# INFLUENCE OF ROCKY REACH DAM AND THE TEMPERATURE OF THE OKANOGAN RIVER ON THE UPSTREAM MIGRATION OF SOCKEYE SALMON

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## ABSTRACT

**Tagging experiments show that Rocky Reach Dam, constructed on the Columbia River 7 miles above Wenatchee, Wash., in 1957–61, has not appreciably increased the time required for adult sockeye salmon (*Oncorhynchus nerka*) to migrate to Zosel Dam on the Okanogan River (a tributary to the Columbia River above Rocky Reach Dam). Water temperature of the Okanogan River is, however, a major cause of delay. Above 70° F., rising or stable Okanogan River temperatures block the entry of the fish from the Columbia River into the Okanogan River; falling temperatures allow the migration to resume. Below 70° F., migration is not blocked by rising or stable temperatures. Delay may reduce survival because it increases the exposure of the sockeye salmon to other factors that affect them adversely.**

## INTRODUCTION

If Pacific salmon (*Oncorhynchus* spp.) and steelhead trout (*Salmo gairdneri*) are to reproduce successfully, sufficient adults in spawning condition must reach the spawning grounds. Consequences can be serious if the migrants are delayed en route. Thompson (1945) showed, for example, that of the tagged sockeye salmon (*Oncorhynchus nerka*) that had been delayed longer than 12 days at the Hell's Gate rock slide on the Fraser River, British Columbia, in 1941, practically none reached their spawning grounds. He also suggested that lesser delays reduced the reproductive capacity of the fish.

Although they are equipped with facilities for passing fish, hydroelectric dams on the migration routes constitute another type of barrier which can delay adults en route to their upstream spawning grounds. To assess and find ways to minimize the effects of these dams as they are built on the Columbia River is a most important aim of the agencies concerned with the salmon and steelhead resources of the stream. One facet of this work is to detect and minimize any delay of the adults as they migrate upstream. The time required for adults to locate and ascend fish ladders is sometimes reduced, for example, by altering the spill pattern to improve attraction to the ladders or even by modifying the ladders themselves.

In this paper we show that Rocky Reach Dam, constructed on the Columbia River, 7 miles above Wenatchee, Wash., in 1957–61, has not appreciably increased the time required for sockeye salmon to migrate from Rock Island Dam (below Rocky Reach Dam) to Zosel Dam on the Okanogan River, a tributary to the Columbia River above Rocky Reach Dam (fig. 1). We also illustrate how the temperature of the Okanogan River periodically blocks the upstream migration of the sockeye salmon at the confluence of the Okanogan and Columbia Rivers.

This study originated as part of a broad program to assess the effects of Rocky Reach Dam on the fish and wildlife resources of the upper Columbia River. The program was developed by representatives of interested State and Federal agencies and financed by Public Utility District Number 1 of Chelan

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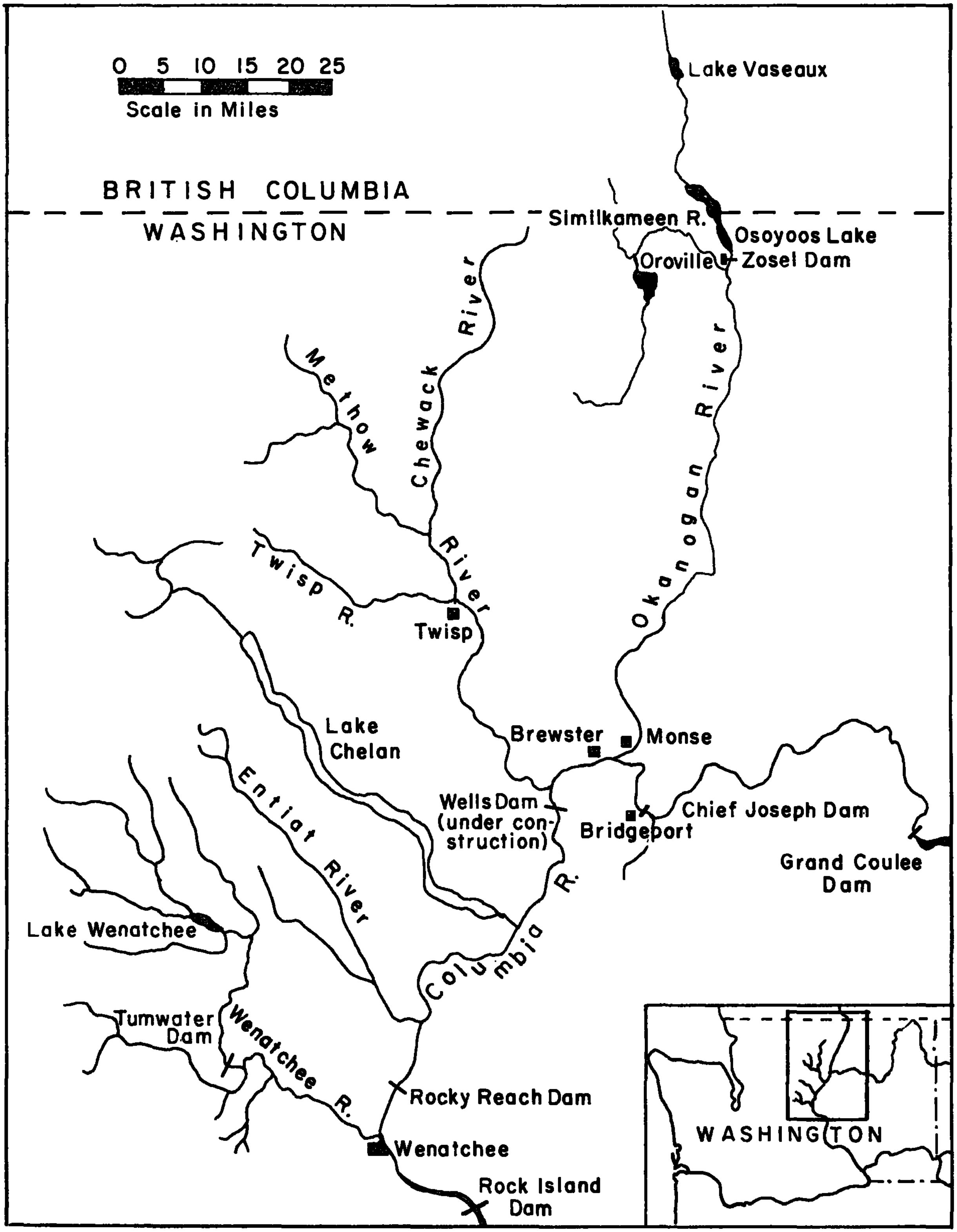


FIGURE 1.—The Columbia River and the locations important to the present study.

County, the builders of Rocky Reach Dam, in accordance with the terms of Federal Power Commission license number 2145. Biologists of the Bureau of Commercial Fisheries were designated to study possible delay because of their experience with a similar investigation at Rock Island Dam in 1953–56 (French and Wahle, 1966).

The study underwent a major expansion as it proceeded. Originally, the sole aim was to measure delay, if any, caused to upstream-migrating adult salmonids by Rocky Reach Dam. This aim was to be accomplished by comparing the time required for tagged sockeye salmon to migrate from the forebay (reservoir) of Rock Island Dam to Zosel Dam, before (1957) and after (1962 and 1963) the completion of Rocky Reach Dam. If minimal influence by other factors were assumed, any major change in travel time could be attributed to the new structure.

French and Wahle (1960) summarized the "predam" work (performed before the dam was built). Because too few tagged fish were observed at Zosel Dam in 1957, they estimated the travel time (10.7 days) from tagged sockeye salmon that had been released in the Rock Island Dam forebay and later observed at Zosel Dam during the earlier (1953–56) study.

The tagging results in the first "postdam" year (1962) had a profound impact on our investigation. Sockeye salmon migrating through the study area were noticeably delayed—apparently by high water temperatures of the Okanogan River. If a temperature block were shown to exist, the assumption of minimal influence by factors other than Rocky Reach Dam would have been invalidated and the straightforward comparison of "predam" and "postdam" travel times as a measure of delay ruled out —unless the influence of the various factors could be examined separately. It was necessary, therefore, to confirm the existence of the temperature block, to reexamine the estimated "predam" travel time, and finally to evaluate Okanogan River temperatures as well as Rocky Reach Dam as sources of delay to sockeye salmon in their upstream migration. These expanded objectives greatly increased the complexity of the "postdam" phase of the study.

## METHODS AND MATERIALS

The experimental procedure was as follows: (1) determine, both before and after the completion of Rocky Reach Dam, the time required for tagged sockeye salmon to migrate from the Rock Island forebay to Zosel Dam; (2) determine the time required for tagged sockeye salmon to migrate from the Rock Island forebay to Rocky Reach Dam; (3) examine the variability in passage time in relation to Rocky Reach Dam and the flows and temperatures of the Okanogan and Columbia Rivers.

Tagging experiments provided the answers to items (1) and (2). For item (3), these same tagging data were supplemented by counts of sockeye salmon made at Rock Island and Zosel Dams in years when there was no tagging.

### SOCKEYE SALMON AS THE STUDY SPECIES

Observations were confined to sockeye, the only salmon that can be intercepted in significant numbers above Rocky Reach Dam while still actively migrating to the spawning grounds.

Most sockeye salmon that pass Rock Island Dam are bound for spawning areas in the Wenatchee and Okanogan River systems. Those that pass Rocky Reach Dam are, on the other hand, mostly Okanogan-bound fish, because the Wenatchee population leaves the main Columbia River below Rocky Reach Dam. After sockeye salmon pass Rocky Reach Dam, they move to the mouth of the Okanogan River near Brewster, Wash., and continue up the Okanogan into Lake Osoyoos, where they remain until they migrate to the spawning grounds, 10 to 15 miles above the lake, in late September. We have assumed that the Okanogan and Wenatchee populations pass Rock Island Dam simultaneously. The close similarity in the shapes of the graphs of sockeye salmon counts for Rock Island and Rocky Reach Dams (examples of which are shown in figure 10, in conjunction with other data) suggests that this assumption is reasonable.

### TAGGING

Sockeye salmon were tagged at Rock Island Dam in 1953–57, before Rocky Reach Dam was constructed, and in 1962 and 1963, after construction. The numbers of tagged sockeye salmon that were later observed at Zosel Dam in 1953, 1954, 1962, and 1963 are presented in table 1. The effort to observe tagged sockeye salmon at Zosel Dam was so variable and so ineffective in 1955–57 (for reasons given later) that data for these years are not included.

The tagging procedure was the same each year. Tagging was started when the daily count reached about one thousand fish and continued until it dropped to about one thousand near the end of the

TABLE 1.—*Number of sockeye salmon tagged at Rock Island Dam and observed at Zosel Dam in 1953, 1954, 1962 and 1963*

| Year | Tagged at Rock Island Dam | Observed at Zosel Dam |
|---|---|---|
| | *Number* | *Number* |
| 1953 | 710 | 334 |
| 1954 | 1,234 | 215 |
| 1962 | 1,009 | 89 |
| 1963 | 730 | 193 |

run. In 1954 and 1963, tagging was continued for periods of 2 to 4 consecutive days, separated by intervening 3 to 4 day periods of no tagging. Tagging was all at the end of the run in 1953 and was confined to the middle portion of the small run in 1962.

The method of tagging was standard for these studies. Fish were trapped at Rock Island Dam in either the fishway or forebay (figs. 2 and 3), transported by tank truck to the release sites, tagged, and released. Tagging time seldom exceeded 30 seconds per fish.

Several types and colors of tags were used. Petersen plastic disks were used alone in 1962 and 1963, but were used in combination with plastic bars and vinyl streamers in 1953 and 1954. Nickel pins, inserted through the body just below the dorsal fin, provided the attachment. Tags were always applied in pairs, so that the same color and type of tag showed on both sides of the fish.

## STATIONS FOR COUNTING SOCKEYE SALMON AND OBSERVING TAGS

Zosel Dam, which lies on the Okanogan River at Oroville, Wash., 1 mile below Lake Osoyoos, is the principal upstream location for the observation of tagged fish. The dam, which forms a sawmill pond, is provided with two fishways, each with a trap at its exit for the capture of upstream-migrating fish. Sockeye salmon were counted at Zosel Dam in 1935–37, 1944, 1952–57, 1962, and 1963. Since the dam was modified in 1948, however, fish have been able to pass upstream at certain water levels without using the fishways. When stream flow exceeds the

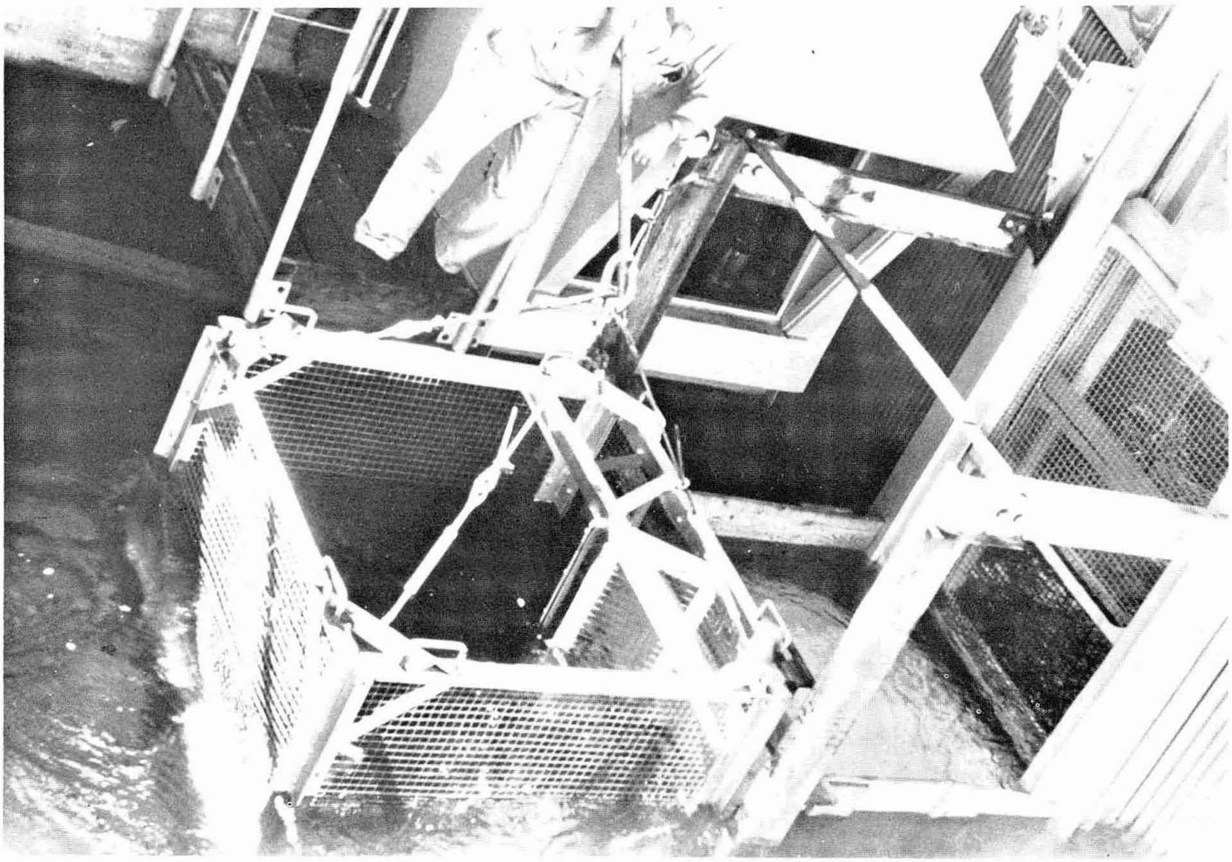

FIGURE 2.—Fishway trap, Rock Island Dam.

amount required to maintain the desired pond level, the surplus water flows either over the top of the dam or is released under lifting gates. Increased flow raises the water depth just below the dam and thereby decreases the velocity of water flowing under the gates. Under these conditions, we saw sockeye salmon swim upstream under the gates, especially when the water depth on the wooden apron just below the dam exceeded 12–18 inches. Consequently, the number of fish passing through the fishways was not always a reliable index of the number passing upstream.

Sockeye salmon have been counted and tags observed (when present) at Rock Island Dam since 1933 and at Rocky Reach Dam since 1961. Complete counts are obtained at Rock Island Dam. During midsummer, when sockeye salmon are migrating, the counting gates near the exits of the three fish ladders are open during daylight but closed at night. At Rocky Reach Dam, on the other hand, the counting gate near the exit of the single fish ladder is open 24 hours daily. Fish are counted 50 minutes per hour from 5 a.m. to 9 p.m. The 50-minute counts are multiplied by 1.2 to estimate the total hourly count. A nighttime correction factor is obtained by counting 24 hours per day once a week. All fish-count data from Rocky Reach Dam used in this report have been corrected by both the hourly and nighttime factors.

## STREAM FLOW AND TEMPERATURE

The sockeye salmon migration between Rock Island and Zosel Dams is marked by movement from a larger, cooler river to a smaller, warmer stream. Comparative data on stream flow and temperature are, therefore, potentially important to this study. Data provided by the annual surface-water reports of the U.S. Geological Survey show, however, that the flow of both the Columbia and Okanogan Rivers generally decreases during July and August and has no apparent effect on the migration of sockeye salmon from Rock Island Dam to Zosel Dam.

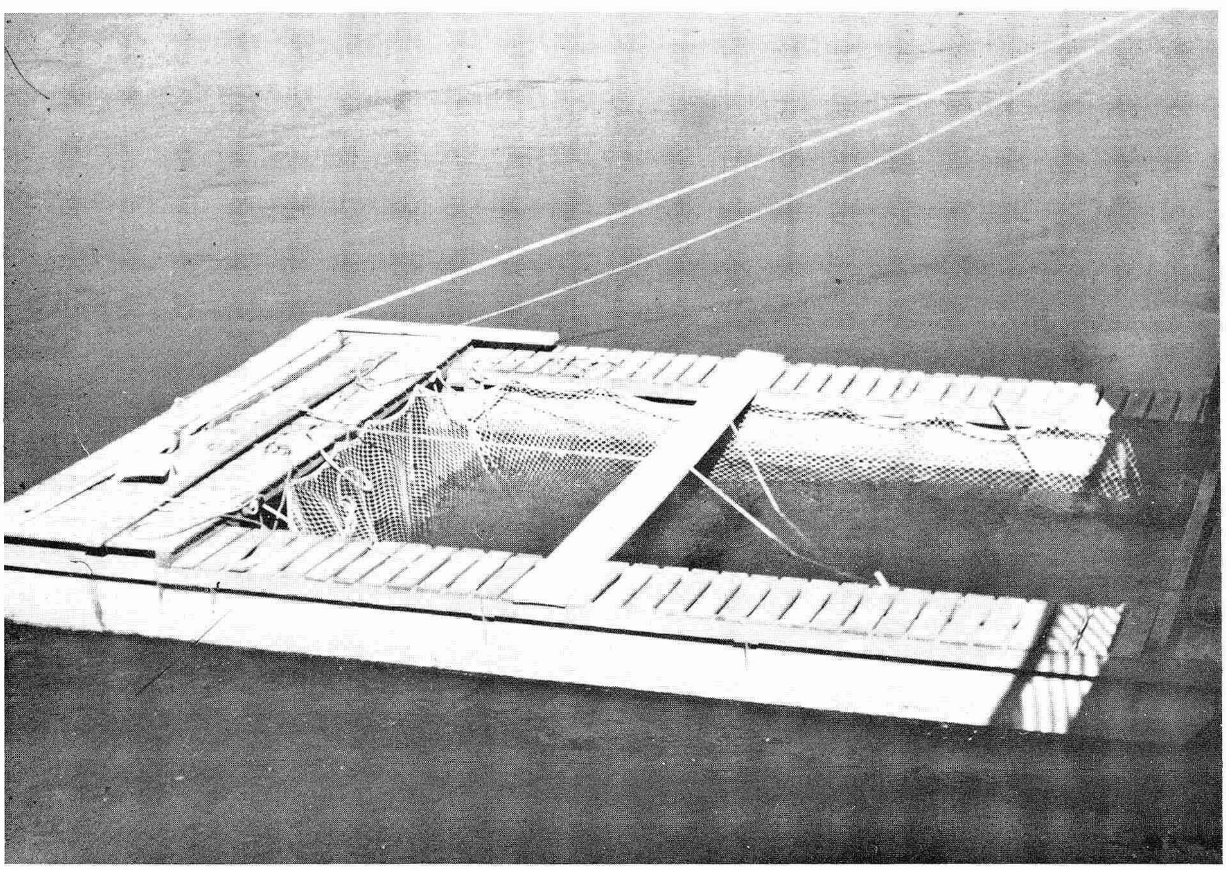

FIGURE 3.—Forebay trap, Rock Island Dam.

Consequently, stream flow is not considered further in our analysis.

It was immediately apparent, on the other hand, from our first observations in 1962 that the water temperature of the Okanogan River greatly influences the migration of sockeye salmon bound for Lake Osoyoos. To understand the effects of temperature better, we have assembled migration-route water temperatures dating back to 1937. Temperature was originally recorded by thermographs or by hand-held thermometers. Daily averages have been computed from the highs and lows on the thermograph charts or from the 8 a.m. and 4 p.m. thermometer readings.

## LIMITATIONS AND ADJUSTMENTS OF THE DATA

Before proceeding, it is appropriate to review certain limitations and adjustments of the data that are potential sources of error.

### Reliability of the Fish Counts and Tag Observations at Zosel Dam

After 1948, varying proportions of the Okanogan run passed Zosel Dam by means other than the fishways, and the reliability of the counts and tag observations recorded at Zosel Dam since 1948 varies accordingly. We used two criteria to determine which data were adequate for this study. First, by comparing the counts at Zosel Dam with estimates of numbers of fish on the spawning grounds, we calculated the percentage trapping efficiency for 1952–57 and 1962—years for which both fish counts and spawning ground estimates were available. These percentages, however crude, are our best estimates of trapping efficiency at Zosel Dam. Second, we determined from the detailed notes maintained by the fish counters at Zosel Dam whether the modal counts corresponded to the modal numbers estimated to be passing the dam.

Estimates of trapping efficiency are shown in table 2. The overall accuracy of the fish counts in 1955–57 was severely limited. Equally important, the modal counts for those years did not correspond to the modal numbers estimated to be passing the dam. We have accordingly deleted the 1955–57 data from our analysis. Although trapping efficiency was not much higher in 1952, 1954, and 1962, the modal counts agreed closely with the numbers estimated by the counters to be available below the dam. The data for 1952, 1954, and 1962 have been retained, therefore, and, together with the data of high-efficiency years, 1937, 1944, 1953, and 1963, constitute the basis of our evaluation of the effect of water temperature on the migration of sockeye between Rock Island and Zosel Dams. Although no spawning ground estimate was made in 1963, our regular observations indicated a relatively high trapping efficiency at Zosel Dam for that year. A fish-tight weir enabled the counters to make complete fish counts in 1935–37 and 1944. Although the counts of fish were complete in 1935 and 1936, we cannot use them here because there are no water temperature records for those years.

TABLE 2.—*Information on the efficiency of the trapping system at Zosel Dam*

| Year | Count of sockeye at Zosel Dam | Spawning-ground estimate[1] | Trapping efficiency |
|---|---|---|---|
| | *Number* | *Number* | *Percent* |
| 1952 | 3,217 | 25,000 | 13 |
| 1953 | 67,542 | 34,260 | High |
| 1954 | 3,760 | 13,206 | 28 |
| 1955 | 4,130 | 47,930 | 9 |
| 1956 | 668 | 39,256 | 2 |
| 1957 | 2,019 | 25,350 | 8 |
| 1962 | 944 | 6,405 | 15 |

[1] Tufts, Dennis F., and Donovan R. Craddock. 1963. Spawning escapement of Columbia River sockeye salmon (*O. nerka*), 1962. U.S. Bur. of Comm. Fish. Biol. Lab., Seattle, Wash., 17 pp., Jan. 1963 (Processed).

### Adjustment of the Tagging Data

French and Wahle (1960) estimated that, before the construction of Rocky Reach Dam, 10.7 days were required for sockeye salmon to migrate from the forebay of Rock Island Dam to Zosel Dam. Their estimate was based on a small sample of 30 tagged sockeye salmon that had been released just above Rock Island Dam in 1954 and 1955 and later observed at Zosel Dam.

To estimate migration time, we have used the large numbers of tagged sockeye salmon (334 and 215) that were released just *below* Rock Island Dam in 1953 and 1954, and later observed at Zosel Dam. Tagged sockeye salmon were released above Rock Island Dam in 1962 and 1963. An adjustment was obviously necessary before the travel time to Zosel Dam of tagged fish that had been released below Rock Island Dam could be compared with the travel time of tagged fish that had been released above Rock Island Dam. We adjusted the data according to the day or days when the number of tagged fish which had been released below Rock Island Dam peaked at the counting stations of Rock Island Dam. The dates of these peaks were treated as dates of release in the forebay. For example, sockeye that had been released below Rock Island Dam on August 2, 1953, peaked at the Rock Island counting stations on August 4, 1953. In our analysis, therefore, we treated this tagged lot as though it had been released in the Rock Island forebay on August 4. This adjustment made it possible to treat all tagged lots in all years as if they had been released in a common location—the forebay of Rock Island Dam.

**Water Temperatures Along the Migration Route**

Records of temperatures are frequently lacking from the Okanogan River at Monse and the Columbia River at Brewster, near their confluence, but are available instead from Oroville on the Okanogan River and from Rock Island Dam and Bridgeport on the Columbia River (fig. 4). Certain features are clearly evident in figure 4. First, in July and August the Okanogan River is considerably warmer than the Columbia River. Second, in terms of trends (rises and falls over a period of several days) the readings at Oroville and Rock Island (or Bridgeport) reflect the situation in the two streams near their confluence. The absolute readings vary considerably within a river, however, particularly in the Okanogan River, where daily differences occasionally reach 4 or 5° F. (neither station was regularly the higher). Caution must be used, therefore, in comparing the absolute readings from the Oroville and Monse stations.

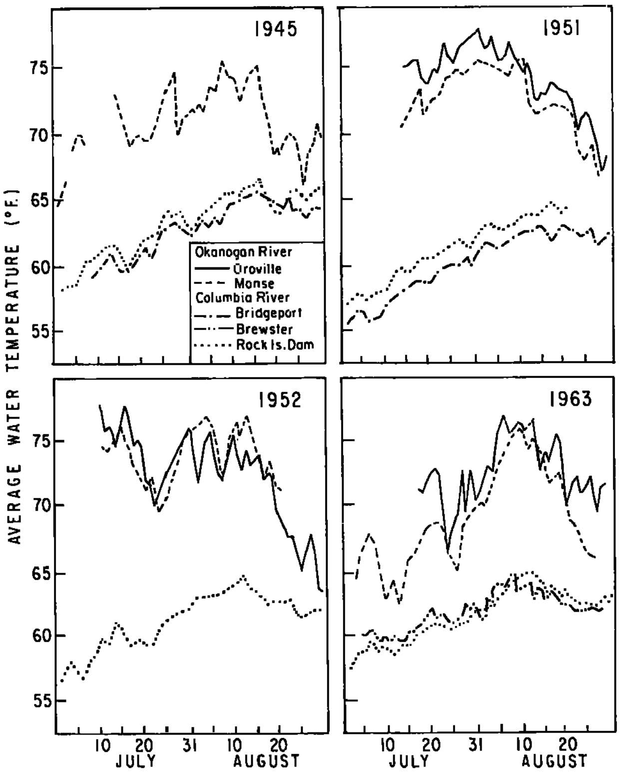


FIGURE 4.—Comparison of Columbia and Okanogan River temperatures, 1945, 1951, 1952, and 1963.

The methods we describe are not rigorous, and our data are not precise. Yet we believe them to be adequate for the purposes of this report.

## TRAVEL TIME BETWEEN DAMS

Travel time of sockeye salmon from Rock Island Dam to Zosel Dam was estimated in 1953 and 1954 before Rocky Reach Dam was built and in 1962 and 1963 after construction. Travel time from Rock Island Dam to Rocky Reach Dam was measured in 1962 and 1963, after Rocky Reach Dam was built.

### TRAVEL TIME BETWEEN ROCK ISLAND AND ZOSEL DAMS

In the examination of the basic tagging data for this phase of the study (tables 3–4 and figs. 5–6), attention should be given first to the years before Rocky Reach Dam was constructed. In 1953 the sockeye salmon that had been tagged below Rock Island Dam on July 31, August 1, and August 2, peaked at Rock Island Dam on August 2, 3, and 4 in that order, and at Zosel Dam 6, 9, and 9 days later. The tagged fish that were released below

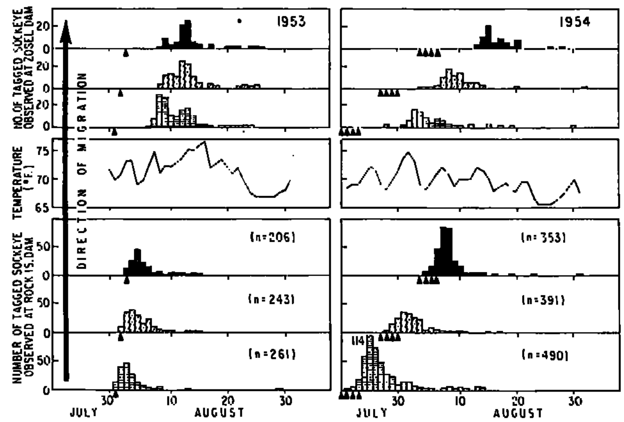


FIGURE 5.—Number of tagged sockeye observed at Rock Island and Zosel Dams after release below Rock Island Dam in 1953 and 1954. The dates of release are designated by triangles below the base lines and the number of fish released is given in parentheses. Daily average temperature of the Okanogan River is given in the center panel.

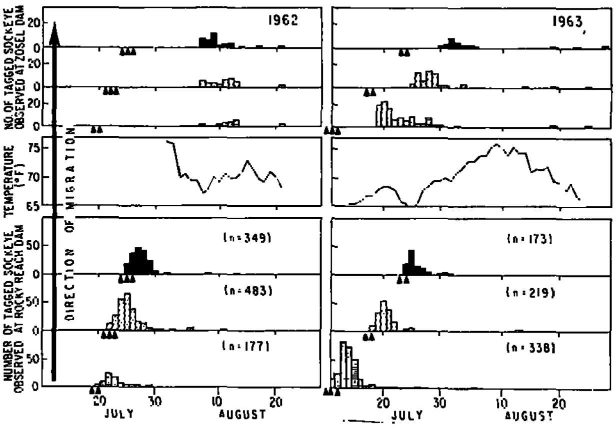


FIGURE 6.—Number of tagged sockeye observed at Rocky Reach and Zosel Dams after release in the Rock Island forebay in 1962 and 1963. The dates of release are designated by triangles below the base lines and the number of fish released is given in parentheses. Daily average temperature of the Okanogan River is given in the center panel.

Rock Island Dam in 1954 have been grouped because of the small numbers which were observed at Zosel Dam. These grouped releases peaked at Rock Island Dam on July 25, July 31, and August 7 and at Zosel Dam 8 to 9, 7 to 8, and 7 to 8 days later.

After Rocky Reach Dam was built, certain changes appeared in the travel time. Tagged sockeye salmon that had been released in the Rock Island forebay on July 19–20, 21–23, and 24–26, 1962, appeared in greatest numbers at Zosel Dam on August 11–13, 7–13, and 7–12. Travel times for the three groups were 22 to 25, 15 to 23, and 12 to 16 days, respectively. The travel times in 1963, on the other hand, were similar to those before Rocky Reach Dam was built—the releases of July 10–12, 17–18, and 23–24 appeared in greatest numbers at Zosel Dam after 7 to 11, 8 to 12, and 8 to 9 days, respectively.

TABLE 3.—*Number of tagged sockeye salmon observed at Rock Island and Zosel Dams after release below Rock Island Dam, 1953 and 1954*

| Date of tagging | Number tagged | Point of observations | Date of observation | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | July | | | | | | | | | | | August | | | | | | | | | |
| | | | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| *1953* | | | | | | | | | | | | | | | | | | | | | | | |
| July 31 | 261 | Rock Island | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 12 | 39 | 45 | 27 | 13 | 9 | 4 | 2 | 5 | ---- | ---- |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 | 8 | 28 | 26 | 11 |
| Aug. 1 | 243 | Rock Island | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 9 | 36 | 40 | 30 | 18 | 24 | 9 | 5 | 4 | 3 |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 4 | 11 | 12 |
| Aug. 2 | 206 | Rock Island | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 12 | 24 | 46 | 22 | 16 | 3 | 5 | 2 | 4 |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 | 8 | 3 |
| *1954* | | | | | | | | | | | | | | | | | | | | | | | |
| July 20–23 | 490 | Rock Island | 2 | 6 | 19 | 57 | 114 | 73 | 47 | 26 | 22 | 10 | 11 | 11 | 5 | 3 | 1 | 1 | ---- | 2 | 3 | 1 | 3 |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 2 | ---- | ---- | 2 | 6 | 16 | 14 | 9 | 4 | 7 | 6 | 3 | 1 | 1 |
| July 27–30 | 391 | Rock Island | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 2 | 16 | 25 | 35 | 34 | 25 | 23 | 3 | 8 | 5 | 2 | 2 | 1 | 1 |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 | 1 | 1 | 2 | 9 | 17 | 10 | 13 |
| Aug. 3–6 | 353 | Rock Island | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 7 | 19 | 48 | 96 | 84 | 26 | 18 |
| | | Zosel Dam | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |

TABLE 3.—*Number of tagged sockeye salmon observed at Rock Island and Zosel Dams after release below Rock Island Dam, 1953 and 1954—Continued*

| Date of tagging | Number Tagged | Point of observation | Date of observation | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | August | | | | | | | | | | | | | | | | | | | | |
| | | | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| *1953* | | | | | | | | | | | | | | | | | | | | | | | |
| July 31 | 261 | Rock Island | ---- | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 | ---- | ---- |
| | | Zosel Dam | 10 | 16 | 17 | 10 | 3 | 3 | 2 | ---- | 1 | 1 | 1 | 1 | 2 | 2 | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| Aug. 1 | 243 | Rock Island | ---- | ---- | 1 | 1 | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | | Zosel Dam | 10 | 24 | 21 | 10 | 4 | ---- | 4 | 1 | ---- | ---- | ---- | 1 | 3 | 1 | 2 | ---- | ---- | ---- | ---- | ---- | ---- |
| Aug. 2 | 206 | Rock Island | 3 | 2 | 1 | 2 | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | | Zosel Dam | 5 | 21 | 24 | 5 | 4 | 1 | 3 | ---- | ---- | 1 | 1 | 1 | ---- | 2 | 2 | 1 | ---- | ---- | ---- | ---- | ---- |
| *1954* | | | | | | | | | | | | | | | | | | | | | | | |
| July 20–23 | 490 | Rock Island | 1 | ---- | 4 | 2 | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | | Zosel Dam | ---- | 2 | ---- | ---- | 3 | ---- | 1 | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 | ---- |
| July 27–30 | 391 | Rock Island | 1 | ---- | ---- | ---- | 1 | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| | | Zosel Dam | 5 | 5 | 5 | 2 | ---- | ---- | ---- | ---- | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 |
| Aug. 3–6 | 353 | Rock Island | 4 | 4 | 4 | 4 | ---- | 1 | ---- | ---- | 1 | ---- | ---- | ---- | 1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | 1 |
| | | Zosel Dam | ---- | ---- | 3 | 10 | 20 | 5 | 8 | 5 | 2 | 7 | ---- | ---- | ---- | ---- | ---- | 1 | ---- | 2 | ---- | ---- | ---- |

The travel times between Rock Island and Zosel Dams are summarized in table 5. In view of the discrepant results of 1962 and the confinement of the 1953 tagging to the end of the run, the effect of Rocky Reach Dam on the travel time between Rock Island and Zosel Dams is best obtained from the records for 1954 and 1963. The travel times tended to be slightly longer in 1963 than in 1954, but the significance of this small difference is questionable.

In any event, the difference between travel times in 1963 and 1954 is greatly overshadowed by the difference between 1962 and 1963, after Rocky Reach Dam was completed. The travel time in 1962 was much the longer and varied erratically within the season—decreasing as the season progressed. This variability was not evident at Rocky Reach Dam, where the appearance of the various tagged lots was orderly in both years (fig. 6). It is appropriate, however, to examine in greater detail

TABLE 5.—*Travel time of tagged sockeye salmon from Rock Island Dam to Zosel Dam, 1953, 1954, 1962, and 1963*

| Year | Date of tagging[1] | Best estimate of travel time |
|---|---|---|
| *Pre-Rocky Reach:* | | *Days* |
| 1953 | Aug. 2 | 6 |
| | Aug. 3 | 9 |
| | Aug. 4 | 9 |
| 1954 | July 25 | 8–9 |
| | July 31 | 7–8 |
| | Aug. 7 | 7–8 |
| *Post-Rocky Reach:* | | |
| 1962 | July 19–20 | 22–25 |
| | July 21–23 | 15–23 |
| | July 24–26 | 12–16 |
| 1963 | July 10–12 | 7–11 |
| | July 17–18 | 8–12 |
| | July 23–24 | 8–9 |

[1] For 1953 and 1954, the dates are those when tagged fish which had been released below Rock Island Dam reappeared in peak numbers at the counting stations of Rock Island Dam.

TABLE 4.—*Number of tagged sockeye salmon observed at Rocky Reach and Zosel Dams after release in the Rock Island Dam forebay, 1962 and 1963*

| Date of tagging | Number tagged | Point of observation | Date of observation: July 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1962* | | | | | | | | | | | | | | | | | | | | | | | |
| July 19–20 | 177 | Rocky Reach | | | | | | | | | | 4 | 10 | 24 | 16 | 8 | 5 | 5 | 1 | | 1 | | |
| | | Zosel Dam | | | | | | | | | | | | | | | | | | | | | |
| July 21–23 | 483 | Rocky Reach | | | | | | | | | | | | 12 | 26 | 55 | 66 | 39 | 18 | 13 | 2 | 1 | 1 |
| | | Zosel Dam | | | | | | | | | | | | | | | | | | | | | |
| July 24–26 | 349 | Rocky Reach | | | | | | | | | | | | | | | 20 | 38 | 48 | 43 | 22 | 6 | |
| | | Zosel Dam | | | | | | | | | | | | | | | | | | | | | |
| *1963* | | | | | | | | | | | | | | | | | | | | | | | |
| July 10–12 | 338 | Rocky Reach | 18 | 24 | 82 | 73 | 50 | 17 | 2 | 6 | 1 | 1 | 1 | 1 | | | | 1 | | | | | |
| | | Zosel Dam | | | | | | | | | 20 | 23 | 16 | 7 | 8 | 6 | 9 | 3 | 3 | 8 | 1 | 1 | |
| July 17–18 | 219 | Rocky Reach | | | | | | | | 10 | 34 | 53 | 39 | 7 | | 1 | 2 | | | | | | |
| | | Zosel Dam | | | | | | | | | | | | | | | 3 | 13 | 5 | 15 | 12 | 1 | 1 |
| July 23–24 | 173 | Rocky Reach | | | | | | | | | | | | | | 20 | 43 | 13 | 12 | 5 | | 2 | 4 |
| | | Zosel Dam | | | | | | | | | | | | | | | | | | | | 2 | 3 |

TABLE 4.—*Number of tagged sockeye salmon observed at Rocky Reach and Zosel Dams after release in the Rock Island Dam forebay, 1962 and 1963—Continued*

| Date of tagging | Number tagged | Point of observation | Date of observation: August 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1962* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| July 19–20 | 177 | Rocky Reach | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Zosel Dam | | | | | | | 1 | | | 1 | 3 | 4 | 5 | | | | | | | | 2 | | | | | | | |
| July 21–23 | 483 | Rocky Reach | | 1 | | | 5 | | | | | | 1 | | | | | | | | | | | | | | | | | |
| | | Zosel Dam | | | | | | | 6 | 3 | 3 | 2 | 6 | 7 | 5 | | | | | | | | 1 | | | | | | | |
| July 24–26 | 349 | Rocky Reach | 1 | | | | | | | 2 | | | | | 1 | | | | | | | | | | | | | | | |
| | | Zosel Dam | | | | | | | 8 | 6 | 3 | 1 | 3 | 4 | | 2 | | | 2 | | | | 1 | | | | | | | |
| *1963* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| July 10–12 | 338 | Rocky Reach | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| | | Zosel Dam | | 1 | | | | | | | | | | | | | | | | | 1 | | | | | | 1 | | | |
| July 17–18 | 219 | Rocky Reach | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| | | Zosel Dam | | | 4 | | | | | | | | | | | 1 | | | | | 1 | | | | | | 1 | | | |
| July 23–24 | 173 | Rocky Reach | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | Zosel Dam | 9 | 5 | 2 | 2 | 1 | | | | | | | | | | | | | | 1 | | | | 1 | | | | | 2 |

the movement of tagged fish between Rock Island Dam forebay and Rocky Reach Dam in 1962 and 1963.

### TRAVEL TIME BETWEEN ROCK ISLAND AND ROCKY REACH DAMS

Fifteen lots of tagged fish were released in the forebay of Rock Island Dam in the combined tagging seasons of 1962 and 1963. The reappearance of these lots at Rocky Reach Dam 15 miles upstream varied little; 12 peaked on the second day, 1 on the first day, and 2 on the third day after release.

We plotted the observations of tags at Rocky Reach Dam by 4-hour intervals (fig. 7). Only the tags observed during the first 4 days after release have been included because tagged fish became scarce after the fourth day. Fish tagged on July 17 and 19–21, 1962, have not been included because the precise time that these fish passed Rocky Reach Dam was not recorded. The agreement of the data for the 2 years is extremely close. For each release the greatest numbers of tags were observed at 1 p.m. to 5 p.m. on the second day after release. If we consider 10 a.m. as the average release time and 3 p.m. (the midpoint of the 1 p.m. to 5 p.m. period) on the second day out as the average time when tagged fish passed Rocky Reach Dam, the modal travel time was 53 hours. Diurnal consistency is also evident: seven times in eight the numbers of tags observed increased from the first 4-hour period (5 a.m. to 9 a.m.) to the second (9 a.m. to 1 p.m.), peaked during the third period (1 p.m. to 5 p.m.), and decreased during the last (5 p.m. to 9 p.m.).

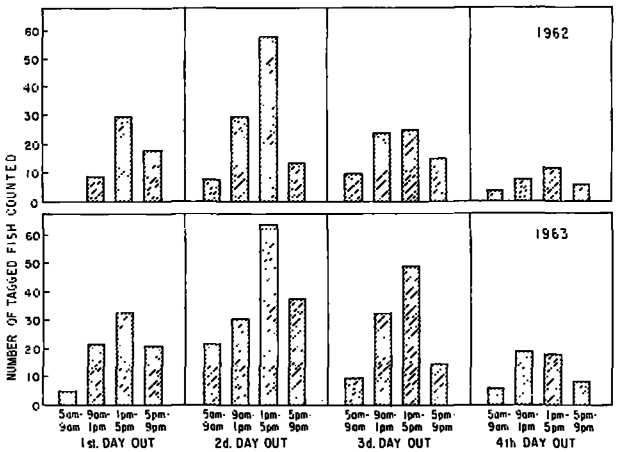


Figure 7.—Number of tagged sockeye counted over Rocky Reach Dam in different 4-hour periods during the 4 days after release in the Rock Island forebay in 1962 and 1963. The periods (shown at the bottom of the graph) were 5 a.m.–9 a.m., 9 a.m.–1 p.m., 1 p.m.–5 p.m., and 5 p.m.–9 p.m. Counting was discontinued between 9 p.m. and 5.a.m.

The consistency of the data indicates that fish passage was uniform and orderly at Rocky Reach Dam in 1962 and 1963, and that the much greater travel time from Rock Island Dam to Zosel Dam in 1962 must be attributed to longer travel time above Rocky Reach. Thus, it is necessary to look to the stretch between Rocky Reach Dam and Zosel Dam for the causes of the slow travel time.

## EFFECTS OF WATER TEMPERATURE ON THE MIGRATION OF SOCKEYE SALMON

On August 1, 1962, after sockeye had failed to appear at Zosel Dam despite high counts at Rocky Reach Dam, the 133-mile migration route between Rocky Reach and Zosel Dams was searched by plane for schools of salmon. Despite optimum aerial-survey conditions, not a single sockeye salmon was sighted—evidence that the run had not yet entered the Okanogan River.

On August 2, the following day, I (Major) visited the area on the bank of the Columbia River immediately adjacent to the confluence of the Okanogan and Columbia Rivers—a traditional fishing site of the Colville Indians. Of the 8 to 10 Indians present, only 1 responded to questions. He answered that "blueback (sockeye) were milling in the area and fishing was getting better every day."

Sockeye salmon did not reach Zosel Dam until August 7; at that time the counter reported several hundred below the dam and captured 155 in the traps, including 15 with tags. Tag recoveries included individuals from six of the seven lots. This breakdown of the usual chronological order, and the resultant mixing and accumulation of the various segments of the run, indicated that the run had been delayed. Information from the aerial search and from the Indian's report pinpoints the delay at the confluence of the Okanogan and Columbia Rivers.

We hypothesized that the sockeye salmon had been blocked from the Okanogan River by unfavorably high water temperatures until a sharp temperature drop on August 2–3 permitted them to enter the stream on or about August 3 and to reach Zosel Dam on August 7.

To examine the validity of the general hypothesis as it applies to all years, we shall use fish counts and water temperatures along the migration route for 1937, 1944, 1952–54, 1962, and 1963 (table 6 and figs. 8–10). For years when sockeye salmon were tagged (1953, 1954, 1962, and 1963), we will reexamine as part of the analysis the tagging data in figures 5 and 6.

Although the data, particularly the fish counts at Zosel Dam, are not precise enough for us to make

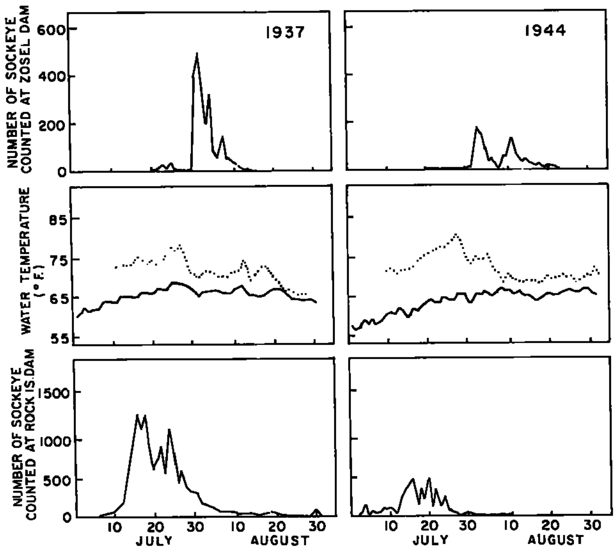


FIGURE 8.—Number of sockeye salmon counted at Rock Island and Zosel Dams, July and August, 1937 and 1944. Average temperatures of the Okanogan (dotted line) and Columbia (solid line) Rivers are given in the middle panel.

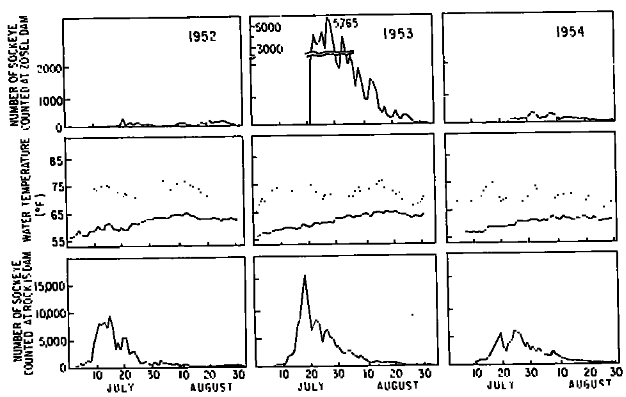


FIGURE 9.—Number of sockeye salmon counted at Rock Island and Zosel Dams, July and August, 1952, 1953, and 1954. Average temperatures of the Okanogan (dotted line) and Columbia (solid line) Rivers are given in the middle panel.

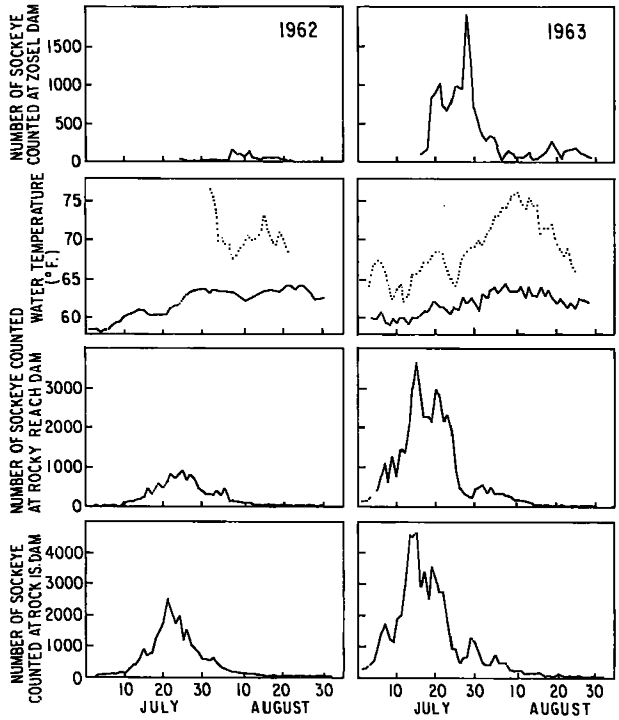


FIGURE 10.—Numbers of sockeye salmon counted at Rock Island, Rocky Reach, and Zosel Dams in 1962 and 1963. Average temperatures of the Okanogan (dotted line) and Columbia (solid line) Rivers are given in the second panel from the top.

a quantitative analysis of the relations involved, we do have evidence pertinent to our hypothesis that unfavorable water temperature (or related factors) blocks the sockeye salmon from the Okanogan River until falling temperatures allow the migration to continue.

Figures 8 to 10 establish clearly the general relation between temperature and movement of fish in the Okanogan River. When fish are presumably available to the river, highs and lows in the count at Zosel Dam not evident in the counts at Rock Island Dam or Rocky Reach Dam, regularly follow falling and rising temperature in the Okanogan River. This relation is particularly striking when the temperature drop is preceded by prolonged high temperatures. No influence of the temperature of the Columbia River on the upstream migration of sockeye salmon is apparent.

Knowledge of the normal travel time from Rock Island Dam to Zosel Dam under favorable temperature conditions is highly relevant to an understanding of the effects of unfavorable temperatures

TABLE 6.—*Counts of sockeye salmon passing Rock Island, Zosel, and Rocky Reach Dams, and Okanogan and Columbia River temperatures, 1937, 1944, 1952-54, 1962, and 1963*

| Date | 1937 | | | | 1944 | | | | 1952 | | | | 1953 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sockeye | | Temperature | | Sockeye | | Temperature | | Sockeye | | Temperature | | Sockeye | | Temperature | |
| | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River |
| | Number | Number | °F. | °F. | Number | Number | °F. | °F. | Number | Number | °F. | °F. | Number | Number | °F. | °F. |
| July 1 | 0 | ----- | ----- | 60.0 | 3 | ----- | ----- | 57.5 | 68 | ----- | ----- | 56.5 | ----- | ----- | 66.5 | 56.0 |
| 2 | 0 | ----- | ----- | 60.5 | 4 | ----- | ----- | 56.5 | 132 | ----- | ----- | 56.5 | ----- | ----- | 68.0 | 56.5 |
| 3 | 0 | ----- | ----- | ----- | 8 | ----- | ----- | 57.0 | 329 | ----- | ----- | 57.5 | ----- | ----- | 70.0 | 57.5 |
| 4 | 1 | ----- | ----- | 62.5 | 148 | ----- | ----- | 58.5 | 998 | ----- | ----- | 58.5 | ----- | ----- | 69.0 | 57.5 |
| 5 | 1 | ----- | ----- | 61.5 | 56 | ----- | ----- | 58.0 | 739 | ----- | ----- | 57.5 | ----- | ----- | 70.0 | 57.0 |
| 6 | 1 | ----- | ----- | 62.0 | 72 | ----- | ----- | 59.0 | 1,019 | ----- | ----- | 57.0 | 5 | ----- | 71.5 | 57.5 |
| 7 | 1 | ----- | ----- | 62.0 | 60 | ----- | ----- | 58.0 | 1,232 | ----- | ----- | 57.0 | 31 | ----- | 73.5 | 58.0 |
| 8 | 2 | ----- | ----- | 62.5 | 85 | ----- | ----- | 58.5 | 1,143 | ----- | ----- | 58.5 | 96 | ----- | 73.5 | 58.5 |
| 9 | 1 | ----- | ----- | 64.0 | 128 | ----- | ----- | 59.5 | 4,777 | ----- | ----- | 58.5 | 146 | ----- | 74.5 | 58.5 |
| 10 | 0 | ----- | ----- | 64.0 | 126 | ----- | 71.5 | 60.5 | 6,810 | ----- | 74.5 | 59.5 | 232 | ----- | 74.5 | 58.5 |
| 11 | 8 | ----- | 72.5 | 64.0 | 110 | ----- | 72.0 | 61.0 | 8,135 | ----- | 74.0 | 60.5 | 375 | ----- | 74.5 | 59.0 |
| 12 | 13 | ----- | ----- | 64.0 | 58 | ----- | 71.5 | 60.5 | 7,981 | ----- | 74.5 | 59.5 | 1,626 | ----- | 74.5 | 59.0 |
| 13 | 156 | ----- | 73.0 | 64.5 | 255 | ----- | 70.5 | 62.0 | 8,293 | ----- | 75.5 | 59.5 | 2,094 | ----- | 73.0 | 59.5 |
| 14 | 425 | ----- | 73.0 | 65.5 | 355 | ----- | 71.5 | 61.0 | 7,200 | ----- | 76.0 | 61.0 | 2,732 | ----- | 72.5 | 59.5 |
| 15 | 962 | ----- | 73.0 | 65.5 | 402 | 0 | 71.5 | 59.5 | 9,581 | 0 | 76.0 | 61.5 | 7,332 | ----- | 73.0 | 58.5 |
| 16 | 1,317 | ----- | 74.5 | 65.5 | 455 | ----- | 72.0 | 60.5 | 7,728 | 0 | 74.5 | 60.5 | 8,201 | ----- | 74.5 | 58.5 |
| 17 | 1,171 | ----- | 75.0 | 65.5 | 170 | ----- | 72.5 | 62.0 | 3,797 | 0 | 74.0 | 59.5 | 11,984 | ----- | 76.0 | 59.5 |
| 18 | 1,288 | ----- | 74.5 | 66.0 | 378 | ----- | 73.5 | 61.5 | 4,790 | 0 | 73.0 | 59.5 | 15,355 | ----- | 76.0 | 60.5 |
| 19 | 925 | ----- | 73.5 | 66.5 | 237 | ----- | ----- | 62.5 | 3,544 | 0 | 72.5 | 59.5 | 11,348 | ----- | 73.5 | 60.0 |
| 20 | 670 | 1 | 74.0 | 66.5 | 460 | ----- | 72.5 | 63.5 | 5,435 | 7 | 72.5 | 60.0 | 6,240 | ----- | 73.5 | 59.5 |
| 21 | 738 | 1 | 73.5 | 66.5 | 136 | ----- | 75.5 | 64.0 | 5,490 | 287 | 71.0 | 59.5 | 7,403 | 10 | 74.5 | 59.5 |
| 22 | 929 | 10 | 73.5 | 66.5 | 398 | ----- | 76.5 | 63.5 | 2,644 | 70 | 72.5 | 59.5 | 8,158 | 2,090 | 73.0 | 60.5 |
| 23 | 595 | 15 | 74.0 | 67.5 | 137 | ----- | 77.0 | 63.0 | 2,850 | 107 | 69.5 | 60.5 | 7,464 | 4,175 | 72.0 | 61.0 |
| 24 | 1,125 | 3 | 76.0 | 67.5 | 249 | ----- | 78.0 | 64.5 | 2,851 | 125 | 69.5 | 61.5 | 4,166 | 3,293 | 71.0 | 60.5 |
| 25 | 756 | 23 | 77.5 | 67.5 | 83 | ----- | 78.0 | 64.5 | 2,037 | 63 | 70.5 | 61.5 | 6,327 | 3,576 | 70.0 | 61.0 |
| 26 | 479 | 8 | 77.0 | 68.5 | 47 | ----- | 78.0 | 64.0 | 847 | 99 | 72.0 | 61.5 | 6,397 | 4,463 | 70.5 | 61.0 |
| 27 | 622 | 3 | 78.0 | 68.5 | 66 | ----- | 79.5 | 64.0 | 882 | 90 | 72.5 | 62.0 | 5,191 | 3,059 | 71.0 | 61.5 |
| 28 | 461 | 3 | 75.5 | 68.5 | 59 | ----- | 80.5 | 65.0 | 904 | 74 | 73.5 | 62.0 | 4,929 | 5,765 | 71.0 | 61.5 |
| 29 | 366 | 3 | 74.0 | 68.0 | 34 | ----- | 79.0 | 65.5 | 490 | 52 | 75.5 | 62.5 | 3,419 | 5,180 | 72.5 | 61.5 |
| 30 | 268 | 0 | 71.0 | 68.0 | 38 | ----- | ----- | 65.5 | 403 | 34 | ----- | 62.5 | 3,692 | 3,396 | 71.5 | 62.5 |
| 31 | 299 | 393 | ----- | 67.0 | 17 | ----- | 74.0 | 63.0 | 914 | 10 | ----- | 62.5 | 2,953 | 2,153 | 70.0 | 62.5 |

TABLE 6.—*Counts of sockeye salmon passing Rock Island, Zosel, and Rocky Reach Dams, and Okanogan and Columbia River temperatures, 1937, 1944, 1952-54, 1962, and 1963—Continued*

| Date | 1937 | | | | 1944 | | | | 1952 | | | | 1953 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sockeye | | Temperature | | Sockeye | | Temperature | | Sockeye | | Temperature | | Sockeye | | Temperature | |
| | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Zosel Dam | Okan. River | Col. River |
| | Number | Number | °F. | °F. | Number | Number | °F. | °F. | Number | Number | °F. | °F. | Number | Number | °F. | °F. |
| Aug. 1 | 198 | 494 | 70.5 | 66.5 | 9 | 0 | 73.0 | 63.5 | 492 | 11 | 76.5 | 63.5 | 2,161 | 1,891 | 70.5 | 62.5 |
| 2 | 62 | 343 | 71.0 | 65.5 | 28 | 4 | 75.0 | 65.5 | 1,324 | 3 | 76.0 | 63.5 | 2,499 | 2,823 | 73.0 | 62.5 |
| 3 | 80 | 200 | 71.5 | 66.0 | 12 | 176 | 74.0 | 65.5 | 907 | 1 | 77.0 | 63.5 | 2,875 | 3,959 | 73.0 | 63.5 |
| 4 | 100 | 336 | 71.5 | 66.5 | 14 | 157 | 74.5 | 66.0 | 874 | 0 | 77.0 | 63.5 | 2,433 | 1,984 | 69.0 | 63.5 |
| 5 | 101 | 81 | 70.5 | 66.5 | 11 | 95 | 75.5 | 65.5 | 726 | 2 | 76.0 | 63.5 | 1,809 | 2,310 | 69.5 | 63.0 |
| 6 | 79 | 60 | 70.0 | 66.5 | 6 | 20 | ----- | 66.5 | 743 | 4 | 74.0 | 63.5 | 1,651 | 2,076 | 72.5 | 63.5 |
| 7 | 6 | 139 | 70.0 | 66.5 | 16 | 39 | 71.5 | 66.5 | 686 | 1 | 73.5 | 64.0 | 1,899 | 1,314 | 74.5 | 63.5 |
| 8 | 0 | 59 | 70.0 | 66.0 | 20 | 17 | 71.0 | ----- | 788 | 0 | 74.0 | 64.0 | 1,462 | 1,864 | 71.0 | 63.5 |
| 9 | 190 | 35 | 71.0 | 66.0 | 4 | 2 | 69.0 | 66.0 | 587 | 13 | 76.0 | 64.5 | 1,177 | 1,676 | 72.0 | 64.0 |
| 10 | 48 | 14 | 71.5 | 66.0 | 0 | 54 | 70.5 | 65.0 | 392 | 68 | 76.5 | 64.5 | 746 | 950 | 72.0 | 64.5 |
| 11 | 47 | 4 | 71.5 | 66.5 | 1 | 55 | 70.0 | 65.5 | 250 | 136 | 75.5 | 64.5 | 444 | 882 | 73.0 | 63.5 |
| 12 | 21 | 13 | 74.0 | 67.5 | 2 | 117 | ----- | 65.0 | 408 | 55 | 76.5 | 65.5 | 436 | 1,676 | 73.5 | 63.5 |
| 13 | 44 | 8 | 72.5 | 68.0 | 5 | 57 | 70.0 | 65.0 | 218 | 21 | 77.5 | 65.0 | 807 | 1,551 | 75.0 | 64.5 |
| 14 | 53 | ----- | 69.0 | 66.0 | 5 | 19 | 70.0 | 64.5 | 187 | 2 | 75.0 | 64.0 | 758 | 1,152 | 75.0 | 64.5 |
| 15 | 22 | ----- | 70.5 | 65.5 | 3 | 31 | 70.0 | 64.0 | 183 | 1 | 74.5 | 64.0 | 487 | 698 | 76.0 | 64.5 |
| 16 | 44 | ----- | 71.5 | 65.5 | 7 | 12 | 69.5 | 64.5 | 116 | 0 | 73.0 | 63.5 | 361 | 376 | 76.5 | 64.5 |
| 17 | 32 | ----- | 72.5 | 65.5 | 4 | 11 | 69.5 | 65.0 | 101 | 0 | 73.5 | 63.0 | 333 | 610 | 72.0 | 65.0 |
| 18 | 38 | ----- | 72.5 | 65.5 | 3 | 13 | 70.0 | 65.5 | 138 | 148 | 71.5 | 63.0 | 287 | 311 | 72.5 | 65.0 |
| 19 | 70 | ----- | 71.5 | 66.0 | 1 | 4 | 69.0 | 65.0 | 114 | 124 | 71.5 | 63.0 | 226 | 209 | 73.5 | 64.5 |
| 20 | 32 | ----- | 70.5 | ----- | 2 | 1 | 69.5 | 65.0 | 123 | 104 | 71.5 | 63.0 | 172 | 214 | 72.0 | 64.5 |
| 21 | 19 | ----- | ----- | 67.5 | 0 | 5 | 70.0 | 65.5 | 175 | 201 | ----- | 63.0 | 74 | 525 | 71.0 | 64.5 |
| 22 | 11 | ----- | 67.5 | 67.0 | 2 | 2 | 70.5 | ----- | 79 | 93 | ----- | 63.5 | 68 | 292 | 72.0 | 64.0 |
| 23 | 18 | ----- | 66.0 | 66.0 | 1 | 0 | 69.5 | ----- | 42 | 115 | ----- | 63.0 | 146 | 191 | 69.0 | 64.0 |
| 24 | 12 | ----- | 66.5 | 65.5 | 1 | 1 | 70.0 | 66.0 | 76 | 169 | ----- | 62.5 | 69 | 335 | 67.5 | 64.0 |
| 25 | 8 | ----- | 66.0 | 64.5 | 3 | 1 | 68.5 | 66.0 | 34 | 148 | ----- | 62.0 | 47 | 346 | 67.0 | 63.5 |
| 26 | 0 | ----- | 65.3 | 64.5 | 0 | 2 | 69.0 | 66.0 | 46 | 186 | ----- | 62.5 | 37 | 65 | 67.0 | 62.5 |
| 27 | 6 | ----- | 65.3 | 64.0 | 1 | 1 | 69.5 | 66.5 | 38 | 164 | ----- | 62.5 | 29 | 28 | 67.0 | 62.5 |
| 28 | 3 | ----- | 65.3 | 64.0 | 0 | ----- | 70.5 | 66.5 | 34 | 119 | ----- | 62.5 | 22 | 74 | 67.0 | 63.5 |
| 29 | 0 | ----- | ----- | 64.0 | 1 | ----- | 70.0 | 66.5 | 12 | 13 | ----- | 63.0 | 60 | ----- | 67.5 | 63.5 |
| 30 | 79 | ----- | ----- | 64.0 | 0 | ----- | 72.5 | ----- | 14 | 60 | ----- | 62.5 | 12 | ----- | 68.0 | 63.5 |
| 31 | 24 | ----- | ----- | 63.0 | 1 | ----- | 70.5 | 65.5 | 9 | 26 | ----- | 62.5 | 9 | ----- | 70.0 | 64.5 |

TABLE 6.—*Counts of sockeye salmon passing Rock Island, Zosel, and Rocky Reach Dams, and Okanogan and Columbia River temperatures, 1937, 1944, 1952-54, 1962, and 1963—Continued*

| Date | 1954 | | | | 1962 | | | | | 1963 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sockeye | | Temperature | | Sockeye | | | Temperature | | Sockeye | | | Temperature | |
| | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Rocky Reach Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Rocky Reach Dam | Zosel Dam | Okan. River | Col. River |
| | Number | Number | °F. | °F. | Number | Number | Number | °F. | °F. | Number | Number | Number | °F. | °F. |
| July 1 | 7 | -------- | 64.5 | -------- | 40 | 0 | -------- | -------- | 58.5 | 285 | 121 | -------- | -------- | 57.5 |
| 2 | 8 | -------- | 64.0 | -------- | 16 | 0 | -------- | -------- | 58.5 | 287 | 131 | -------- | -------- | 59.0 |
| 3 | 15 | -------- | 66.5 | -------- | 23 | 4 | -------- | -------- | 58.5 | 484 | 196 | -------- | 64.0 | 59.0 |
| 4 | 27 | -------- | 68.5 | -------- | 36 | 8 | -------- | -------- | 58.5 | 521 | 299 | -------- | 66.5 | 59.5 |
| 5 | 39 | -------- | 70.0 | -------- | 54 | 12 | -------- | -------- | 58.0 | 1,023 | 406 | -------- | 67.5 | 59.5 |
| 6 | 93 | -------- | 69.5 | -------- | 69 | 26 | -------- | -------- | 58.5 | 1,401 | 732 | -------- | 67.0 | 59.5 |
| 7 | 136 | -------- | 68.5 | 56.5 | 90 | 28 | -------- | -------- | 59.0 | 1,719 | 1,123 | -------- | 66.0 | 59.0 |
| 8 | 182 | -------- | 68.0 | 57.0 | 163 | 22 | -------- | -------- | 59.5 | 1,291 | 602 | -------- | 64.0 | 59.5 |
| 9 | 272 | -------- | 69.0 | 56.5 | 96 | 43 | -------- | -------- | 60.0 | 1,238 | 1,277 | -------- | 62.5 | 59.0 |
| 10 | 375 | -------- | 65.5 | 57.0 | 140 | 66 | -------- | -------- | 60.5 | 1,819 | 807 | -------- | 63.5 | 58.5 |
| 11 | 398 | -------- | 67.0 | 56.5 | 292 | 66 | -------- | -------- | 60.5 | 1,971 | 1,426 | -------- | 64.0 | 59.0 |
| 12 | 768 | -------- | 68.0 | 57.0 | 389 | 66 | -------- | -------- | 61.5 | 2,893 | 1,337 | -------- | 62.0 | 59.5 |
| 13 | 715 | -------- | 70.0 | 57.0 | 416 | 140 | -------- | -------- | 61.0 | 4,567 | 2,042 | -------- | 63.0 | 59.5 |
| 14 | 843 | -------- | 72.0 | 57.5 | 638 | 166 | -------- | -------- | 61.0 | 4,548 | 2,981 | -------- | 65.5 | 59.5 |
| 15 | 1,158 | -------- | 73.5 | 58.5 | 932 | 235 | -------- | -------- | 61.5 | 4,601 | 3,636 | -------- | 65.5 | 59.5 |
| 16 | 2,383 | -------- | 74.5 | 58.5 | 745 | 415 | -------- | -------- | 61.5 | 2,986 | 2,891 | 114 | 66.0 | 60.5 |
| 17 | 3,396 | -------- | 74.5 | 58.5 | 788 | 334 | -------- | -------- | 61.0 | 3,300 | 2,367 | 148 | 67.0 | 60.5 |
| 18 | 4,368 | -------- | 74.0 | 58.5 | 1,272 | 474 | -------- | -------- | 60.5 | 2,653 | 2,321 | 187 | 67.0 | 60.5 |
| 19 | 5,440 | -------- | 72.5 | 58.5 | 1,587 | 553 | -------- | -------- | 60.5 | 3,572 | 2,171 | 810 | 68.0 | 61.0 |
| 20 | 3,417 | -------- | 68.0 | 58.5 | 1,733 | 454 | -------- | -------- | 61.0 | 3,116 | 2,888 | 898 | 68.5 | 61.0 |
| 21 | 2,136 | -------- | 68.5 | 58.5 | 2,541 | 571 | -------- | -------- | 61.0 | 2,734 | 2,783 | 1,018 | 68.5 | 61.5 |
| 22 | 3,778 | -------- | 69.0 | 58.5 | 2,133 | 800 | -------- | -------- | 61.5 | 2,725 | 2,127 | 766 | 68.0 | 61.5 |
| 23 | 4,178 | 9 | 69.0 | 59.5 | 1,702 | 708 | -------- | -------- | 62.5 | 1,814 | 2,308 | 626 | 66.0 | 61.5 |
| 24 | 5,908 | 117 | 70.5 | 59.5 | 1,956 | 803 | 51 | -------- | 62.5 | 886 | 1,901 | 776 | 65.5 | 60.5 |
| 25 | 5,811 | 101 | 72.0 | 59.5 | 1,237 | 856 | 32 | -------- | 62.5 | 841 | 932 | 971 | 64.0 | 60.5 |
| 26 | 5,584 | 110 | 71.5 | 60.5 | 1,544 | 683 | 1 | -------- | 63.0 | 475 | 438 | 968 | 65.5 | 60.5 |
| 27 | 4,137 | 87 | 69.0 | 60.5 | 1,160 | 793 | 1 | -------- | 63.5 | 633 | 315 | 934 | 68.0 | 60.5 |
| 28 | 3,347 | 74 | 68.0 | 60.5 | 880 | 670 | 8 | -------- | 64.0 | 1,015 | 307 | 1,900 | 68.5 | 61.0 |
| 29 | 3,753 | 61 | 69.5 | 60.5 | 853 | 480 | 0 | -------- | 64.0 | 1,267 | 215 | 1;233 | 69.5 | 62.0 |
| 30 | 2,815 | 117 | 71.0 | 60.5 | 573 | 460 | 0 | -------- | 63.0 | 1,138 | 479 | 768 | 69.5 | 62.0 |
| 31 | 2,913 | 226 | 73.5 | 61.0 | 666 | 315 | 0 | -------- | 62.5 | 753 | 546 | 482 | 70.0 | 62.0 |

TABLE 6.—*Counts of sockeye salmon passing Rock Island, Zosel, and Rocky Reach Rams, and Okanogan and Columbia River temperatures, 1937, 1944, 1952-54, 1962, and 1963—Continued*

| Date | 1954 | | | | 1962 | | | | | 1963 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sockeye | | Temperature | | Sockeye | | | Temperature | | Sockeye | | | Temperature | |
| | Rock Is. Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Rocky Reach Dam | Zosel Dam | Okan. River | Col. River | Rock Is. Dam | Rocky Reach Dam | Zosel Dam | Okan. River | Col. River |
| | Number | Number | °F. | °F. | Number | Number | Number | °F. | °F. | Number | Number | Number | °F. | °F. |
| Aug. 1 | 2,158 | 386 | 74.5 | 61.5 | 503 | 344 | 0 | 76.5 | 62.5 | 490 | 594 | 356 | 69.5 | 62.0 |
| 2 | 2,573 | 311 | 73.0 | 61.5 | 583 | 365 | 0 | 76.0 | 61.5 | 380 | 198 | 281 | 71.0 | 62.0 |
| 3 | 1,654 | 159 | 69.0 | 61.5 | 489 | 298 | 0 | 70.0 | 62.0 | 491 | 484 | 305 | 71.5 | 62.5 |
| 4 | 1,506 | 88 | 68.0 | 61.0 | 360 | 232 | 2 | 70.5 | 62.5 | 706 | 327 | 248 | 73.0 | 63.0 |
| 5 | 1,542 | 130 | 69.5 | 61.0 | 273 | 400 | 2 | 69.5 | 61.5 | 513 | 309 | 83 | 73.0 | 63.5 |
| 6 | 1,415 | 146 | 71.0 | 61.5 | 196 | 139 | 16 | 69.5 | 62.0 | 469 | 339 | 20 | 74.0 | 64.0 |
| 7 | 1,832 | 234 | 72.0 | 61.5 | 174 | 142 | 155 | 67.5 | 62.0 | 360 | 241 | 101 | 74.0 | 64.0 |
| 8 | 1,575 | 280 | 71.0 | 62.0 | 168 | 112 | 102 | 68.0 | 62.5 | 222 | 219 | 149 | 75.5 | 64.5 |
| 9 | 1,317 | 234 | 68.5 | 62.5 | 94 | 109 | 100 | 70.0 | 61.5 | 242 | 183 | 31 | 76.0 | 64.5 |
| 10 | 975 | 126 | 70.0 | 62.0 | 76 | 73 | 61 | 69.5 | 61.0 | 197 | 172 | 29 | 75.0 | 64.5 |
| 11 | 913 | 106 | 70.0 | 61.5 | 116 | 61 | 135 | 70.5 | 60.5 | 152 | 128 | 38 | 74.0 | -------- |
| 12 | 752 | 103 | 70.0 | 61.5 | 116 | 73 | 96 | 70.0 | 60.5 | 132 | 78 | 0 | 75.5 | -------- |
| 13 | 527 | 116 | 72.0 | 62.5 | 100 | 81 | 46 | 70.0 | 61.5 | 154 | 68 | 43 | 74.5 | 64.5 |
| 14 | 718 | 118 | 71.5 | 62.0 | 67 | 61 | 11 | 71.0 | 61.5 | 192 | 51 | 116 | 74.5 | 63.5 |
| 15 | 502 | 104 | 70.0 | 61.5 | 65 | 50 | 31 | 73.0 | 62.0 | 189 | 42 | 42 | 71.0 | 63.5 |
| 16 | 332 | 47 | 68.0 | 61.5 | 101 | 46 | 17 | 71.5 | 62.0 | 58 | 55 | 47 | 71.5 | 64.0 |
| 17 | 320 | 57 | 68.5 | 61.5 | 59 | 45 | 15 | 70.0 | 62.5 | 74 | 37 | 12 | 71.5 | 63.5 |
| 18 | 349 | 45 | 69.0 | 62.0 | 65 | 54 | 3 | 69.5 | 62.0 | 70 | 10 | 159 | 72.0 | 63.0 |
| 19 | 279 | 42 | 68.0 | 62.0 | 52 | 18 | 14 | 71.0 | 62.0 | 67 | 9 | 257 | 69.5 | 63.5 |
| 20 | 177 | 46 | 68.0 | 62.5 | 63 | 18 | 6 | 70.0 | 62.5 | 51 | 12 | 107 | 69.0 | 62.5 |
| 21 | 129 | -------- | 69.5 | 62.5 | 43 | 17 | 24 | 68.5 | 62.5 | 71 | 16 | 36 | 68.0 | 62.5 |
| 22 | 173 | -------- | 69.5 | 62.0 | 61 | 22 | 15 | -------- | 62.5 | 48 | 8 | 117 | 69.0 | 62.5 |
| 23 | 105 | -------- | 66.5 | 61.5 | 38 | 15 | -------- | -------- | 62.5 | 55 | 4 | 141 | 67.0 | 62.5 |
| 24 | 144 | 3 | 65.5 | 62.0 | 30 | 42 | -------- | -------- | 62.5 | 33 | 4 | 166 | 66.0 | 62.5 |
| 25 | 67 | 12 | 65.5 | 61.5 | 38 | 14 | -------- | -------- | 62.5 | 38 | 29 | 170 | -------- | 62.5 |
| 26 | 78 | 26 | 65.5 | 60.5 | 29 | 8 | -------- | -------- | 62.5 | 53 | 5 | 125 | -------- | 62.0 |
| 27 | 54 | 10 | 66.0 | 61.0 | 54 | 8 | -------- | -------- | 61.5 | 28 | 26 | 108 | -------- | 63.0 |
| 28 | 44 | 10 | 67.0 | 61.0 | 39 | 18 | -------- | -------- | 61.5 | 32 | 52 | 99 | -------- | 62.5 |
| 29 | 40 | 9 | 68.0 | 61.5 | 38 | 9 | -------- | -------- | 61.5 | 28 | 9 | 48 | -------- | 62.5 |
| 30 | 39 | 14 | 69.5 | 61.5 | 36 | 11 | -------- | -------- | 62.0 | 13 | 49 | -------- | -------- | 63.0 |
| 31 | 33 | 17 | 67.5 | 62.0 | 17 | 8 | -------- | -------- | 62.5 | 12 | 25 | -------- | -------- | 63.5 |

on the migration of sockeye salmon. As has been brought out earlier, the travel time was 8 to 9, 7 to 8, and 7 to 8 days for the three groups tagged in 1954 before Rocky Reach Dam was constructed. In 1963, after Rocky Reach Dam was completed, the most frequent time was 9 days. On the basis of these travel times, we may assume that the sockeye salmon arrive at the mouth of the Okanogan River, 80 miles above Rock Island Dam or roughly halfway on the 154-mile distance from Rock Island Dam to Zosel Dam, on the fourth or fifth day after passing Rock Island Dam. Accordingly, the remaining 3 to 5 days of the typical 8- or 9-day total migration time are spent negotiating the 74-mile route from the confluence to Zosel Dam.

Under this assumption, we can retrace the migration of certain segments of the runs in several years. In 1937, for example, fish were abundant at Rock Island Dam beginning July 13. Had the Okanogan-bound segment of this run moved without delay, we would have expected it at Zosel Dam beginning July 21. Yet, the counts at Zosel Dam remained practically nil until July 31—3 days after the temperature of the Okanogan River began a sharp decline. Prior to July 28, the temperature had been either relatively stable or climbing sharply; either condition apparently delayed the fish—some as long as 10 days.

The events of 1937 were essentially repeated in 1944; fish counts increased significantly at Rock Island beginning July 13, 1944, but not at Zosel Dam until August 3—5 days after the water temperature decreased on July 29 and up to 13 days later than expected. Then, following several days of high counts, the number of sockeye salmon arriving at Zosel Dam dropped sharply, finally reaching a low of two fish on August 9. These low counts corresponded with rising or stable water temperatures. The count surged again on August 10—3 days after a sharp drop in water temperature.

Fish migration was similar in 1952. Counting of fish began at Zosel Dam on July 15, but no sockeye salmon were seen until the evening of July 20, when seven were taken in the traps. The count increased markedly the next day, and sockeye salmon were relatively abundant the following 9 days. This increased abundance of fish began 5 days after the beginning of a temperature drop which eventually lasted 9 days. Then, beginning July 25, the temperature rose steadily until August 5, when it began to decline. This second rise in temperature brought a second period of low counts which lasted until August 10—5 days after the temperature fell on August 5. Movement was suppressed a third time by a general 6-day rise in temperature from August 8 to 13. A decrease of temperature on August 14 resulted in a surge of fish at Zosel Dam on August 18—4 days later. Thereafter, the temperature dropped steadily and, judging by the counts, fish migration through the area was unimpeded.

The counts at Zosel Dam in 1953 generally reflected the counts at Rock Island. This agreement probably occurred because increases in water temperature were short (2–4 days) and were followed by falling temperatures during the time when the greater portion of the run was migrating through the critical area.

A late-season temperature rise on August 6–7, 1953, coincided with the arrival of tagged fish. This event provides the first opportunity to study the effects of water temperature in terms of a marked segment of the population. For this analysis, we need to refer to figure 5, which depicts the Okanogan River temperatures and the movement of tagged fish from Rock Island to Zosel Dam. On the assumption that the normal travel time from Rock Island Dam to the confluence of the two rivers is 4 to 5 days, we reason that some individuals from the lot tagged on July 31 reached the confluence on August 4 or 5, before the temperature rise of August 6–7. These early arrivals peaked initially at Zosel Dam on August 8. The rising water temperatures on August 6–7 suppressed entry of the later arrivals into the Okanogan River until a drop of temperature on August 8. This decrease of temperature resulted in another surge of tagged fish at Zosel Dam on August 11 to 12, and gave the count of tagged fish at Zosel a bimodal distribution not evident at Rock Island. Apparently, few fish from the lot tagged on August 1 arrived at the river mouth before the temperature rose; most arrived during the rise of August 6 to 7 and therefore did not appear at Zosel Dam until August 12—4 days after the temperature fell on August 8. Similarly, few fish from the lot tagged on August 2 arrived at the confluence before the temperature rise suppressed their entry. Most of these fish arrived at Zosel Dam on August 12 to 13—4 or 5 days after the temperature drop.

The movement of the various tagged segments of the 1954 run can also be retraced from figure 5.

Fish released below Rock Island Dam on July 20–23 peaked at Rock Island Dam on July 25, and at Zosel Dam on August 2–3, 8 to 9 days later. From these records we infer that most of the tagged fish reached the Okanogan River on July 29, when the temperature was just beginning to increase, and that this increase did *not* suppress entry to the stream. Similarly, the collective releases of July 27–30 peaked at Rock Island Dam on July 31 to August 1 and at Zosel Dam on August 8. On the assumption of 4 days for travel, we estimate that most of these fish arrived at the mouth of the Okanogan on August 5–6 when the temperature began a new rise. Again, however, migration was not affected. Finally, the August 3–6 releases of tagged fish peaked at Rock Island Dam on August 7–8 and probably arrived at the mouth of the Okanogan River on August 11–12, when temperatures were fairly stable. These fish also appear to have migrated freely through the Okanogan River. A possible explanation of the normal progress of the migration despite rising temperatures is given below in our discussion of the 1963 migrations.

Temperatures of the Okanogan River were not recorded in 1962 until August 1. High air temperatures indicate, however, that the water temperature almost surely had been rising prior to August 1. Rising temperature would account for the July 26 to August 5 lull in the count at Zosel Dam (figs. 6 and 10). On the basis of counts at Rocky Reach Dam, we would have expected the arrival of sockeye salmon, both tagged and untagged, at Zosel Dam during this interval. The arrival of the fish at the mouth of the Okanogan River coincided, however, with rising water temperatures, a condition which apparently blocked their entry.

The 1963 migration progressed from Rocky Reach Dam to Zosel Dam without major delay (figs. 6 and 10). Tag recoveries were orderly in contrast to those of 1962; peaks at Zosel Dam followed comparable peaks at Rocky Reach Dam by 6, 6 to 8, 6, 7 to 9, 6 to 9, and 6 to 10 days. Thus, migration was normal in 1963, despite generally rising water temperatures.

The absence of delay in 1954 and 1963, despite rising water temperatures, focuses attention on the importance of the level at which the temperature is changing. For example, migration was unimpeded by rising temperatures in the 62° to 69° F. range in 1963, but was halted by rises in the 75° to 78°, 70° to 77°, and 74° to 78° F. ranges in 1952.[2] Furthermore, a temperature rise in the 73° to 78° F. range at Oroville interrupted the migration in 1937, a year in which occasional temperature readings taken at Monse on the lower Okanogan River were even higher than those at Oroville (Chapman, 1941). On the other hand, the 1954 migration was apparently unaffected by rises in the 68° to 70° F. range. The dependability of the latter example is subject to some question, however, because the temperature readings were recorded at Oroville, not at Monse.

These several examples suggest a threshold temperature of about 70° F., below which migration is not affected, but above which rising or stable temperatures inhibit migration—a condition which endures until a sharp drop allows the migration to resume.

We have not considered here a situation in which fish enter the Okanogan River under favorable conditions only to be confronted enroute by sharply rising water temperatures. We have no data on this aspect of the problem, but suspect that the behavior and survival of the fish depend on several factors, including: (1) their location at the time they are confronted by rising temperatures; (2) their ability to acclimate; (3) their size, general health, and stage of maturity; and (4) the level to which the water temperature rises.

## RESULTS OF OTHER STUDIES AND THEIR POSSIBLE BEARING ON THE PROBLEM IN THE OKANOGAN RIVER

The environmental factors that control the migrations of adult Pacific salmon have long been of practical and theoretical interest to fishery biologists. The literature gives many examples of environmental influences that affect different populations in different ways. Rather than present another review of the extensive literature on this broad subject, a matter so capably handled by Hoar (1953) and Allen (1956), we refer here only to the more important papers that deal with the environmental factors that influence the sudden mass movement of migrating salmon.

Several investigators have found that rainfall and streamflow affect the migration of adult salmon. Pritchard (1936), and Davidson, Vaughan, Hutchinson, and Pritchard (1943), who studied pink

[2] These temperatures, recorded at Monse, are not subject to the possible error of estimating temperatures in the lower river from actual readings at Oroville.

salmon (*O. gorbuscha*), and Hunter (1959), who worked with pink salmon and chum salmon (*O. keta*), concluded that entry into a river follows increases in stream flow. Shapavalov and Taft (1954) noted a correlation between the general periods of the spawning runs of silver salmon (*O. kisutch*) and rainfall. They further believed, but were unable to demonstrate quantitatively, that fish movement increased with a rise of stream flow. Allen (1956), on the other hand, related the movement of silver salmon and chinook salmon (*O. tshawytscha*) to nighttime rainfall and low barometric pressure, respectively. Ellis (1963) believed that the entry of silver salmon and sockeye salmon into rivers was associated with the appearance of atmospheric warm fronts over the estuary.

Only Foerster (1929) and Cramer and Hammack (1952) attributed the sudden movement of salmon to changes in water temperature. Foerster, who reported on sockeye salmon at Cultus Lake, British Columbia, noted that the numbers of fish arriving at a counting fence synchronized closely with temperature change; increases in the daily run accompanied declines in temperature. Cramer and Hammack, who studied chinook salmon in Deer Creek, a tributary to the Sacramento River, Calif., concluded that at the close of a period of clear weather and relatively cool water, sudden increases in water temperature to 75° F. caused an upsurge of fish.

Andrew and Geen (1960), in their appraisal of all available information on the possible effects of dam construction on the Fraser River, British Columbia, devoted considerable attention to the effects of temperature and delay on upstream-migrating salmon. High water temperatures, they concluded, are detrimental to salmon in their upstream migration because they increase the rate of energy consumption and the incidence of disease and parasites, and may be directly lethal.

In the matter of delay, Andrew and Geen (1960) cited Thompson (1945) as having shown that a delay of 12 days at Hell's Gate (before construction of the fishways) was sufficient to prevent sockeye salmon from reaching their spawning grounds, and that lesser delays reduced the reproductive capacity of the fish. The same authors also referred to an incident in the Fraser Canyon at Yale, British Columbia, in 1955 where the early run to the Stuart River was blocked 6 days by high water. Of an estimated 30,000 to 35,000 sockeye salmon, only 2,170 reached the spawning grounds.

The effect of delay on the productivity of salmon has been illustrated by studies of fish passage at a rock slide on the Babine River, British Columbia (Godfrey, Hourston, Stokes, and Withler, 1954). Concerning this study, Andrew and Geen (1960) stated:

> . . . . Tagging of fish below the point of difficult passage and recovery of the tagged fish at a counting fence 40 miles upstream showed that some of the fish delayed below the obstruction were able to migrate to their spawning grounds but relatively few were able to spawn successfully. Because fish were delayed and weakened below the obstruction they were not able to migrate at a normal rate after passing the obstruction. The effective spawning in 1952, when some sockeye were delayed for extended periods, was estimated as 30 to 42 percent of the numbers of female sockeye that reached the spawning grounds or 7 to 10 percent of the total escapement. From 30 to 40 percent of the female sockeye examined on the spawning ground died unspawned and others died after passing the obstruction but before reaching the spawning grounds.

The previous references indicate that salmon that have been delayed enroute to spawning grounds can be affected in two ways. First, some die enroute to the spawning grounds and second, some complete the journey but are unable to spawn successfully. We conclude that temperature blocks of the type outlined in this paper similarly affect sockeye salmon bound for the Okanogan River spawning grounds.

## SUMMARY

Sockeye salmon were tagged at Rock Island Dam and later observed at Zosel Dam on the Okanogan River in 1953–54 and 1962–63. These experiments were used to detect any changes in the migration time caused by Rocky Reach Dam, which was constructed on the migration route during the intervening years.

Travel time varied greatly, both between and within years. The difference between 1962 and 1963 exceeded the difference between 1963 and 1953–54. The best estimate of the time required for sockeye salmon to migrate from Rock Island Dam to Zosel Dam is 7 to 9 days, barring major delay due to environment. This travel time has not been increased by Rocky Reach Dam.

Water temperature of the lower Okanogan River, or factors linked with it, is by far the greatest source of delay. Below 70° F., entry into the Okanogan River is relatively unimpeded. Above 70° F., relatively stable or rising temperatures delay entry until a sharp drop occurs.

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