

**STUDIES ON THE EFFECT OF WINTER CLIMATE ON
SURVIVAL OF SOCKEYE SALMON EMBRYOS IN THE
WOOD RIVER LAKES, ALASKA, 1952-1959**

by

Wilbur A. Church and Robert L. Burgner
Fisheries Research Institute (FRI), University of Washington

1960
(Revised 2009)



FRI cabin at Lake Nerka in winter (photo by pilot Don Wren)



**UNIVERSITY OF WASHINGTON
SCHOOL OF AQUATIC
& FISHERY SCIENCES**

STUDIES ON THE EFFECT OF WINTER CLIMATE ON SURVIVAL OF SOCKEYE SALMON EMBRYOS IN THE WOOD RIVER LAKES, ALASKA, 1952-1959

Wilbur A. Church and Robert L. Burgner

ABSTRACT: A 7-year study (1952-1959) was conducted on the effects of winter climatic conditions on survival of sockeye salmon (*Oncorhynchus nerka*) eggs and alevins in the Wood River Lake system, Bristol Bay, Alaska. Daily records of air temperature, precipitation, snowfall, snow depth, lake water temperature, lake ice depth, and lake level were maintained at Nerka Station, Lake Nerka. Freezing in the spawning gravel was more severe in lake-beach spawning areas than in rivers, tributary streams, and spring areas. Spawning occurred in littoral beach areas of upwelling ground water. Winter progression of freezing in lake-beach spawning areas was measured with a portable potentiometer with iron-constantan thermocouples and by freezing of small water-filled vials inserted in the gravels. In four lake-beach study areas, annual redd distribution by locality and depth of spawning was plotted over a period of three years to estimate egg-alevin mortality resulting from freezing of spawning gravels. Distribution and density of redds varied among the beach localities. All spawning occurred between the 0.6- and 3.0-m depth contours, and the areas of greatest spawning density were located in the middle depth ranges and in areas of strong upwelling of ground water. For the 1956 year class, estimated winter mortality in redds ranged between zero and 18% among the four study beaches. The size of the spawning population and water level at time of spawning caused considerable year-to-year variation in the observed spawning distribution and in vulnerability of redds to freezing mortalities. Mortality estimates from freezing in the study areas for six of the seven study years ranged between zero and 30%.

TABLE OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES	v
LIST OF FIGURES	v
INTRODUCTION	1
The Wood River Lakes	1
History of Winter Studies	2
Scope of Report.....	4
Previous Studies.....	4
THE SEASONAL CLIMATIC CYCLE.....	5
Air Temperature.....	6
Lake Temperature	7
Precipitation	8
Lake Water Level.....	9
Snow Depth.....	10
Lake Ice Formation	12
INFLUENCE OF CLIMATE ON SPAWNING AREAS: GENERAL OBSERVATIONS	13
Influence of Ground Water on Gravel Temperature.....	13
Progression of Freezing in Winter	15
Lake beach areas	15
Stream areas	18
COMPARISONS OF EGG AND ALEVIN MORTALITY IN THE LAKE BEACH STUDY AREAS	19
Necessity for Study Areas.....	19
Description of Study Areas.....	20
Methods of Observation.....	20
Mapping of study areas.....	20
Marking of redds.....	20
Measuring gravel temperatures.....	21
Egg and alevin recovery	22
Freezing vials	23
Mortality Comparisons Among Lake Beach Areas, 1956-1957 Winter.....	24
Between-Year Comparisons of Climatic Effects.....	28
ACKNOWLEDGMENTS	33
REFERENCES	34

LIST OF TABLES

Table 1. Mean monthly precipitation, snowfall, and air temperature at Lake Nerka (January 1952-October 1958) and Dillingham, Alaska (1881-1933; Mertie 1938). Dillingham climate data prior to March 1919 were from Fort Alexander, 6.4 km southeast of Dillingham.	5
Table 2. Dates of break-up and freeze-up of lake ice at Lake Nerka, 1952-1958.	8
Table 3. Percentage distribution of sockeye salmon redds by depth contour from a fixed reference point on study beaches on Lake Nerka, 1956-1958.	24
Table 4. Distribution of sockeye salmon redds by depth contour from a reference point on study beaches on Lake Nerka, 1956-1958.	30

LIST OF FIGURES

Figure 1. The Wood River Lake system, Bristol Bay, Alaska. Drawing by Marg Burgner based on maps in Mertie (1938).	1
Figure 2. Lake Nerka winter study area, Wood River Lake system, Bristol Bay, Alaska (from a sketch by Lee Church).	3
Figure 3. The seasonal pattern of daily mean air temperatures at Lake Nerka, January 1952-October 1958 (averaged by 5-day periods).	7
Figure 4. Average Cabin Bay water surface temperatures (°C), Lake Nerka 1952- 1958 (6:00 P.M. temperatures). Shaded boxes indicate lake ice.	7
Figure 5. Cumulative monthly average precipitation (cm) at Cabin Bay, Lake Nerka, 1952-1958.	9
Figure 6. Mean annual cycle of water level at Cabin Bay, Lake Nerka, 1952-1958.....	10
Figure 7. Cumulative monthly average snowfall (cm) at Cabin Bay, Lake Nerka, October-May, 1952-1958.....	10
Figure 8. Mean annual cycle of snow depth (cm) at Cabin Bay, Lake Nerka, October-June 1952-1958.....	11
Figure 9. An example of lake ice formation (depth of freezing in cm) at Cabin Bay, Lake Nerka, November-May 1955-1956.....	12
Figure 10. The spring-fed spawning area of Pick Creek on Lake Nerka (photo by Robert Burgner, August 1959).	13
Figure 11. Progression of freezing in a sockeye salmon spawning beach, as illustrated by observations made at A-Creek beach, Little Togiak Lake during winter 1955-1956.....	16
Figure 12. Distribution of sockeye salmon redds in unfrozen and frozen areas at A-Creek beach, Little Togiak Lake during winter 1955-1956.	18
Figure 13. Wilbur Church deploying thermocouples used to measure gravel temperatures in sockeye salmon beach spawning areas.	21
Figure 14. The distribution of redds and frozen redds of sockeye salmon by depth contour in South Pick Creek Beach, winter 1956-1957.....	25
Figure 15. The distribution of redds and frozen redds of sockeye salmon by depth contour in North Pick Creek Beach, winter 1956-1957.....	26
Figure 16. The distribution of redds and frozen redds of sockeye salmon by depth contour in North Elva Creek Beach, winter 1956-1957.	27
Figure 17. The distribution of redds and frozen redds of sockeye salmon by depth contour in South Elva Creek Beach, winter 1956-1957.	28

INTRODUCTION

The Wood River Lakes

The studies described herein were conducted in 1952-1959 in the Wood River Lakes, Alaska. These lakes are the major spawning grounds of sockeye salmon (*Oncorhynchus nerka* Walbaum) of the Nushagak district, Bristol Bay. Annual sockeye salmon runs to this district varied between one and five million fish during the study period, of which approximately half were allowed to pass through the fishery to the spawning grounds.

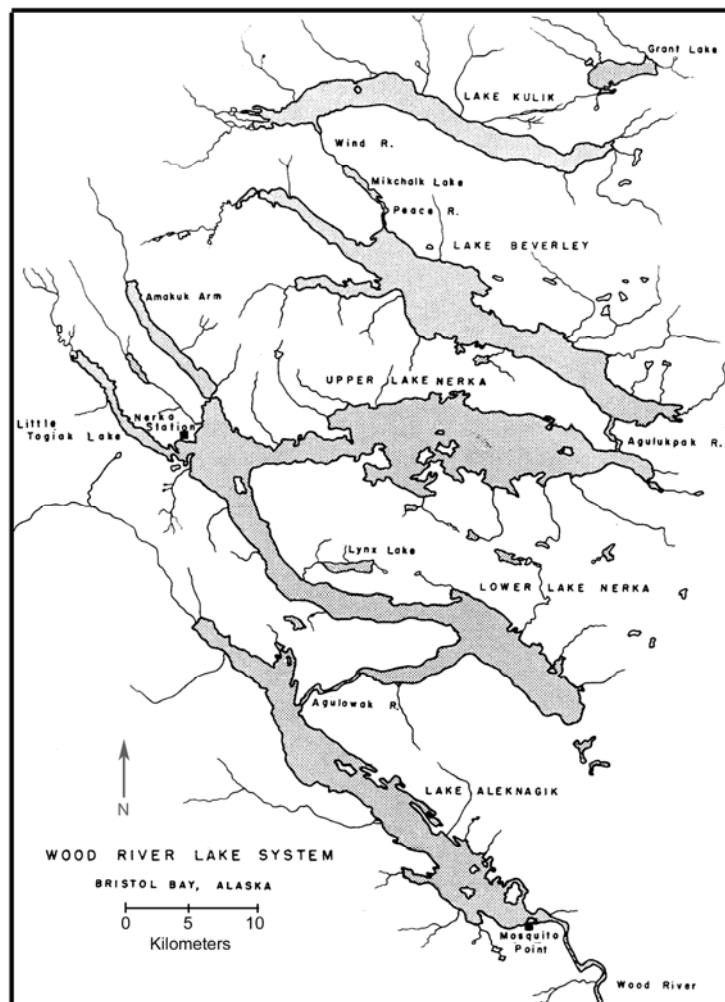


Figure 1. The Wood River Lake system, Bristol Bay, Alaska. Drawing by Marg Burgner based on maps in Mertie (1938).

The Wood River Lake system is a chain of four major lakes connected by short rivers (Figure 1). Each lake supports a share of the spawning runs, individual lakes varying in relative importance from year to year. Spawning in the lakes takes place in tributary creeks, lake beaches, and the connecting rivers of the system. Although sometimes included as part of creek spawning, upwelling spring areas form an additional important type of spawning area. Tributaries may be divided further into spring-fed and non-spring-fed creeks.

Each lake is a rearing area for the young sockeye produced by the spawning along its beaches and in its tributaries. The production of sockeye in individual lakes fluctuates from year to year as a result of differences in spawning density and differing mortalities of the resultant progeny.

History of Winter Studies

Studies of fluctuations in abundance of sockeye salmon in the Wood River Lakes were begun in 1946 by the Fisheries Research Institute of the University of Washington. Following a basic plan established by Dr. W. F. Thompson, as first Director of the Institute, systems of observation were established where possible to determine the relative numbers of sockeye surviving each life stage, in order to fix the time, place and causes of changes in abundance. These observations have shown that freshwater survival is highly variable (Burgner 1958). Lake environment studies, of which the winter studies were a part, were initiated to pin-point if possible the time and causes of major mortalities in fresh water. The winter studies were directed primarily at the extent and causes of mortalities in the egg and alevin stages of development.

Following a reconnaissance survey by Richard Charlton in 1950, winter environment studies were begun in January, 1952, under the direction of Robert L. Burgner. Lake Nerka was chosen as the study site because it was centrally located and had varied spawning area types. A year-round field station was constructed in Cabin Bay, near the mouth of Little Togiak River (Figure 2). The winter field studies were conducted primarily by Wilbur A. Church, assisted by his wife, Lee.

Early studies were mainly exploratory, seeking to determine what program could be carried out under winter conditions. Observations were made on the effect of weather on the flow of ground water, formation of ice, and the water levels of lakes and streams. An experimental study of the insulating value of snow was conducted. Comparisons were made of environmental conditions in spawning and non-spawning areas.

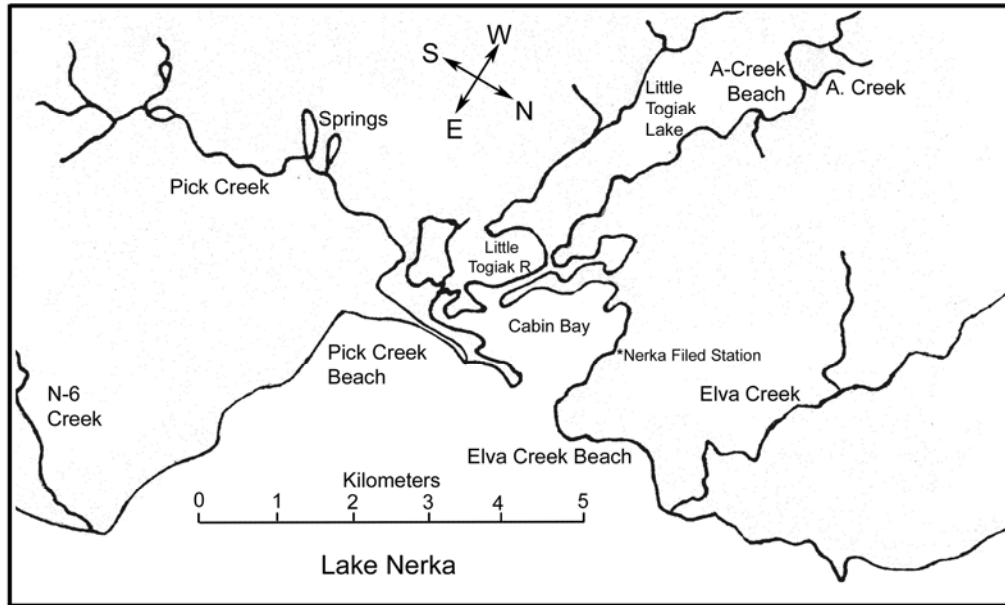


Figure 2. Lake Nerka winter study area, Wood River Lake system, Bristol Bay, Alaska (from a sketch by Lee Church).

Gravel temperature studies were begun in the winter of 1952-1953 and continued until 1958-1959. Beach spawning study areas included Elva Creek Beach and Pick Creek Beach, Lake Nerka and A-Creek Beach, Little Togiak Lake (Figure 2). Creek study areas included Elva Creek, Pick Creek, and Little Togiak River. Although other beaches and creeks of Lake Nerka and Little Togiak Lake were investigated, winter travel difficulties limited operations in those areas. Samples of eggs or larvae were taken during the winter and spring to determine the effect of temperature and changing gravel conditions on the rate of development and survival. Spring sampling was conducted every year in all areas where gravel temperature records had been obtained.

Beginning in 1956 the areas of detailed study were limited to selected sections of the larger areas then under observation in order to obtain more detailed information. Studies in these areas included size and distribution of spawning populations, weather observations, ice and snow depths, gravel temperatures, egg sampling to determine mortality and effect of climate on gravel conditions.

Scope of Report

A major objective of the winter environment studies was to determine the time and cause of mortalities to sockeye salmon eggs and alevins in the gravel. It was found during the course of the studies that freezing in the spawning gravel was a particularly important source of egg mortality. The present report deals with freezing, its causes, and its effect on eggs and larvae. Since freezing was most severe in lake-beach spawning areas, studies in these areas are described in more detail.

An understanding of the climatic cycle of the Wood River Lakes is necessary to relate climatic and environmental factors to the occurrence of freezing in the spawning gravel. The normal annual cycle of climatic factors is first presented, and deviations from these patterns will later be shown to determine the progression and extent of freezing that occurs in the gravel. Differing egg mortalities in areas subjected to the same climatic conditions will be discussed.

In our initial study temperatures were recorded in degrees Fahrenheit and physical measurements in feet and inches. In this revised report the temperature data have been converted to Celsius and physical measurements to the metric system.

Previous Studies

At the time of these studies there was little published information on the effect of climate on survival of sockeye embryos. Studies by Russian scientists indicated that winter climate was an important factor in survival of sockeye salmon eggs on the Kamchatka Peninsula. Krogus (1951, p. 12) stated: "...in Lake Dalnee in 1938 and 1947 the spawning places were frozen over and the mortality rate of the eggs was very high: as a result the production of migrants was very small." She commented further (p. 12): "Unfavorable environmental conditions during the incubation period can become so damaging to the development of the eggs that their survival sharply decreases, and the low abundance of the fry cannot be compensated even by the increased survival of the young fish." Krogus made no mention of the climatic factors which brought about the freezing or the unfavorable environmental conditions.

Krogus and Krokhin (1956) discussed the importance of ground water in removing the harmful products of metabolism from the sockeye nests, but did not mention ground water in connection with freezing. They did find that precipitation was important in maintaining the flow of ground water to the spawning grounds. They stated

(pp. 8-9): "A decrease in the ground-water flow in years with small quantities of precipitation frequently is the cause of considerable loss of eggs during incubation."

THE SEASONAL CLIMATIC CYCLE

Essentially, the winter conditions existing on a sockeye lake spawning beach are the result of the balance achieved between low temperatures and protective cover afforded by lake water level and snow cover. During the early winter, most of the protective cover is afforded by the depth of water over the redds. As the winter progresses, however, the water level drops and protection thus lost must be replaced by snow depth. In the Wood River system, low temperatures are inevitable at some time during the winter. The extent of mortalities is then determined by the severity of the weather and the protection afforded against it. While there is little actual loss of eggs in late fall (October, November), weather conditions at this time are extremely important. High temperatures will be accompanied by precipitation, maintaining water levels and beginning the build-up of snow cover. The opposite is of course true with low temperatures.

Table 1. Mean monthly precipitation, snowfall, and air temperature at Lake Nerka (January 1952-October 1958) and Dillingham, Alaska (1881-1933; Mertie 1938). Dillingham climate data prior to March 1919 were from Fort Alexander, 6.4 km southeast of Dillingham.

Month	Mean precipitation (cm)		Mean snowfall (cm)		Mean air temperature (°C)	
	Lake Nerka	Dilling- ham	Lake Nerka	Dilling- ham	Lake Nerka	Dilling- ham
July	15.21	7.37	0.00	0.00	13.17	12.89
August	17.35	10.16	0.00	0.00	12.50	12.50
September	17.27	10.49	0.00	0.51	8.17	8.22
October	16.21	6.81	8.89	8.13	1.17	2.11
November	15.95	4.52	60.71	22.61	-4.28	-4.22
December	6.71	3.58	66.80	33.02	-14.61	-9.00
January	11.25	4.45	78.49	28.70	-14.00	-8.72
February	10.54	3.45	104.14	22.61	-13.89	-8.50
March	10.29	4.72	59.44	34.80	-7.67	-5.83
April	7.21	3.10	33.27	9.91	-1.89	-1.56
May	11.96	4.11	2.29	5.84	4.56	4.94
June	10.72	4.60	0.00	0.00	10.50	11.11
Annual	150.67	67.36	414.02	166.12	-0.50	1.17

Weather records were kept at Lake Nerka beginning in January 1952 and continuing until October 1958. Records of air temperature, precipitation, snowfall, and snow depth were taken in cooperation with the U.S. Weather Bureau. Other records kept at the Lake Nerka station include water temperature, ice depth and lake level. Climatic data had been recorded by the U.S. Weather Bureau at Dillingham and vicinity since 1881. However, although Dillingham is only 40 miles south of Lake Nerka station, significant climatic differences exist (Table 1). Much more precipitation falls at Lake Nerka, and air temperatures are much lower in winter, although very similar for the rest of the year.

Although the climatological data at Lake Nerka were obtained over a relatively short period of seven years, it enabled the observer to compile a seasonal weather cycle representative of that vicinity. The weather cycle is discussed below. It will be shown later how deviations from this cycle altered survival of sockeye eggs and alevins in the gravel of the lake beaches.

Air Temperature

The seasonal pattern of mean air temperatures at Lake Nerka during the study period is shown in Figure 3. Daily means $((\text{maximum} + \text{minimum})/2)$ are averaged over 5-day periods. During the summer season, from the middle of June to late August, there was little variation from the mean air temperature of 12.8°C. The warmest days may reach 27°C or higher, but there were few days when the temperature rose above 21°C. Freezing temperatures were uncommon after June 1 and before September 1. The seasonal pattern was for daily mean temperatures to drop below freezing by late October, and remain below until late April.

The pattern indicated a sharp drop in air temperature in early December to a mean of -14.2°C for the three winter months of December-February. Any of the three months may be the coldest of the winter. The coldest month of the winter always had a mean temperature below -17.8°C. Minimum temperatures dropped below -40°C only during the coldest weather, but temperatures in the vicinity of -34°C were common. Although minimum temperatures below -17.8°C still occurred in March and April, maximum temperatures were increasing, rising above freezing in April.

The mean annual temperature for the seven years of observation was -0.5°C. The recorded extremes were 34.4°C maximum and -45°C minimum.

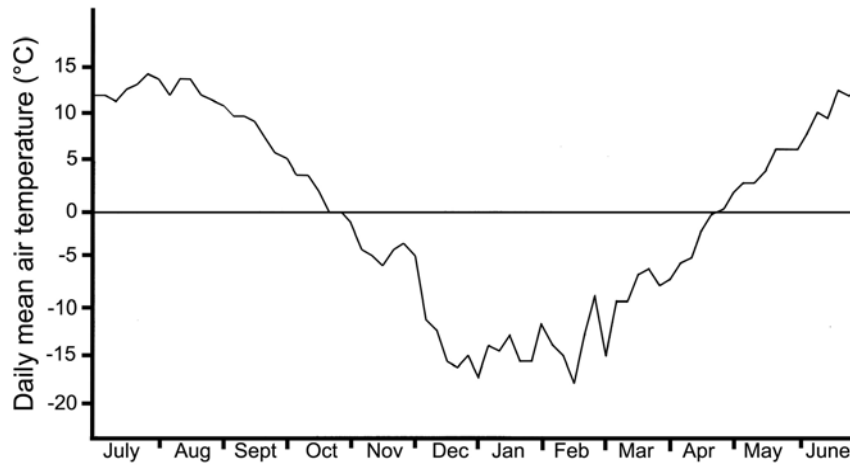


Figure 3. The seasonal pattern of daily mean air temperatures at Lake Nerka, January 1952-October 1958 (averaged by 5-day periods).

Lake Temperature

Water surface temperatures (Figure 4) were taken in Cabin Bay at the Lake Nerka weather station as part of the daily 6 P.M. weather observations. Late fall surface temperatures shown were lower than those on more exposed parts of the lake because Cabin Bay froze at an earlier date than the main body of the lake.

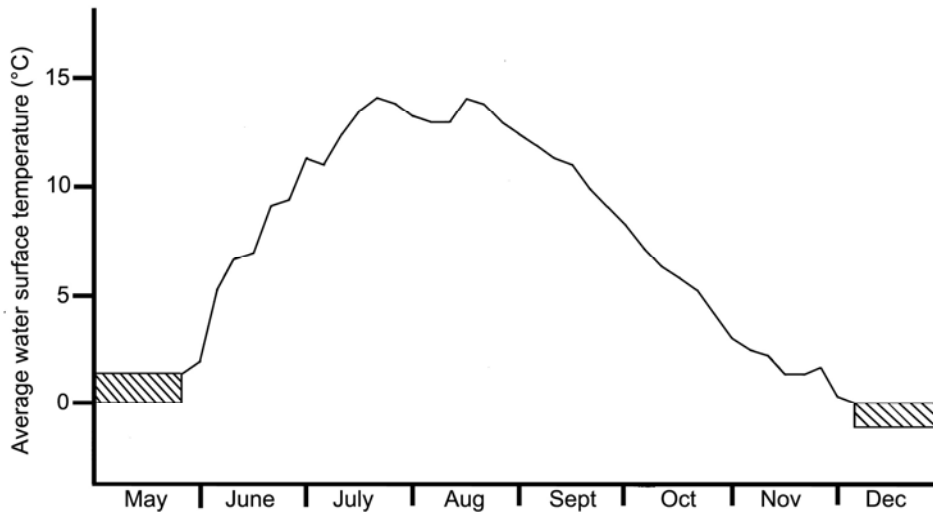


Figure 4. Average Cabin Bay water surface temperatures (°C), Lake Nerka 1952- 1958 (6:00 P.M. temperatures). Shaded boxes indicate lake ice.

Lake ice break-up occurred in late May or early June (Table 2). Following break-up the lake surface temperature rose rapidly to 3.3-3.9°C. It generally reached 10°C in late June, but on occasion was delayed until July by unfavorable weather. Peak temperatures, which reached as high as 18.3°C, occurred in July. The average surface temperature for the months July-August was 13.3°C, dropping to 10° C in late September and to 4.4°C in late October. The temperature remained at about 3.3-3.9°C until shortly before lake freeze-up in late November or December.

Table 2. Dates of break-up and freeze-up of lake ice at Lake Nerka, 1952-1958.

Year	Break-up	Freeze-up
1952	June 7	December 12
1953	May 30	December 11
1954	May 26	December 14
1955	June 14	November 30
1956	June 11	November 14
1957	June 2	December 20
1958	May 31	-----

Precipitation

Monthly precipitation (Figure 5) includes the water content of melted snow during the winter months. There was no distinct rainy season at Lake Nerka. Heavy precipitation may occur in any season of the year. During the years of observation the period from July through November had the highest average precipitation at about 16.5 cm. per month. However, this period on occasion was relatively dry. April and December were the most consistently dry months with an average of less than 7.6 cm. each. The average for the remaining 5 months (January-March, May and June) was 10.9 cm.

During the 7-year period, monthly precipitation ranged from 1.3 cm. to over 30.5 cm. The mean annual precipitation, including snowfall, was 151 cm., with annual precipitation ranging from 114 to 178 cm.

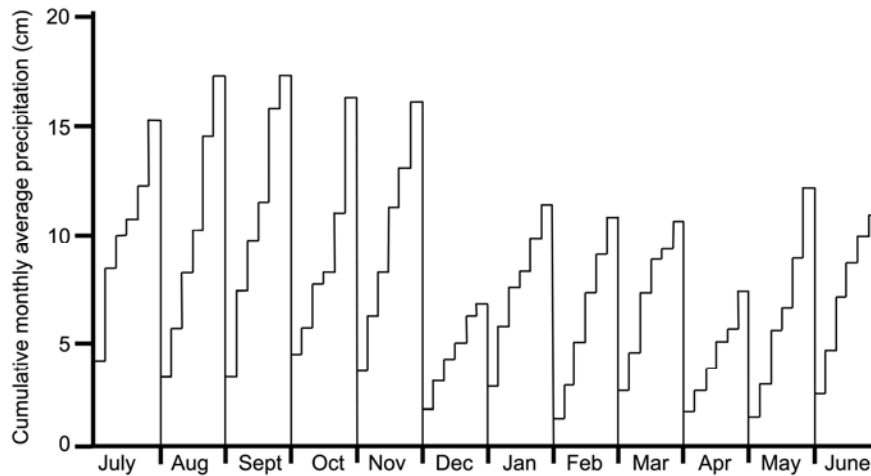


Figure 5. Cumulative monthly average precipitation (cm) at Cabin Bay, Lake Nerka, 1952-1958.

Lake Water Level

Water level readings were obtained at the Lake Nerka weather station as the vertical distance of the water surface from a fixed reference point above it. In Figure 6, which shows the mean annual cycle of lake water level, the higher readings denote the lower levels. The lake water level generally reached its greatest height in late June as the lake is fed by the melting winter snows. The height reached was dependent on snow depth and the amount of spring rainfall. Variation in maximum was about 91 cm.

During July and early August the water level dropped about 74 cm. on the average. In the absence of heavy precipitation the level continued to drop at a lesser rate through the fall months. However, fall rains generally maintained or raised the lake level until early November. Then, as sources of water supply were frozen and precipitation fell as snow, the lake level again dropped. By the end of December the lake was 91 to 183 cm. below its summer high. The extreme variation from the average at the end of the year was about 30 cm. for the several years of record.

The water level continued to drop through the rest of the winter, but more slowly. The lowest level was reached in late April, from 122 to 213 cm. below the high of the previous summer. The low water point reached was nearly the same each year, the extreme variation of the annual low from the average being only 18 cm.

The spring thaw raised the water level rapidly and continuously until the peak was again reached in late June.

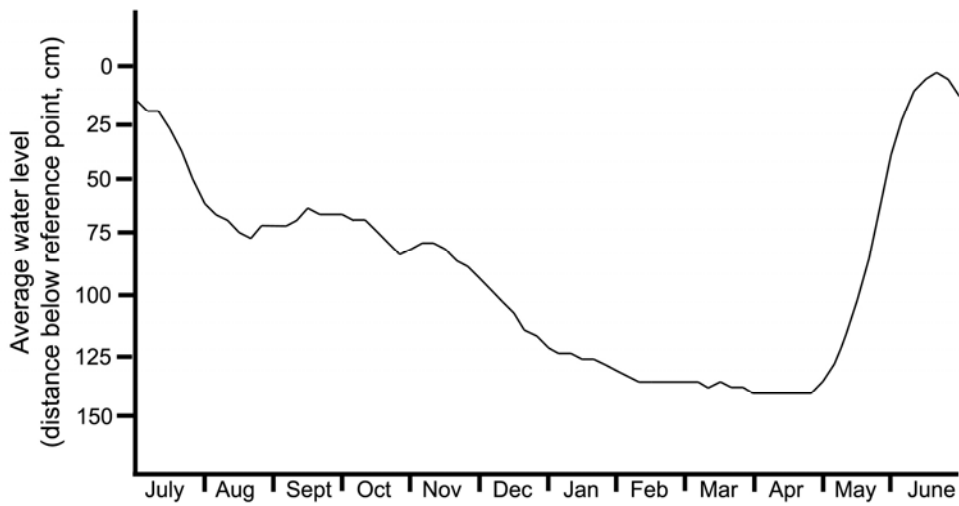


Figure 6. Mean annual cycle of water level at Cabin Bay, Lake Nerka, 1952-1958.

Snow Depth

Snowfall began in October but usually only a few centimeters were measurable since it was often mixed with rain (Figure 7). Rain was also common in November, but the average snowfall was about 60 cm.

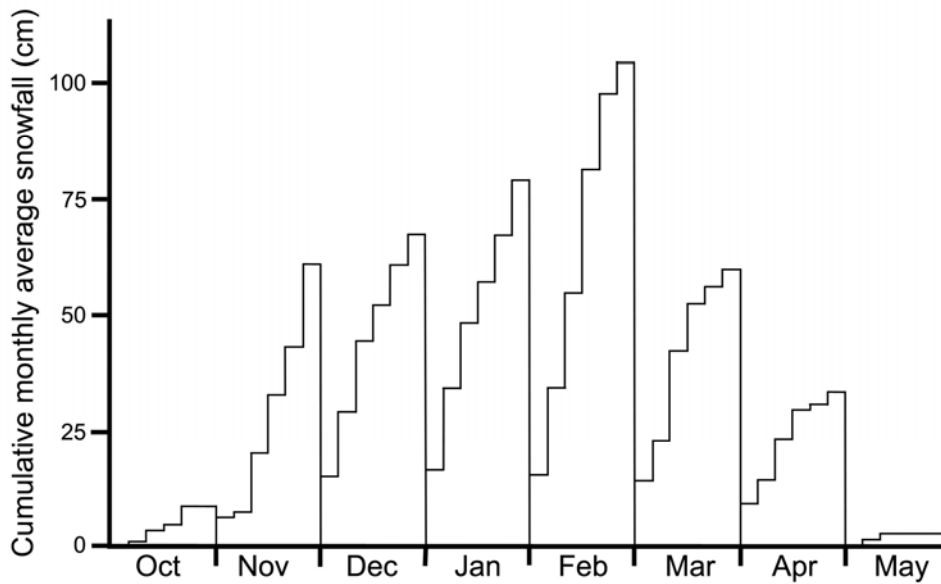


Figure 7. Cumulative monthly average snowfall (cm) at Cabin Bay, Lake Nerka, October-May, 1952-1958.

Any of the three winter months may have the heaviest snowfall of the winter. However, average snowfall was 61 cm. in December, 76 cm. in January, and 107 cm. in February for the seven winters of observation.

Snowfall decreased in March to an average of 61 cm. Snow in April was generally light, but up to 90 cm. of snow did occur during the month. Only occasional snow flurries occurred in May, generally mixed with rain.

The greatest amount of snowfall in any month was 229 cm. in January, 1955. The least midwinter snowfall in one month, also in January, was less than 15 cm. in 1954. Mean annual snowfall was 414 cm., range 356 to 559 cm.

After packing and settling, less than half the snowfall was reflected in snow depth (Figure 8). The snow depth increased gradually at the rate of a little over 30 cm. per month from a trace at the end of October to about 137 cm. at the end of February. Variation from the average was considerable, for example, from little or no snow to 60 cm. at the end of November, and snow depth at the end of February varied between 91 and 183 cm.

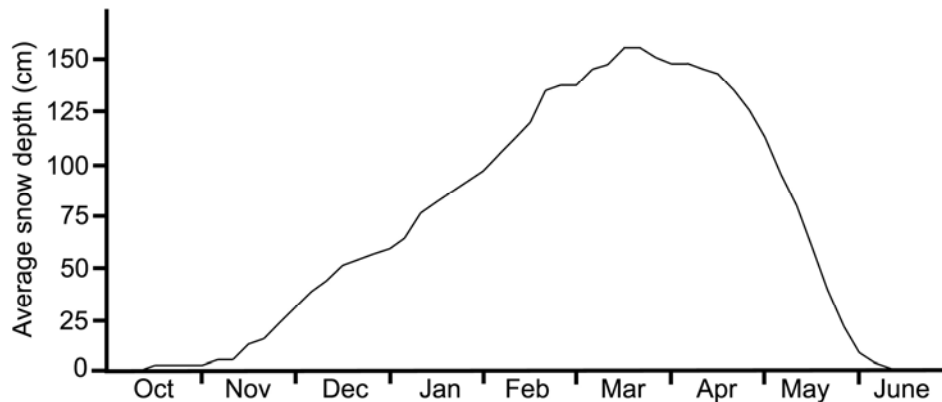


Figure 8. Mean annual cycle of snow depth (cm) at Cabin Bay, Lake Nerka, October-June 1952-1958.

Snow generally reached the greatest depth in mid March, averaging 167 cm, range 137 to 213 cm. Occasionally the greatest depth was not reached until April, but usually the snow depth decreased despite continuing snowfall through March and April. The remaining snow then disappeared rapidly during May and was gone except for occasional drifts by the end of May.

Lake Ice Formation

Measurements of lake ice cover were obtained in Cabin Bay. Since the bay usually froze at an earlier date than the main lake, early measurements are not representative. However, when the lake did freeze, ice thickness soon equaled that of Cabin Bay and ice formation was then essentially identical.

Lake Nerka usually froze over in early December (November 14-December 20) and continued to freeze down until early January when the maximum depth of freezing was reached at about 60 cm (Figure 9, 1955-1956 example). Although another 30 cm or so of ice was usually formed through the rest of the winter, this was overflow ice, frozen at the surface above the original ice formation. Overflow is formed by the weight of snow, which depresses the ice below the water level. Often the overflow did not completely freeze before the occurrence of another heavy snowfall. It was then depressed below the water surface where it remained unfrozen between layers of ice for the remainder of the winter.

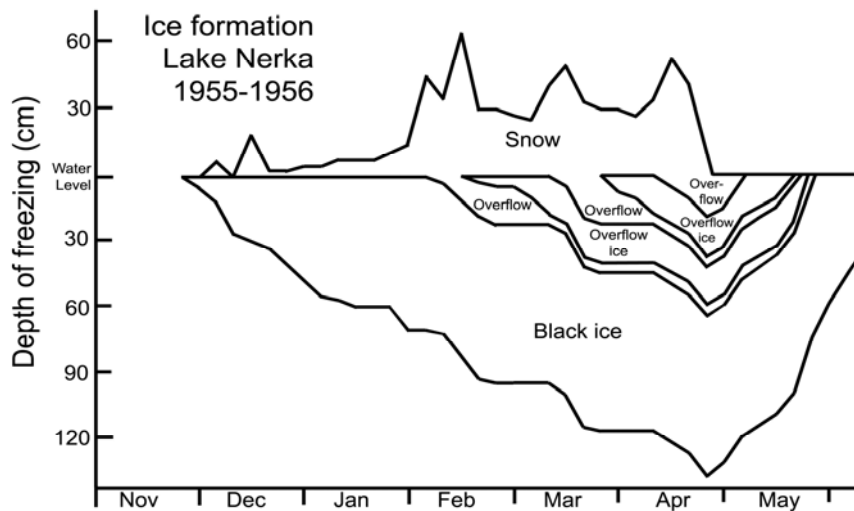


Figure 9. An example of lake ice formation (depth of freezing in cm) at Cabin Bay, Lake Nerka, November-May 1955-1956.

Because of the formation of overflow, snow on the lake seldom reached a depth over 45 cm. Maximum lake cover of about 150 cm. was usually reached by mid-March. The average formation consisted of 60 cm. of black ice and 30 cm. each of overflow, overflow ice, and snow.

Usually the surface of the cover began to melt in mid-April and continued until early June break-up. The ice usually broke up when it had been reduced to about 30 cm. in thickness.

INFLUENCE OF CLIMATE ON SPAWNING AREAS: GENERAL OBSERVATIONS

Influence of Ground Water on Gravel Temperature

Upwelling ground water was found to exert a strong moderating influence on gravel temperatures. The presence or absence of ground water accounted for most of the variation in gravel temperatures between types of spawning areas. Upwelling springs appear along the course of most tributary streams and form the source of many. Where suitable gravel characteristics were found, the spring areas were observed to be favored spawning locations. In the important spring-fed spawning area of Pick Creek on Lake Nerka (Figure 10), gravel temperatures showed little variation, remaining at 3.3-4.4°C throughout the year. Temperatures taken in other spring areas have been similar. Most of the springs remained entirely ice-free through the winter; others had a thin covering of ice only during the coldest weather.



Figure 10. The spring-fed spawning area of Pick Creek on Lake Nerka (photo by Robert Burgner, August 1959).

Lake-beach spawning areas bore a resemblance to spring spawning areas because of presence of upwelling ground water. Upwelling of ground water in the beach areas occurred in the littoral zone of the lake. It was within such areas of upwelling that the lake beach spawning was observed to take place. Where there was no upwelling, the gravel temperature closely followed that of the lake water, higher than ground water temperature in summer, lower in winter. The effect of ground water on gravel temperature was greatest in the area of strongest upwelling. As the distance from the central area of emergence increased, the upwelling was reduced until it no longer had an effect on the gravel temperature. However, areas of ground water emergence often overlapped, creating a continuous area of spawning along the beach line.

As in the spring areas, the gravel temperature tended to remain constant in areas where upwelling was strong. With reduced upwelling, the influence of lakewater temperature became greater. Spawning was not observed to take place in the absence of ground water, but it may occur with very weak upwelling. Thus gravel temperatures in beach spawning areas were found to vary from an almost constant 3.3-4.4°C to those which approached that of the surrounding lake water.

Sockeye salmon spawning is also important in the rivers connecting the lakes of the Wood River system. Because the temperature of the water entering the river at its head is that of the near surface of the lake above, river water temperature varies with the climate and season. However as the water flows down the river, its temperature may be influenced by its changed environment. Ground water entering the river along its course can be a modifying influence. Essentially, however, the river water temperature varies with the temperature of the lake water which is its source, and since there is a constant interchange of surface and intra-gravel water, gravel temperatures can be expected to vary near that of the surface water.

Lake tributary streams may be fed by springs, small lakes, or reservoir drainage. Streams fed only by surface drainage tended not to be assured of a good water supply throughout the winter and were seldom found to support a significant sockeye population. Most spawning creeks, whatever their primary source, had detectable springs along their source. However Elva Creek, a study stream draining Elva Lake into Lake Nerka, had no detectable springs. In this respect it resembled the connecting rivers of the system, except that gravel temperatures taken in the lower creek indicated that its thermal regime was cooler than that of the connecting rivers. Because of its smaller volume of flow, Elva Creek cooled more quickly and winter temperatures dropped to 0°C in Elva Creek spawning gravel.

Pick Creek, a study stream on Lake Nerka, is an example of a tributary creek where gravel temperatures are modified by flow from various springs. The influence is greatest immediately below a spring source, becoming less with distance. Because of the stream flow and consequent interchange of surface and intragravel water, the influence of ground water extends for a greater distance than in beach areas. In Pick Creek, springs were found to enter the creek in many places. As in the beach spawning areas, the gravel temperatures vary with the degree of influence of the upwelling ground water. However, in any part of the creek there was less seasonal variation than in creeks such as Elva Creek which were not spring-fed. In Pick Creek summer gravel temperatures were lower, winter temperatures higher.

Progression of Freezing in Winter

Lake beach areas

Immediately following the initial freezing over of the lake, additional ice is formed by relatively moderate freezing air temperatures. As the thickness of the ice increases, lower air temperatures are required to cause further freezing because of the increasing insulation of the ice cover. Eventually the ice thickness becomes great enough to insulate against freezing below it. Ice formed later is formed from freezing of overflow water on top of the original ice resulting generally from the weight of additional snowfall. At Lake Nerka 76 to 97 cm of ice was found to be sufficient to prevent additional freezing on the lower surface of the ice. This thickness of ice was usually formed before the end of January. Cold periods of the late winter did not add to the ice thickness except through freezing of overflow.

On lake beaches where no upwelling of ground water occurs, freezing progresses in the same way, and that part of the beach beneath the water surface is included in the depth of freeze. As freezing progresses the lake level continues to drop. The dropping water level permits more and more gravel to be exposed to freezing until the maximum depth of freezing permitted by the snow and ice insulation above has been reached. When the maximum penetration of freezing has been reached the lake level has no further effect on gravel freezing. The ice no longer supported by water will rest on the bottom, but will not freeze the gravel.

Beaches on Lake Nerka where sockeye salmon spawning occurred were found to be areas of upwelling ground water. These shallow beach areas differed from the non-spawning beaches in progression of freezing because of the presence of the upwelling

ground water. The ameliorating influence of groundwater made it possible for eggs and alevins to survive in areas where freezing would otherwise be extensive. Essentially, the winter conditions for survival existing on a lake spawning beach are the result of the balance achieved between air temperature and the protection afforded by warm upwelling ground water, lake water level, and the cover of ice and snow.

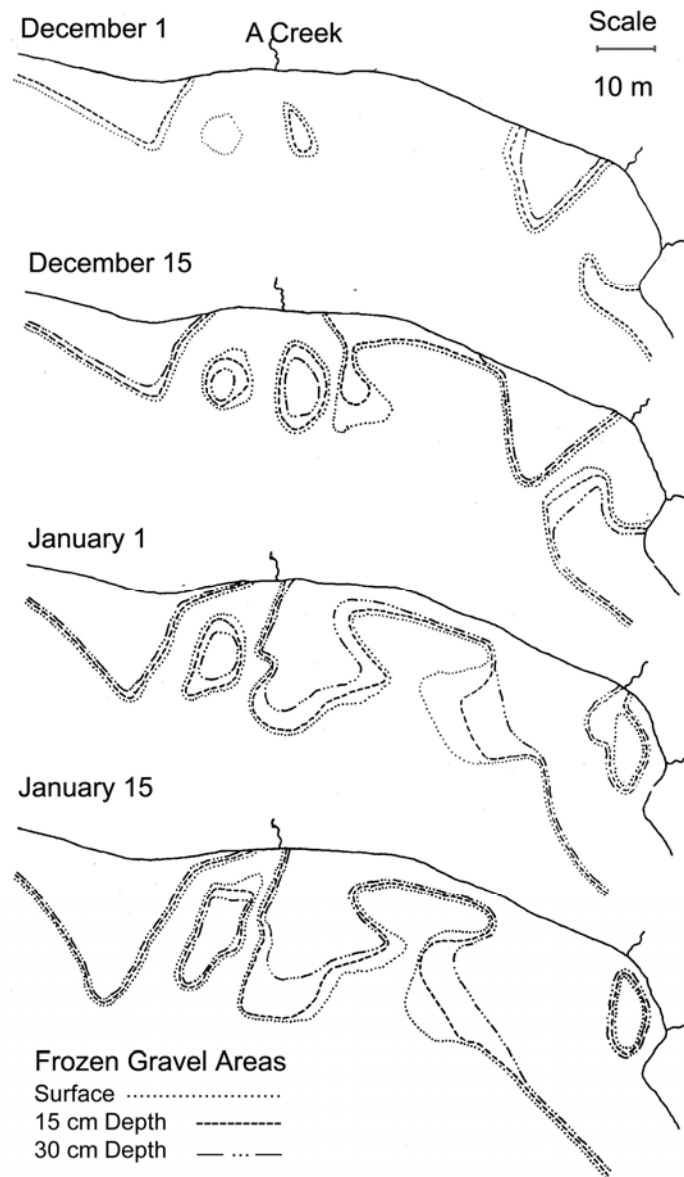


Figure 11. Progression of freezing in a sockeye salmon spawning beach, as illustrated by observations made at A-Creek beach, Little Togiak Lake during winter 1955-1956.

Upwelling ground water was observed to be the chief deterrent to ice formation in beach spawning areas. Much of the effectiveness of the ground water can be lost,

however, if the beach gravel is exposed to low winter temperatures without intervening insulation of snow or water. Although several feet of snow may have fallen before freeze-up of the lake, none can accumulate until ice is formed. Since much of the cold weather will have occurred before effective snow cover is formed, water depth is of great importance in the prevention of freezing in spawning gravel.

The progression of freezing in a sockeye spawning beach is illustrated by observations made at A-Creek beach, Little Togiak Lake during the winter of 1955-1956 (Figure 11). The freezing that occurred was the result of a long continued period of unfavorable weather conditions from October 1 to February 1. Air temperatures were continuously below normal, there was only half the usual amount of snowfall, and the lake level dropped steadily through the whole period. Gravel above lake water level was already frozen before the lake froze over in November. As the lake level dropped, more area was exposed above water level with consequent freezing. In the areas still covered by water, the ice thickened rapidly but was prevented from extending into the gravel by the warm upwelling ground water. However as the water level dropped, ice was constantly melted by the ground water as it approached the gravel. Thus the thickness of the ice and its insulating effect was gradually reduced by the dropping water level.

The reduced insulation was insufficient to prevent freezing of the gravel surface in shallow water areas of weak upwelling. Since gravel transmits heat more readily than water, the rate of freezing increased as soon as a small surface area was frozen. Freezing at the gravel surface was followed shortly by freezing at six and twelve inch gravel depths. Small areas of freezing enlarged rapidly. As the cold weather continued, the water level became lower and ice thickness less in areas of stronger upwelling. Without snowfall to increase the insulation, frozen gravel areas continued to enlarge and join. Before the cold period ended only the areas of strongest upwelling remained unfrozen. A period of snowfall eventually provided sufficient snow depth to prevent further freezing in the gravel. However, a large part of the spawning area had been frozen before this occurred (Figure 12).

Observations at other beaches, although less extensive than at A-Creek Beach, showed the same progression of freezing. The water depth necessary to prevent freezing varied with the quantity of the ground water flow. A few areas completely above water level did not freeze. However, a definite relationship existed between the extent of freezing and the winter lake level.

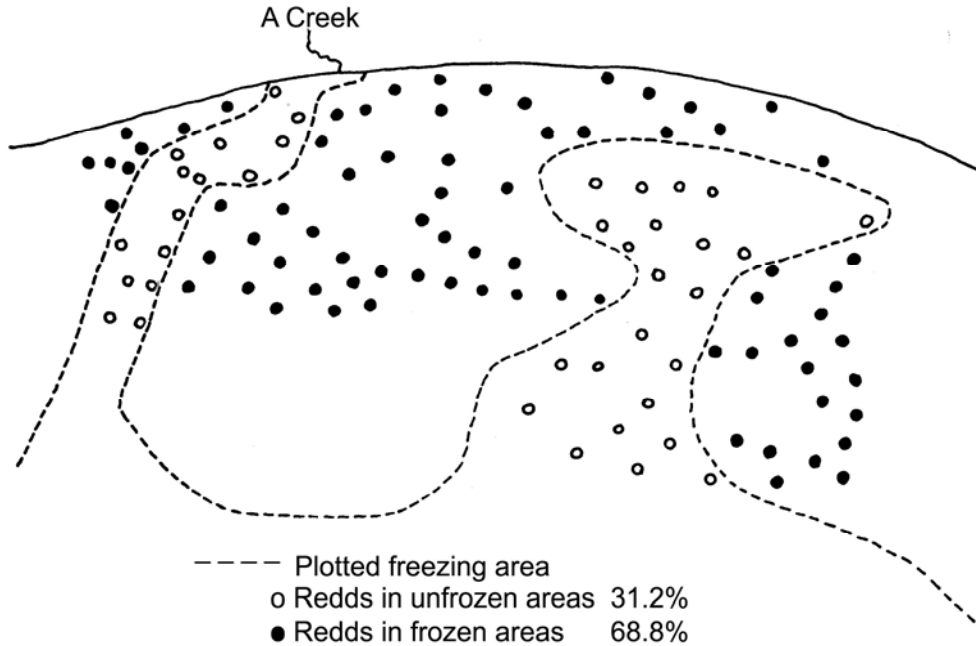


Figure 12. Distribution of sockeye salmon redds in unfrozen and frozen areas at A-Creek beach, Little Togiak Lake during winter 1955-1956.

Stream areas

Streams with sockeye spawning were observed to be less susceptible to freezing in the gravel than beach spawning areas. During the winter of 1955-1956, when extensive freezing was observed on the lake spawning beaches, almost no freezing was observed in creek spawning gravel. During that winter, Pick Creek and Elva Creek were observed closely, with fewer but substantiating observations made at other creeks.

The manner in which initial freezing occurs in the creeks is partly responsible for the lack of freezing in the gravel. Low temperatures cause formation of anchor ice on the creek bottom. Forming on a shallow riffle, the ice creates a dam which raises the water level preceding freezing on the surface. After the water surface has frozen, the anchor ice is melted or swept away, allowing the water to drop again. The water then flows beneath an insulating layer of ice, but not in contact with it.

Even when freezing does not occur in this manner, it is usually accompanied by some rise in water level. Since the ice is supported on each bank, it remains nearly at the height at which it was formed. When the water level drops, the water drops away from the ice above it. An additional protection is provided by drifting snow, which collects more readily on the ice of stream beds than on the lake spawning beaches. The running water below this superior insulation is thus more resistant to freezing than the water of the

spawning beaches already in contact with the lake ice. Observed freezing in the gravel of spawning streams has been limited to very shallow areas on the bar sides of the stream.

A more anomalous situation was observed in Little Togiak River, the short connecting stream between Little Togiak Lake and Lake Nerka. There quite extensive freezing was observed in Little Togiak River in the winter of 1955-1956. However, nearly all the observed freezing took place near the mouth of the river. Water depth over the lower river spawning area is influenced by the water level of Lake Nerka. As the lake level dropped, freezing in the gravel of the lower river progressed in the same manner as on the spawning beaches. With distance upstream the lake level had less influence on the level of the river and the extent of freezing decreased. Above the influence of the water level of Lake Nerka there was still some limited frozen gravel since flow in the river itself had dropped more than usual. However the river is assured of a more or less constant winter water flow from the lake above.

It is significant that the dead recovered in the 1956 redd sampling in Little Togiak River were all in the alevin stage, indicating a late winter kill. This suggests that snow cover, so important in protection of the lake spawning beaches, is not a great factor in river survival. Because the rivers are only intermittently frozen during winter, snow cover does not have a chance to build up.

COMPARISONS OF EGG AND ALEVIN MORTALITY IN THE LAKE BEACH STUDY AREAS

Necessity for Study Areas

The winter observations of 1955-1956 established the necessity for more exact knowledge of spawning distribution in determining the extent of egg mortality caused by freezing. The extent of the frozen area was known on several beaches, but the extent of egg mortality depended on the spawning distribution on those beaches. Groundwater and gravel temperatures showed considerable variation, and it was known that spawning was not equally distributed over any given area. It was possible that a large gravel area could be frozen without causing much mortality if redds were more scattered in that area. To permit a detailed study of the distribution of spawning sockeye and the effects of winter environment on survival of eggs and alevins, it was necessary to limit the areas of study.

Description of Study Areas

Sections of Elva Creek Beach and Pick Creek Beach on Lake Nerka were chosen as beach spawning study sites. Both were close to the Lake Nerka field station and could be reached easily even with difficult winter travelling conditions. In addition, some knowledge of each beach had been obtained by previous winter observations. The two sections chosen at each beach were areas which tended to become ice-free early before the spring rise in water level, thus making early spring redd examination and larval recovery more feasible. These areas could not be said to be completely representative, although each had characteristics found in other beach spawning areas of the system. Three study sections were about 91.4 meters long, the fourth (south section of Elva Creek beach) was 105.7 meters in length. This corresponded roughly with the area known to become ice-free early in the spring. Approximately 0.4 hectares of spawning area was contained in each section, except for the south section of Pick Creek Beach. This section of beach, much flatter than the others, contained about 0.8 hectares of spawning area.

Methods of Observation

Mapping of study areas

Depth contour maps were prepared of each beach study area. Since the lake water level was subject to fluctuation, an arbitrary fixed reference point was selected as the zero contour common to all beaches. This was the approximate level of the beach line, i.e., the limit of brush, grass, or other vegetation, and a permanent marker was affixed to a rock outcropping to mark the level. At each beach section a base line was established above the beach line and marked by stakes at approximately 15 m. intervals. The distance from the base line to each depth interval was measured perpendicular to the base line from each stake. Each one foot (ca. 30 cm) interval of depth below the base line was marked along the perpendiculars with a large painted rock placed on the bottom.

Marking of redds

A scaffolding tower mounted on two boats was used as an observation platform to locate redds in the beach areas during the sockeye spawning period. When located, the redds were marked by placement of painted rocks at the direction of the observer on the tower. After marking, redd locations were plotted on maps using the depth contour markers as a guide in plotting. Redd marking was done at intervals of a few days on each study beach. The marking of successive spawning was necessary to insure that redds of

early spawning were marked before possibly being obscured by later spawners. Rocks painted a different color were used at each successive marking to make plotting easier.

The primary purpose of marking redds was to plot the spawning distribution. However, the colored rocks were also helpful in locating redds for egg sampling in the spring.

Measuring gravel temperatures

Gravel temperatures were measured to detect the occurrence of freezing in the gravel and to determine the thermal pattern of each study area. Establishment of the thermal pattern made it possible to determine not only the areas of upwelling ground water and the extent of mortality by freezing, but to determine any relationships which existed between gravel temperatures and spawning distribution or with other egg mortality.



Figure 13. Wilbur Church deploying thermocouples used to measure gravel temperatures in sockeye salmon beach spawning areas.

Gravel temperatures were obtained with a Leeds and Northrup portable precision potentiometer with iron-constantan thermocouples. Each couple was joined in a copper tube, protected and held in place by paraffin and plastic tape. It was then placed in a hole drilled in a 5- x 5-cm wooden stake at the desired distance from the top. The stake was then driven into the gravel with its top flush with the gravel surface. It was necessary to use enough wire to extend above the ice and snow cover which would form above the thermocouple. Temperatures were initially taken at 0-, 15-, and 30-cm gravel depths, but

in order to obtain temperatures from a larger area without increasing the number of readings, installations were later limited to the 15-cm depth.

Thermocouples were installed 15 m apart on each 30-cm contour interval within the limits of spawning in each study area. Temperatures were read at weekly intervals whenever possible from those thermocouples that gave the best coverage of the area within the limitations of the number which could be read. In practice, this meant that as many thermocouples as possible were read as often as possible. Problems of installing, maintaining, and reading limited the number of thermocouples that could be used effectively.

Temperature readings began at time of spawning. At that time, readings were taken only along the 1.2- and 1.5-m depth contours (and the 0.9-m contour at south Pick Creek Beach section) because water depth prevented obtaining gravel temperatures at that time from the deeper contours. As water level permitted, temperatures were added from the thermocouples on the 1.8- and 2.1-m depth contours. Water depth prevented obtaining gravel temperatures from the thermocouples on the 2.4-m contour until after freeze-up.

The light thermocouple wires were subject to considerable breakage from wave action in the late fall and still later by ice movement. Broken wires were frequent, and replacement of thermocouples was a continuous task. In cold weather the process of temperature reading became a slow, time-consuming task. Although the potentiometer may be used in extremely cold weather if protected, the practical limit for the operator was about -18°C . The winter air temperature often was above that level for only a short time in mid-day or did not reach that level at all. These factors limited the number of thermocouples which could be maintained and read on a regular schedule during the short winter days. Therefore to provide more time to obtain temperatures from other thermocouples, readings were omitted at a given thermocouple after it had shown below-freezing temperatures.

Egg and alevin recovery

Spring egg and alevin sampling was conducted to check the area of freezing in the gravel established by the thermocouple temperatures and to obtain an estimate of egg mortality outside the area of freezing. Whereas in stream areas the current could be used to sweep dug eggs and alevins downstream into a collecting net, in beach spawning areas there was no current to be utilized. Attempts to collect live eggs and alevins from redds by syringe were unsatisfactory, so a method of pumping eggs and alevins into a net was developed, modified from that used by Mathisen (1962) in Pick Creek ponds.

Since the area of freezing had been rather closely defined by gravel temperatures, checking of this area was not a difficult task. However, it was difficult to estimate mortality outside the area of freezing. Spring thaw was accompanied by an extensive rise in lake level. The period in which egg recovery was possible was limited because the digging area had to be free of ice, yet shallow enough to permit digging. Only those areas of strongest ground water upwelling were ice-free early enough to permit digging before the water was prohibitively high. Since these areas were expected to be most favorable to the development of eggs and alevins in the gravel, alevins may already have emerged from the redds before sampling could be done. Mortality estimates based on the eggs and alevins recovered would be in error if a partial or complete emergence had occurred. Partial emergence was especially difficult to detect. Since random sampling plans could not be followed, the samples obtained were not necessarily representative.

Freezing vials

The 1956 program was repeated in 1957. Spawning distribution was plotted in the study areas, gravel temperatures were obtained, and redds were sampled in the spring. This provided two comparative years of spawning distribution, gravel temperatures, and mortality by freezing. However this program could not be followed in 1958 because observations had to be discontinued during the 1958-1959 winter as well as egg recovery sampling in spring of 1959. In anticipation, another method for determination of the extent of freezing in the gravel was employed. Thermocouples were replaced by water-filled vials to detect freezing. The small (1/2 dram) vials were installed in the gravel in the same wooden stakes used previously for the thermocouples. When removed in the spring, vial breakage would indicate that freezing had taken place in the gravel.

The vials had been used previously in a limited way and had proven to be satisfactory indicators of freezing in the gravel. However, care had to be taken to prevent breakage as the stakes were being pounded into the gravel. To accomplish this the gravel was first prepared by pounding in a tool larger than the stake containing the vial. Upon removal of the tool, the stake could be inserted easily and be placed at the proper depth with a few light taps. Trials in an area of compacted gravel showed no breakage using this method.

In the previous two winters, the extent of freezing was determined by thermocouple readings supplemented by continual winter observations and further checked by spring egg sampling. Such supplementary observations were not possible in

the 1958-1959 winter. This necessitated using many more vials than the number of thermocouples previously used in order to establish reliably the pattern of freezing. The vials were therefore installed in the study sections on each succeeding 7.6-cm depth contour interval in rows approximately 15 m apart from the inshore spawning limit to the limit of possible freezing. The vials were recovered during the spring and summer of 1959. Since the spawning distribution had been plotted, the mortality rate from freezing could be estimated after charting the area of freezing as determined by vial breakage.

Mortality Comparisons Among Lake Beach Areas, 1956-1957 Winter

Observations conducted of the 1956 sockeye spawning and the plotting of redd distribution in the four lake beach areas made it possible for the first time to estimate egg-alevin mortality resulting from freezing of spawning gravels. Since the winter of 1956-1957 presented severe weather conditions, the effects of climate on winter survival of the 1956 year class in the four study beaches will be described in some detail.

The distribution of spawning sockeye salmon appeared to be determined by local ground water and gravel characteristics, and as a result, distribution and density in relation to depth contours varied among beach localities (Table 3). All spawning in the four study sections took place between the 0.6- and 3.0-m depth contours. However, only the area between the 1.2- and 2.4-m contours was utilized on all four study beaches. At North Elva Creek Beach and North Pick Creek Beach, the overwhelming majority of the spawning occurred between the 1.5- and 2.1-m contours. Spawning took place in shallower water at South Pick Creek Beach, and at South Elva Creek Beach distribution of redds was generally deeper.

Table 3. Percentage distribution of sockeye salmon redds by depth contour from a fixed reference point on study beaches on Lake Nerka, 1956-1958.

Water feet	depth meters	N. Pick Cr.			S. Pick Cr.			N. Elva Cr.			S. Elva Cr.		
		1956	1957	1958	1956	1957	1958	1956	1957	1958	1956	1957	1958
2-3	0.6-0.9				2		3						
3-4	0.9-1.2	2		1	22		17			1			
4-5	1.2-1.5	14		24	45	26	38	3	1	19	3		14
5-6	1.5-1.8	35	19	29	21	32	21	59	45	56	32	40	27
6-7	1.8-2.1	44	69	43	10	27	12	32	51	22	35	47	27
7-8	2.1-2.4	5	12	3	T	8	7	6	3	2	23	11	16
8-9	2.4-2.7					6	2				6	2	11
9-10	2.7-3.0					1	T				1		5

The areas of greatest spawning density were in the middle depth ranges on all four study beaches. Gravel temperature records showed that the areas of heaviest spawning density were also in areas of strong upwelling of ground water. Redds further offshore were protected from freezing by water depth. Therefore, from the standpoint of freezing mortality, interest centered on the more scattered but vulnerable inshore portion of the redds. Although early winter freezing in the spawning gravel affected only a few scattered redds, continued freezing approached the area of greatest egg density. Thus the difference of a few centimeters in freezing depth became increasingly important as the area of high egg density was approached.

The lake water level during the 1956 spawning period was between the 0.8- and 0.9-m contours. This level apparently did not restrict the spawning to any extent, since only at South Pick Creek Beach did considerable spawning take place above the 1.2-m depth contour, and 4 redds were just inside the 0.9-m contour. However, critical conditions arose on the lake beaches because of ensuing climatic conditions in the fall of 1956. An exceptionally cold fall and early winter led to an early freeze-up, and by January 1, 1957, the lake water level had dropped to the 1.4-m depth contour. Because there had been little snow, the redds above that level were protected from freezing only if there was sufficient upwelling ground water.

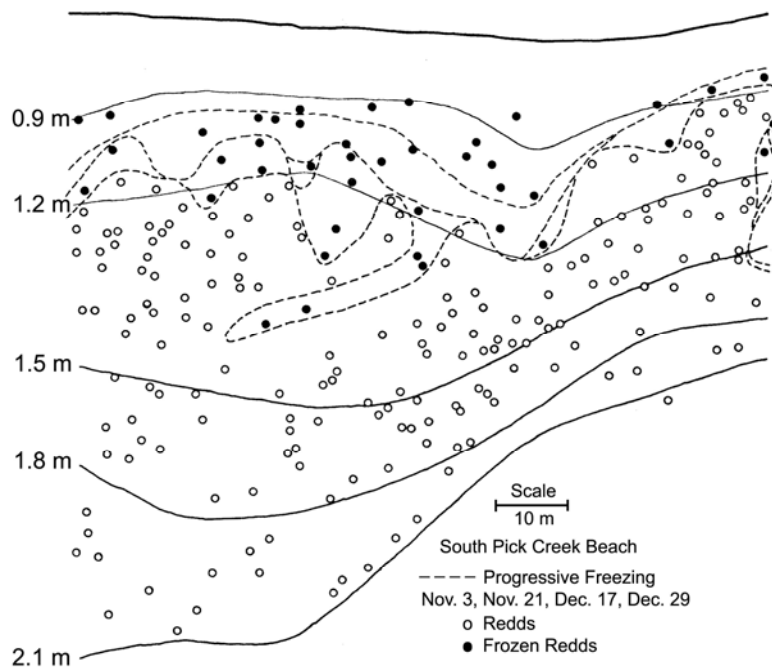


Figure 14. The distribution of redds and frozen redds of sockeye salmon by depth contour in South Pick Creek Beach, winter 1956-1957.

South Pick Creek Beach, with a higher percentage of redds above the winter water level, registered by far the highest egg mortality from freezing, since 18% of the redds were within the area of freezing (Figure 14). All the freezing occurred in redds exposed by the receding lake level. Mortalities included some redds between the 1.2- and 1.5-m depth contours, but did not include all redds between the 0.9- and 1.2-m contours because of differences within the study area in amount of upwelling ground water.

At North Pick Creek Beach, most of the gravel area was frozen above the winter lake level. However most of the redds located above the 1.5 m contour were concentrated in a relatively small area where freezing did not occur (Figure 15). Although 16% of redds were above the 1.5 m. contour, calculated mortality from freezing was only 6 %.

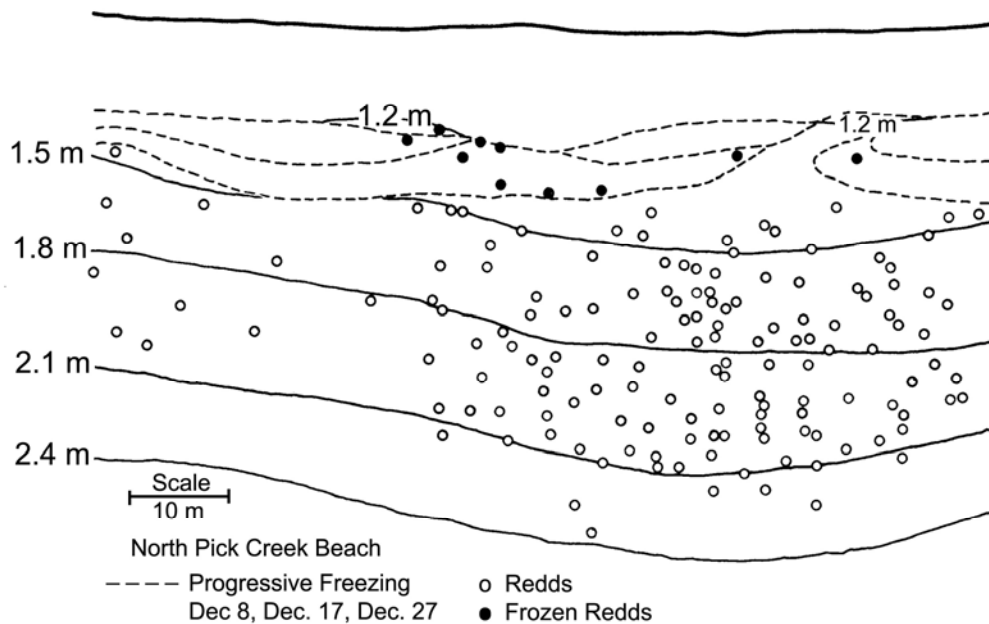


Figure 15. The distribution of redds and frozen redds of sockeye salmon by depth contour in North Pick Creek Beach, winter 1956-1957.

At both Elva Creek study sections, nearly complete freezing occurred above the winter lake level and extended to the 1.7 m. contour in some places. However, although 3% of the spawning at North Elva Creek Beach occurred above the 1.5 m. contour, no redds were included in the frozen area (Figure 16). Superior upwelling in the populated areas prevented freezing in redds.

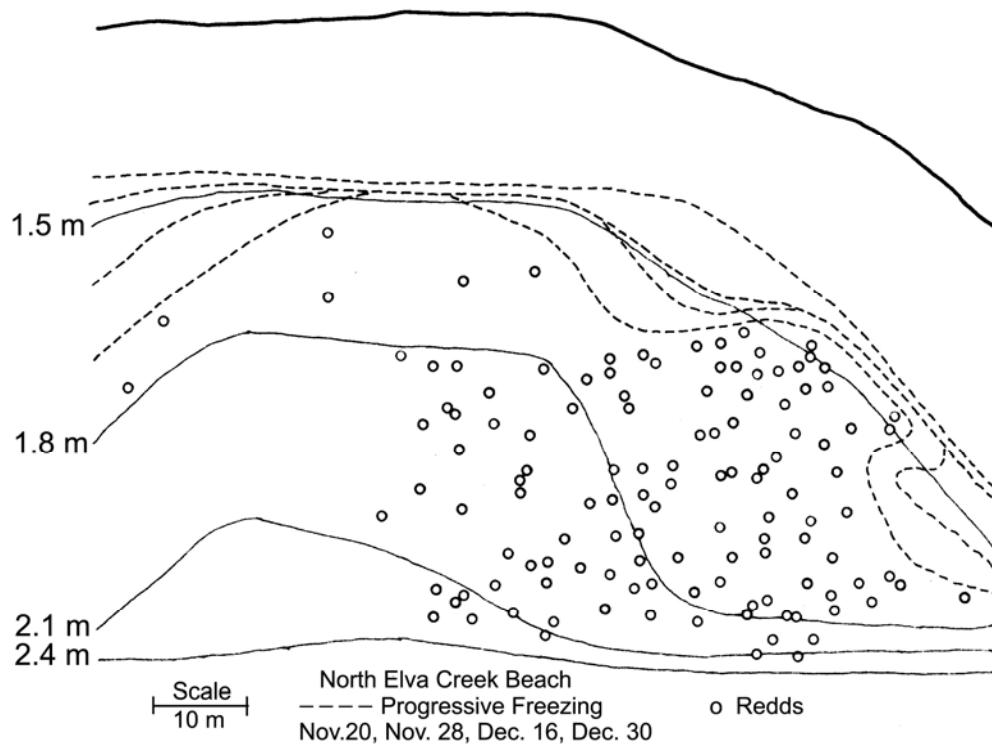


Figure 16. The distribution of redds and frozen redds of sockeye salmon by depth contour in North Elva Creek Beach, winter 1956-1957.

At South Elva Creek Beach only 3% of the spawning had occurred inside the 1.5 m. contour (Figure 17). Only half of these redds were in the area of freezing. However mortality from freezing was 8%. Spawning density was greater at this beach than in the other study areas. Consequently more of the area removed from the center of ground-water upwelling was utilized. Most of the mortality occurred between the 1.5 and 1.7 m. contours. Although these redds were in relatively deep water, upwelling was not strong enough to prevent freezing.

The comparisons conducted of redd distribution and subsequent survival of eggs and alevins in the four beach study areas of Lake Nerka during the severe conditions of the 1956-1957 winter illustrated the potential combined effects of low lake level, low temperature and low snowfall. They demonstrated further the importance of spawner selection of upwelling ground water areas for egg deposition in order to avoid freezing of eggs and alevins during temperature extremes.

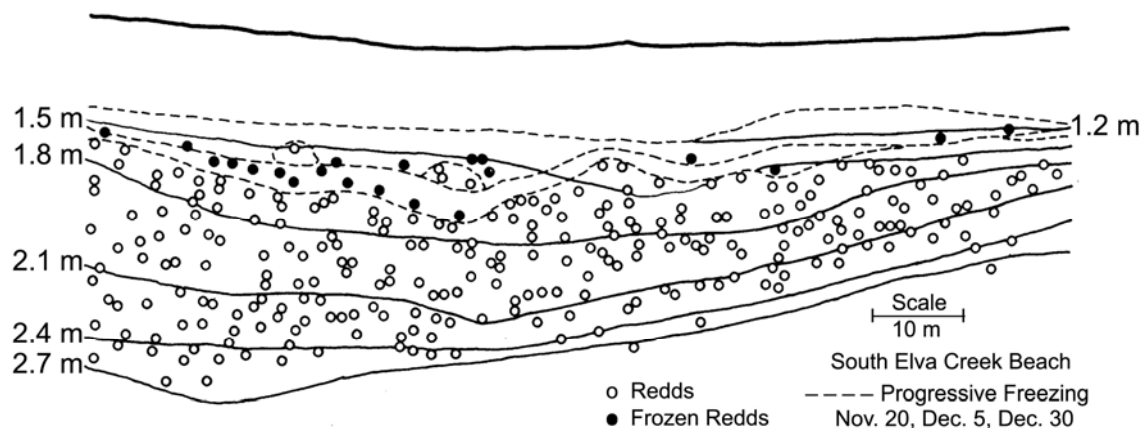


Figure 17. The distribution of redds and frozen redds of sockeye salmon by depth contour in South Elva Creek Beach, winter 1956-1957.

Between-Year Comparisons of Climatic Effects

Winter observations were conducted at Lake Nerka for seven seasons. During three of these seasons, 1952-1953, 1954-1955, and 1957-1958, there was no observed freezing in the spawning gravels of the lake beaches. In each of these seasons relatively heavy rainfall in late October and November raised the lake to a high level. Although the water level subsequently dropped, it was still at a high level through the critical period before snow cover was established. In contrast, in the four seasons in which freezing occurred in the spawning gravel, there was insufficient rainfall in October or November to prevent the water level from dropping prior to heavy snowfall. With the lake at a low level during the cold weather, freezing in gravel occupied by redds became possible. Thus it appears possible to predict to some extent from fall lake level whether or not winter freezing in spawning gravel is likely to occur.

Although the winters could be classified as mild or severe, there was little difference in the minimum temperatures reached. The winters differed primarily in the time of occurrence and duration of the cold periods. A short period of cold weather was found to cause less freezing than a longer one, apparently because of the relatively slow changes in temperature at depth in the gravel. Cold weather that occurred relatively late in the winter was also found to be less harmful because snow cover had a greater opportunity to build up, furnishing more insulation than earlier in the winter.

Climatic effects in winters of low lake level may be expressed in terms of time and duration of the cold period. Two of the winters, 1953-1954 and 1958-1959, had late cold periods. Both had comparatively mild December weather, followed by cold weather

in January. In 1959 the extreme cold lasted only through January, while in 1954 it extended through February. Since snow cover had an opportunity to become established before the cold period, freezing in the spawning gravel was comparatively light in both years. The least freezing occurred in 1958-1959, apparently because the cold period was much shorter. In contrast to the above, early cold periods occurred before snow cover was established in both 1955-1956 and 1956-1957 winters. November and December weather was most severe in 1956-1957 but subsided after December. The cold weather of 1955-1956 continued through January, and the extent of freezing was greater because the cold period was longer.

While the differences among years in the extent of winter freezing influenced the egg-alevin mortality rates observed, between-year differences in spawning distribution also exerted an influence (Table 3). The size of the spawning population and water level at time of spawning caused considerable year to year variation in the observed spawning distribution. For example, during most of the 1957 spawning period the lake level was at the relatively low 1.2 m. depth contour, and although the water level rose toward the end of the spawning period, late spawners did not utilize the newly accessible area. Except at South Pick Creek Beach, only one redd occurred shallower than the 1.5 m. contour (at North Elva Beach), and no spawning occurred above the 1.4 m. contour. This curtailment of the inshore area moved the center of spawning distribution farther offshore than in 1956. With this spawning distribution, no mortalities would have occurred if the freezing had extended as deep as during the previous winter.

The post-spawning lake level conditions in the fall of 1957 exemplify favorable conditions for protection of eggs from freezing. The rainy fall months following the 1957 spawning raised the lake and kept it at a high level. During the coldest part of the winter, which occurred in December, the water level was at the 0.9 m. contour, 0.46 m. above the shallowest redd. The water level did not drop to the 1.2 m. contour until the end of January. The critical cold weather period of the 1957-1958 winter, although severe, was of short duration, snowfall was well above average, and freezing in the spawning gravel was never a serious threat at any time.

An increase in spawning density relative to 1956 was noted in 1958 in three of the four study sections (Table 4). When a spawning population increases it must occupy a larger area, increase in density, or both. In beach spawning areas both of these effects were noted. However, in a fixed section of beach such as the study sections, the area utilized was found to increase only slightly. The inshore area was limited by the shore, and little of the offshore area appeared to be suitable for spawning beyond the area normally utilized. Thus the effect of an increase in population in the study areas was

mainly an increase in spawning density. There was, however, an increased utilization of less favored areas. At both Elva Creek beaches the increase in number of redds was accompanied by a higher percentage of redds in the inshore areas (above 1.5 m.) relative to 1956, increasing from 3% to 14% at South Elva Creek Beach and from 3% to 20% at North Elva Creek Beach.(Table 3). At South Pick Creek Beach the total number of redds in the inshore area increased, but there was a decrease in the percentage, from 69% in 1956 to 58% in 1958. At the Elva beaches, freezing conditions identical to those of 1956 would have produced a higher mortality rate, and at South Pick Creek Beach there would have been little change in mortality rate.

Table 4. Distribution of sockeye salmon redds by depth contour from a reference point on study beaches on Lake Nerka, 1956-1958.

Water feet	depth meters	N. Pick Cr.			S. Pick Cr.			N. Elva Cr.			S. Elva Cr.		
		1956	1957	1958	1956	1957	1958	1956	1957	1958	1956	1957	1958
2-3	0.6-0.9				4		10						
3-4	0.9-1.2	3		1	50		62			2			
4-5	1.2-1.5	22		19	101	52	134	4	1	30	10		46
5-6	1.5-1.8	54	14	23	47	65	76	73	34	89	88	46	89
6-7	1.8-2.1	69	52	34	22	54	43	40	38	35	97	54	89
7-8	2.1-2.4	7	9	2	1	17	24	7	2	3	63	13	55
8-9	2.4-2.7					12	6				17	2	36
9-10	2.7-3.0					3	1				2		16
Totals		155	75	79	225	201	356	124	75	159	277	115	331

The population effect was not at all clear cut, however. In addition to the population increase in 1958, the lake water level was 0.3 m. higher during the spawning period than during the 1956 spawning period. Since the 1956 level did not appear to restrict the spawning area, it might be assumed that changes in distribution were caused by the increased spawning population of 1958. However, North Pick Beach did not exhibit the general increase in population, and in fact the number of redds was only half that of 1956. The number of redds in the inshore area decreased slightly, but because the population was much smaller, the inshore percentage increased from 16% of the total in 1956 to 25% in 1958, which suggests higher lake level may have influenced inshore spawning. Thus it was not clearly established that an increase in population level resulted in a higher percentage vulnerable to winter kill from freezing.

During the 1958-1959 winter the lake level dropped to the 1.4 m. contour during the coldest part of the winter, 5 centimeters higher than during the 1956-1957 winter. In addition, the coldest weather came a month later than in 1956-1957. The later cold

period allowed a greater depth of snow to accumulate on the beaches before the air temperature became critical. But despite the less critical freezing conditions of 1958-1959, the estimated egg-alevin mortality rate was similar only at South Elva Creek Beach. Here the percentage of redds inshore had increased over 1956 but the estimated mortality from freezing decreased slightly from 8% in 1956-1957 to 7% in 1958-1959. At North Elva Creek Beach the estimated egg mortality from freezing increased from no mortality in 1956-1957 to 11% in 1958-1959. The increased mortality estimate here resulted solely from the change in spawning distribution. Although the area frozen in 1958-1959 was less than in 1956-1957, spawning had extended more into shallower water. At North Pick Creek Beach the estimated egg mortality increased from 6% in 1956-1957 to 14% in 1958-1959. This increase was also caused by the higher percentage of redds in the inshore area. The area of freezing was also less than in 1956-1957.

At South Pick Creek Beach the estimated egg mortality from freezing was also higher, increasing from 18% in 1956-1957 to 22% in 1958-1959. In contrast with the other study beaches the increased mortality here resulted from a greater area of freezing than in 1956-1957, since there was a slight decrease in the percentage of redds in the inshore areas. The increase in area of freezing at South Pick Creek Beach can be explained by a difference in spawning distribution peculiar to this beach. Unlike the other study beaches, this beach has a substantial amount of spawning that becomes exposed above the winter lake level. In this area snow does not build up because it is melted as it falls by the upwelling ground water. Since this part of the spawning area rises above lake level during winter low water, ground water offers the only protection against freezing. While water level and snow depth limited freezing in the gravel at the other study beaches, this protection was lacking in the shallower spawning area of South Pick Creek Beach when the cold weather hit in early 1959.

Much of the freezing at South Pick Creek Beach was of a temporary nature. The gravel was frozen for only a short period, thawing as soon as the air temperature moderated. However, even temporary freezing was sufficient to destroy eggs in the gravel. In both 1956 and 1958 the egg mortality from freezing was substantially higher on South Pick Creek Beach than in the other study sections because of the wide area of redds occurring above the winter lake water level.

Freezing observed during the 1955-1956 winter did present a contrasting result. A combination of low lake level, low snowfall, and a lingering period of continuously cold weather created the most severe gravel freezing conditions observed. Spawning distribution had not been plotted, but spring egg recovery established the area of gravel freezing at South Pick Creek and South Elva Creek beaches. The frozen area at South

Elva Creek Beach was of much greater extent than later observed in 1956-1957 or 1958-1959, but the frozen area at South Pick Creek Beach was only slightly greater than in 1956-1957 or 1958-1959. Because redd distribution had not been plotted in 1955, direct estimates of freezing mortality could not be made. However the spawning population was larger and the water level higher at time of spawning in 1955, conditions that probably promoted use of inshore areas. Applying the spawning distribution of the most similar year, 1958, the 1955-1956 mortality by freezing was estimated at 29% at South Pick Creek Beach and 30% at South Elva Creek Beach. Actual mortality was probably higher because of more inshore spawning distributions.

Summarizing estimates for the seven study winters, in the first and third winters 1952-1953 and 1954-1955 there was no observed freezing in the spawning gravel of the lake beaches because of favorable climatic conditions. No estimates could be made for 1953-1954. Estimated mortality from freezing averaged 30% in the two study areas during 1955-1956. Estimated freezing mortality in the four study beaches averaged 8% in 1956-1957, ranging from 0% in North Elva Creek Beach to 18% in South Pick Creek Beach. There was no observed egg mortality from freezing in 1957-1958 because the low lake level at time of spawning restricted inshore spawning distribution and subsequent weather conditions prevented freezing in gravel occupied by redds. Average mortality from freezing was estimated at 13% in 1959, higher than in 1956-1957 because of redd distribution even though the area of freezing in the gravel was less.

The plotting of spawning distribution made it relatively easy to establish mortality rates from freezing. Gravel temperatures and winter observations established the zone of freezing in the gravel, and egg-alevin sampling in the spring determined the validity of the observations. However, other mortalities were noted outside the zone of complete freezing. Some of the mortality was doubtless caused by partial freezing of the redds. This was particularly noticeable after the 1955-1956 winter.

Other beach spawning areas were sampled in the Wood River Lakes during the spring of 1956, and in nearly all, there was a definite relationship between water level and egg mortality. Eggs were sampled in several shallow areas of Lakes Kulik and Beverley as well as in Lake Nerka and Little Togiak Lake. At the Lake Kulik sampling areas there was almost complete mortality out to a depth of 23 cm. of water at the time of sampling, but beyond 30 cm. nearly all live were found, the area between 23 and 30 cm. of water being a transition zone from dead to live. A similar situation was found in the Lake Beverley sampling areas between 23 and 30 cm. of water, and at Elva Creek beach on Lake Nerka between 25 and 38 cm. of water depth at sampling time. The spring rise in water level was occurring at time of sampling and water depths of the different lakes

rise at different rates. However, the same transition zone was apparent in all areas, a zone of partial freezing of redds.

Sampling some of these areas in the spring of 1957 did not define a zone of partial mortality as sharply. In many areas the line of freezing was sharply defined, with complete mortality on one side of a line, complete survival on the other. Although some heavy mortality near the area of freezing appeared to be caused by partial freezing, the area of partial freezing was not clear enough to define.

Substantial egg mortality was found which was presumably not connected with freezing or gravel temperature. Yet this mortality was noticeably higher on those beaches with the highest mortality from freezing. At North Elva Creek Beach, where there was no freezing mortality in 1956-1957, only a few scattered dead eggs were found. After the 1957-1958 winter, when there was no observed mortality from freezing, almost no dead eggs were found on any of the study beaches.

Attempts to measure egg-alevin mortality outside the defined areas of freezing met with considerable frustration because sampling of redds was complicated by the early emergence of fry in relation to the opening up of the study areas. By the time the areas became ice-free, partial or total emergence of fry from the gravel had already taken place in many redds. Thus egg-alevin mortality occurring outside the areas of complete freezing has not been included in the mortality estimates. Many of these mortalities, especially in 1955-1956, were almost certainly caused by freezing. However, due to the difficulty of keeping the estimates of such mortality on a comparative basis from year to year, it has been omitted.

ACKNOWLEDGMENTS

Kenneth Kral worked out the early technical problems of the thermocouples and laying out of many of the installations, particularly those at A Creek beach on Little Togiak Lake.

John Gilbert was in charge of contour mapping of study beaches and plotting of redd distributions during 1956 and 1957 spawning. (Report on file, SAFS archives)

Don Wren, Dillingham pilot, provided critical air contact during winter periods.

Lee Church ably assisted her husband in all phases of the winter observations.

Ole A. Mathisen assisted in supervision of winter studies.

Funding of the winter studies was provided by member companies of the Alaska salmon industry.

Kate Myers assisted greatly in editing, graphics conversion, and reproduction of this updated manuscript.

REFERENCES

- Burgner, R.L. 1958. A study of fluctuations in abundance, growth, and survival in the early life stages of the red salmon (*Oncorhynchus nerka* Walbaum) of the Wood River Lakes, Bristol Bay, Alaska. Ph.D. thesis. University of Washington, Seattle, WA. 200 p.
- Krogus, F.V. 1951. O dinamike chislennosti krasnoi (*Oncorhynchus nerka* (Walbaum)). Izvestiia Tikhookeanskovo Nauchno-issledovatelskovo Inst. Rybnovo Khoziaistva i Okeanog., 35:1-16. (On the dynamics of abundance of the sockeye salmon (*Oncorhynchus nerka* (Walbaum).) Fisheries Research Board of Canada, Transl. Ser., No. 101, 1957. Ottawa.
- Krogus, F.V., and E.M. Krokhin. 1956. Rezultaty issledovaniia biologii nerki-kraznoi, sostoianiia ee saposov i kolebanii chislennosti v vodakh Kamchatki. Voprosy Ikhtiologii. (7):3-20. (Results of a study of the biology of sockeye salmon, the conditions of the stocks and the fluctuations in numbers in Kamchatka waters) Fisheries Research Board of Canada, Transl. Ser., No. 176, 1958. Ottawa.
- Mertie, J.B.,Jr. 1938. The Nushagak District, Alaska. U.S. Geological Survey, Washington. D.C. Bulletin 903, 96 p., illus., maps.



View from Church Mountain of ice cover on south arm, Lake Nerka, June 8, 1956, three days before ice breakup (photo by Robert Burgner).