one considers the exponential rate of departure to the spawning streams from the fishing grounds, the larger total runs during these years would account for such a prolongation of the fishing season. Added to this consideration is the fact that the canneries

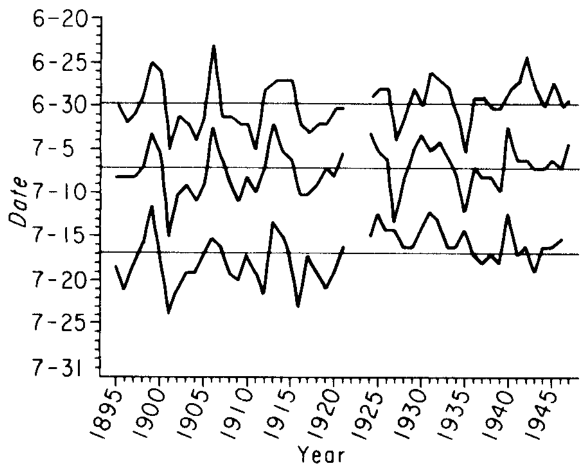

FIGURE 5.—Data on which 10, 50, and 90% of the Nushagak catch was made, 1895-1947. (Subsequent years omitted since a progressively stricter curtailment of fishing time prevented direct comparison with former years.)

usually set production goals in this period and extended fishing until these goals were reached.

As a result, one may conclude that 70 years of intensive harvesting have not drastically affected the timing of the Nushagak runs. All tagging experiments conducted in Bristol Bay point to a complete mixing of all races in the fishery and exposure to the same fishing pressure in a specific river system (Smith, 1964; Mathisen, 1969; Straty, 1969). Thus there is very little evidence of a differential rate of removal in time among all the races that constitute the Nushagak sockeye salmon run. The only exception seems to be the races bound for the Igushik system. Their migration path follows the west side of Nushagak Bay past Nichol's Spit. In earlier years when the main fishing activities were concentrated closer to the confluence of the Nushagak and Wood Rivers than they are today, the fishing pressure on the Igushik races during those years was lower.

A differential fishing pressure could arise from the selectivity of the gill nets if some Nushagak races consisted primarily of 3-ocean fish while in others 2-ocean fish predominated. Burgner (1964) has pointed out the preponderance of 3-ocean fish to the Tikchik as one example. However, if a diminution of such races were of any real consequence, it must manifest itself in changes of the age composition through the recorded history of the Nushagak fishery. The figures in Table 9 are based on the age composition in the commercial catches. Because of the larger net sizes used up to 1926, a bias is introduced in favor of 3-ocean fish and only the last two periods are directly comparable.

Throughout all years the majority of the fish migrated to sea as age 1 smolts and returned in somewhat the same proportion of 2- and 3-ocean fish. Over the years one can notice a shift, with less 3-ocean fish in the catches of males in recent years. If similar data were available for the escapement, and thereby of the total runs, one would in all probability see more of a contrast in the shift from 3- to 2-ocean female fish, especially in the years when mesh sizes were larger than 5½ inches. A mesh size experiment conducted in 1928 by the Bureau of Fisheries illustrates this point. The log ratio of catches made with nets of 5½-inch and 6-inch mesh sizes are plotted by centimeter groups in Figure 6 and form an expected straight line. The aberrant points toward the upper size range are due to a much larger sampling error because of the very few fish present at these sizes.

The essential element of an escapement is not the total number of fish present but the potential egg deposition they represent. During the first period of the Nushagak fishery, when net sizes ranged from 6¼ to 5¾ inches, escapements of the same numerical magnitude as in later years must have represented a substantially higher potential egg deposition since a much higher proportion of 3-ocean females was included in those escapements than in years with 5½-inch mesh size. On the average, 3-ocean females produce 650 eggs more per female than 2-ocean fish. The mean fecundity of these two groups are 3,639 and 4,290 eggs, respectively (Mathisen, 1962).

This net selection has another, more intangible aspect. Not only is fecundity greater in the larger 3-ocean females, but egg size is also a function of the size of the females (Mathisen, 1962). Thus there may be a higher survival of the progeny in this case than from eggs produced by 2-ocean females in the same environment. This concern was expressed in 1927 by

TABLE 9.—Summary of age in the commercial catches of sockeye salmon in Nushagak.

Sex	Period	Age-groups					No. of years sampled	2-ocean	3-ocean
		1.2	2.2	1.3	2.3	Others			
Male	1912-1919	21.32	8.66	57.08	11.11	1.83	6	21.98	68.19
	1925-1945	35.77	8.95	48.16	5.38	1.59	18	44.82	53.54
	1946-1966	42.19	9.55	40.77	4.12	3.37	21	51.74	44.89
Female	1912-1919	27.11	9.80	51.25	11.08	0.76	6	36.91	62.33
	1925-1945	25.42	7.05	60.48	4.97	1.43	18	32.47	65.45
	1946-1966	27.12	5.91	56.62	5.57	4.78	21	33.03	62.19

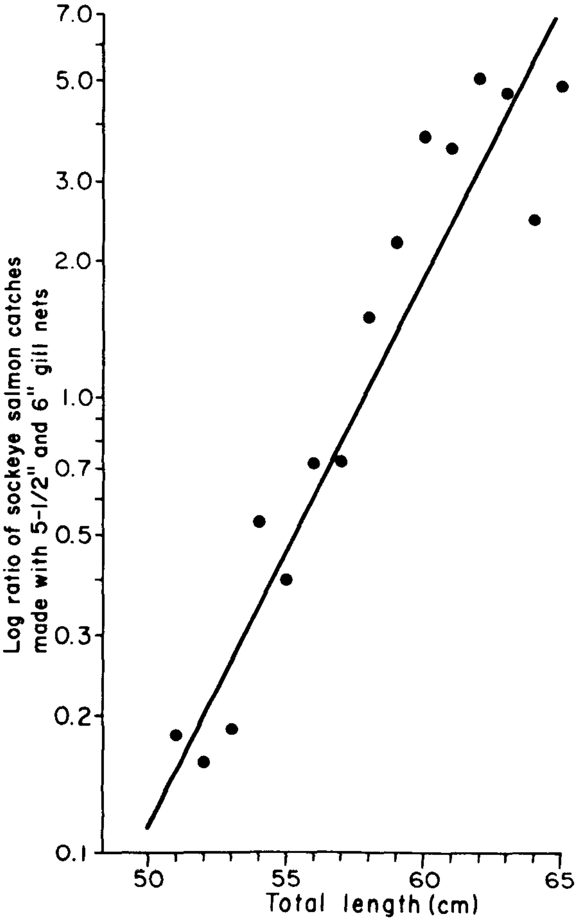

FIGURE 6.—Log ratio of catches made in Nushagak, 1928, by 6- and 5½-inch gill nets. Males and females combined by centimeter groups.

Gilbert, who wrote in a letter to Commissioner H. O'Malley:

> As a result of this screening process, we are selecting for breeding purposes predominantly the younger or less robust members of the colony, those that are dwarfed by reason of early maturity or lack of growth vigor. The effect of such continued breeding from the least fit of the community must result, it would seem, in the gradual impoverishment of the race and the reduction in size and value of the individuals composing it.

The inference may be made that the observed shifts in run strength and productivity in Nushagak are associated with changes in gear selectivity, by a shift to smaller net sizes over the years which reduced the potential egg deposition rather than the numerical size of the escapements. Such an explanation would be most appropriate for the transfer from the first to the second major period of the Nushagak fishery in 1919. But this argument loses some strength when other sockeye salmon systems outside Bristol Bay are considered.

The given description of the Nushagak fishery and reduction of reproductive rate are almost identical to that described for the Karluk sockeye fishery by Rounsefell (1958). A major portion of the Karluk River catches were taken in beach seines at the river mouth or in adjacent traps, both of which are nonselective for size. Gill nets never played a dominant part in harvest of the Karluk sockeye salmon. In spite of the absence of gear selective for size, a selection from the middle part of the run was present (Thompson, 1951).

The Chignik fishery offers another example. Recently Dahlberg (1968) and others before him have pointed out the almost identical catch curves for the Chignik and Nushagak fishery. In the Chignik fishery one can distinguish three major production levels, and the relative position of these are the same as observed in Nushagak (Figure 7). The only difference is that the fall from an initial high production level to an intermediate one came a few years later, 1926-1927, in the case of the Chignik fishery. Traps were for a long time the principal fishing

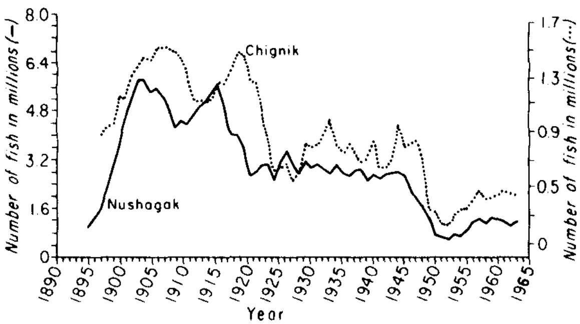

FIGURE 7.—Comparison of catches of sockeye salmon in the Chignik and Nushagak fisheries. Curves smoothed by a moving average of 5's.

gear at Chignik, later supplemented with seines, which today are the only gear operated. Gillnetting never became effective at Chignik because of the clear water there and the narrow channel. But as in the case of the Karluk fishery, there has been a selection and domination of certain races (Dahlberg, 1968).

In three important sockeye-producing systems, the historical development has been the same and resulted in a continuous decline of return per spawner. Dahlberg sees the cause as differential fishing mortality on the Chignik Lake and Black Lake races with an overfishing on the latter ones. Rounsefell (1958) suspects the effect of predation and stabilization of predator populations in the absence of the former large contrast between off and peak years as the principal cause. The evidence presented for the Nushagak fishery points to various effects of net selectivity as a major contributing factor. Viewed by themselves, each of the presented explanations may appear plausible, but the almost identical happenings in three unrelated systems suggest that a common underlying cause also may be operating.

In all three cases the decline started two decades or so after large-scale commercial harvest had been in operation. Provided the initial rate of reproduction remained the same the spawning stock or the potential egg deposition was sufficient to maintain the runs, or rebuild them after stringent regulations were put into effect.

One might conclude that the primary production of the nursery areas, which all are oligotrophic lakes in the three mentioned systems, started a slow decline from the moment fishing began, and the enrichment from salmon carcasses was substantially reduced relative to the situation which prevailed prior to commercial harvest.

Clearly, a hypothesis of this type cannot be demonstrated from the data presented. Rather, conclusive evidence must be sought from other sources. One is descriptive and involves a study of the sedimentation rates in prefishing years and in recent ones from bottom cores. Great changes in basic lake productivity should be reflected in the yearly sedimentation rate of diatom shells. Donaldson (1967) has demonstrated that changes in escapement level are indicated by phosphorus content of corresponding bottom sediments.

Experimental evidence on the role of the biogenic enrichment from salmon carcasses can be obtained from a lake fertilization similar in content, volume, and mode of dispersion to that provided by the dying spawners themselves.

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