# EFFECTS OF STREAMFLOW ON SILVER SALMON PRODUCTION IN WESTERN WASHINGTON

By

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ABSTRACT

In this study the abundance of adult silver salmon, Oncorhynchus kisutch, landed each year in the Western Washington commercial fisheries from 1935 to 1954 was found to be closely correlated with both the annual and low-month average streamflows for Western Washington that occurred during the juvenile residence of the salmon.

Catches of silver salmon from certain specific Washington rivers, or near their mouths, did not correlate to a significant extent with the annual or low-month streamflows.

An index for the streamflow by months from 1933 to 1952 in Western Washington was derived by computing the average runoff for 23 major rivers. Annual, summer, monthly, and lowest-month streamflows provided high correlation coefficients with total commercial silver landings except for some of the winter and spring months. The significant correlations of the summer and low-month flows occurred because they are good indices of annual runoff. Both of these low flow variables, however, showed almost borderline significance and are considered at times to have an independent effect on silver salmon production.

A linear regression formula was derived relating total silver landings to annual streamflows.

Freshets during the incubation period of silver salmon eggs were not found to affect silver yearling production in Minter Creek, but did limit the chum salmon fry production.

Total streamflow during stream residence correlated significantly with the production of yearling silver salmon and two-year old steelhead trout at Minter Creek. The interaction of parent egg deposition with streamflow in the production of silver year-

lings was shown by Minter Creek data.

Various rainfall data for Washington were found to correlate significantly with total silver salmon landings in Western Washington.

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# I. INTRODUCTION.

Unpredictable or unexplainable fluctuations in abundance of fish stocks have presented problems for many years both to men who harvest fish and to those who are charged with management of fish populations. Industry could utilize its investments more wisely if the abundance of fish and the extent of the permissible catch were known in advance of the fishing season. Fisheries management agencies could regulate the production and the catch of fish more effectively if fluctuations in abundance were predictable. Those agencies could also regulate the agricultural, industrial, and domestic uses of streams to provide the best conditions permissible for salmon production if the ways are known in which certain environmental factors such as streamflow, stream rearing areas, or spawning beds determine salmon abundance.

The consistent fluctuation of a salmon population in harmony with known changes in environmental factors has not been generally established. Lindroth (1950) for the Atlantic salmon in Sweden and McKernan et al (1950) for silver salmon in Oregon noted that catches from a number of rivers fluctuated over the years in a similar manner. Lindroth stated,

"There must be some absolute factor in the river areas accessible to spawning adults and feeding parr, but the nature and effect of its fluctuations under natural conditions are unknown."

McKernan et al explored a number of watershed factors that might affect silver salmon but obtained a significant indication only for summer low flow on the Siletz River.

The purpose of this paper is to present a study which is believed to throw some light on the extent to which salmon abundance is affected by the juvenile fresh water environment. The fish chosen for study is the Pacific salmon species, *Oncorhynchus kisutch*, which occurs in the streams of Washington and is commonly known as silver or coho salmon.

## II. DISCUSSION OF THE PROBLEM.

Of the five species of migratory salmon in Washington, the silver salmon is most preferable as a subject for a study of the effects of the fresh water environment. If the incubation period is included, it spends almost one-half of its life span in fresh water. The juveniles leave for the ocean about the same time each year. Only one year class at a time is significant in the annual commercial catch since a given year class becomes large enough to be taken in commercial gear only during its final year of maturity at the end of which it spawns and dies. Thus, all of the silvers landed in one year are of the same generation and all spent their juvenile period in the streams at the same time. Most of the silver salmon spawning in Western Washington complete their life cycle in three years. The first twelve to eighteen months are spent in fresh water. During this time they develop from the egg to the downstream migrant stage when they have attained a length of about four inches. Yearling migrants enter salt water between early winter and late spring and spend the next twelve to eighteen months feeding and maturing. They do not attain a commercial size until early in their third year when they begin to appear in the offshore troll fishery. At this time they have acquired an average weight of about five pounds.

During the last six months of the life cycle, silver salmon complete their development to maturity, move to the mouths of their parent streams and then ascend them to deposit their eggs during the late fall months. In these final stages they attain an average weight of about ten pounds and make the greatest contribution to the commercial fishery in which they are taken by purse seine, gill net, reef net, and Indian traps. It may be premised that the number of fish available for each year's commercial catch of silver salmon is influenced by the earlier success of those fish in surviving their stream life and entering the salt-water rearing areas.

For many years it was believed, but was not established quantitatively, that variations in stream flow conditions affected the survival of all salmon species. The complex and variable life cycles of the various salmon species, combined with the lack of a total fish census, have served to obscure the effects of stream variations on salmon survival. This has been true in spite of the many decades during which Pacific salmon have supported an intensive fishery.

The study described in this paper was initiated in the fall of 1947. A consistent statistical relationship between annual stream runoff and the commercial catches of silver salmon was discovered in the winter of 1948. The study at that time covered the period 1935 through 1947. Subsequent annual catches for 1948 through 1954 were found to agree closely with the expected catches based upon streamflow two years previously and are incorporated in this report. It is hoped that ultimately a more detailed analysis of this relationship will permit accurate predictions of the abundance of Washington silver salmon runs and thus provide an effective tool for management of the sport and commercial fishery. This relationship has already been used extensively in formulating principles of stream management in the state of Washington.

The basic problem in relating silver salmon to stream environment is to associate the fish production from a stream with the runoff of that watershed during the residence of the juveniles. A major difficulty has been the accurate count or measurement of the salmon production of a given stream. In such a complex fishery as that in Washington waters it is impossible to separate the stocks of silvers in a given fishery. They become thoroughly mixed and a small school of fish will contain individuals from widely separated streams. Jensen (1953) in operating an experimental reef net for tagging silvers at the Bush Point area in Puget Sound found silvers bound for the Skagit and Puyallup rivers in the same school. The mouths of these two rivers are seventy-five miles apart with many intervening streams.

Initial attempts in this study to associate silver production, as measured by commercial catch, with specific streams met with poor success. The plotted material for these streams occasionally showed similar fluctuations in discharge and fish production but no overall agreement was apparent. In the light of later studies, it was concluded that this lack of correlation was because the commercial landings, while probably mostly from stocks derived from the rivers concerned, did not correspond to the relative abundance of the stocks when they left the stream for the ocean. To insure that only catch statistics on fish from a specific river were used it was necessary to take them from a fishery operating in the immediate vicinity of the river mouth. However, by the time the adult silvers had been captured near or in the rivers in Washington they had passed through several different fishing operations, the first of which was in the open ocean.

For example, silvers returning to the Nisqually River in South

Puget Sound (Figure 1) have passed through the ocean troll fishery, the Cape purse seine fishery, the Admiralty Inlet - Point No Point purse seine fishery, the Meadow Point - Rolling Bay - East and West Pass purse seine and gill net fisheries, and finally the Indian set net fishery in the lower reaches of the Nisqually River itself. These separate fisheries have been explained and illustrated by Smoker (1954). Only in the final Indian fishery could the silvers be positively accepted as being Nisqually fish. By this time, due to annual variations in the intensity of the fishing effort in other areas, the numbers available to the Indian gear each year might have no relation to the previous numbers of Nisqually fish migrating to salt water. The catch in the river is a poor index of their abundance, particularly if the Indian fishing effort varies from year to year due to such factors as river freshets or seasonal work elsewhere.

A simple model may illustrate this: In Table 1, to brood years A and B are assigned a juvenile escapement to the ocean of 20,000 and 16,000 yearlings respectively. By the time these fish approach adult size, assuming a constant marine mortality, there are only 1,000 and 800 available to the fishery. Suppose, due to weather, strikes, abundance of other species, etc., the various fishing enterprises other than the Indian fishery take 75 percent of the A brood year and only 65 percent of the B brood year during the two fishing seasons. There remain available to the Indian fishery 250 from the A group and 280 from the B group. Assume that the Indians' set nets took 10 percent from each group. The statistics from the Indian fish buyer would indicate that brood year B stocks yielding

Table 1 - Theoretical model showing effect of variations to outside fishing rates on river mouth catches.

| Brood year | Juvenile escapement | Outer gear | | | Indian gear | | | Total fish landings |
|---|---|---|---|---|---|---|---|---|
| | | Adults available to outer fisheries | Fishing rate | Fish landings | Fish available | Fishing rate | Landings | |
| A | 20,000 | 1,000 | 0.75 | 750 | 250 | 0.10 | 25 | 775 |
| B | 16,000 | ~~8,000~~ 800 | 0.65 | 520 | 280 | 0.10 | 28 | 548 |
| B/A | 0.80 | 0.80 | | 0.69 | 1.12 | - | 1.12 | 0.71 |

28 fish were more abundant than brood year A which yielded 25 fish. This is the reverse of the true relationship. However, the total catch of all the gear being 775 fish from brood year A and 548 from brood year B is indicative of the actual differences in abundance.

It will be brought out in the following pages that meaningful single stream analyses using catch as a measure of abundance are not practical and that the problem must be viewed from a broader perspective. The relationships of the abundance of adult silver salmon to streamflow are much more sharply defined when aggregate catches of silver stocks produced by many watersheds are compared with combined streamflows.

# III. REVIEW OF THE LITERATURE.

Among the earlier attempts to associate abundance of stream water and abundance of anadromous fish, Huntsman (1938) demonstrated a possible relationship in eastern Canada between low summer rainfall, increased availability of young Salmo salar to kingfisher and merganser predators due to clearer visibility, and low sports catches of these fish as adults.

Later, on the western side of Canada, Neave and Wickett (1948) and Neave (1949) point out a lower availability to sports fishermen in Cowichan Bay of those silver salmon adults which may have experienced lower summer minimum flows in their juvenile stages in the Cowichan River.

McKernan et al (1950) show a correlation between annual silver salmon catches in Oregon from the vicinity of the Siletz River and the summer low flows two years previously. The study covered the period 1924 to 1945. The relationship of the Coquille River summer low flows and numbers of silvers taken near that stream was not significant. In the Oregon study the summer low flow index was obtained by computing an average of the lowest flow rates for July, August, and September of each year. To correct for downward catch trends, deviations from trend lines were compared in deriving the correlation coefficients.

Figure 3 in the Oregon report is very interesting when the general patterns are observed. The authors point out the surprising common factor of similar annual deviations in nine inside Oregon silver fisheries and the outside troll fishery.

A further study of silver salmon and stream water reported by

Wickett (1951) shows two low counts of silver yearlings leaving Nile Creek on Vancouver Island, British Columbia, Canada, which are associated with two years of low summer rainfall near that watershed in the four-year period 1946 through 1949.

Smoker (1953) published a brief account of some of the more pertinent findings of this thesis as they appeared at that time. A highly significant correlation was demonstrated between annual streamflow in western Washington and the numbers of silver salmon landed in western Washington two years later. This report showed the effects on silver production of annual streamflows from 1933 to 1948.

Minter Creek in southern Puget Sound is the location of one study where the complete measurement of the seaward migrant production of a stream can be made. A description of the operations at this station will appear in a future publication by Salo and Smoker. A preliminary graph showing the interrelationship of adult silver salmon escapement, runoff, and production of seaward migrants at Minter Creek was presented in a review of Puget Sound salmon by Smoker (1954). It was demonstrated that adult escapement at sufficiently low levels was a limiting factor in addition to that of annual streamflow in the production of yearling silvers.

Further evidence that the size of spawning escapement can influence silver production is presented by Shapovalov and Taft (1954) where they state that, for the 1933, 1934, 1935, and 1936 brood years, the numbers of silver salmon downstream migrants was approximately proportional to the number of eggs deposited in Waddell Creek, California.

Possible limiting effects of streamflow during the period of salmon egg incubation on salmon abundance have not been established for silver salmon. However, several studies on chum salmon have demonstrated that the abundance of this species is affected at times by extremes in such streamflows.

Henry (1953) shows that when the streamflows in the Wilson River in Oregon are low during the incubation period of the eggs, the amounts of chum salmon taken in the subsequent fishery tend to be low. On the other hand, Smoker (ms) has found that the chum fry production in Minter Creek, Washington, is low whenever severe freshets occur during the incubation period.

Table 3 - Percent deviation from mean of total annual streamflow and associated silver landings of Washington river fisheries.

| River— Stream flow | Nooksack Stream flow | Nooksack Fish | Skagit Stream flow | Skagit Fish | Snohomish Stream flow | Snohomish Fish | White Stream flow | White Fish | Nisqually Stream flow | Nisqually Fish | Skokomish Stream flow | Skokomish Fish | Quinault Stream flow | Quinault Fish | Chehalis Stream flow | Chehalis Fish |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1933 | - | 118 | 132 | 125 | 148 | 163 | 148 | | 133 | 165 | 131 | 39 | 134 | 225 | 152 | 39 |
| 1934 | 42 | 135 | 120 | 64 | 104 | 100 | 119 | | 98 | 20 | 117 | 50 | 111 | 165 | 114 | - |
| 1935 | 47 | 41 | 92 | 61 | 81 | 182 | 86 | | 69 | 90 | 101 | 8 | 100 | 70 | 77 | 6 |
| 1936 | 108 | 135 | 91 | 166 | 93 | 147 | 98 | | 70 | 30 | 83 | 8 | 85 | 115 | 97 | 11 |
| 1937 | 113 | 82 | 100 | 84 | 104 | 163 | 103 | | 98 | 115 | 119 | 158 | 112 | 160 | 129 | 100 |
| 1938 | 89 | 82 | 91 | 87 | 81 | 144 | 90 | | 75 | 330 | 88 | 127 | 84 | 40 | 80 | 22 |
| 1939 | 118 | 123 | 105 | 148 | 99 | 81 | 86 | | 78 | 210 | 93 | 169 | 102 | 220 | 80 | 44 |
| 1940 | 85 | 12 | 84 | 67 | 74 | 100 | 82 | | 69 | 20 | 108 | 65 | 99 | 40 | 96 | 33 |
| 1941 | 94 | 41 | 79 | 44 | 73 | 31 | 70 | 17 | 64 | 80 | 100 | 69 | 95 | 135 | 76 | 72 |
| 1942 | 80 | 176 | 73 | 133 | 85 | 116 | 86 | 13 | 82 | 210 | 68 | 96 | 70 | 55 | 78 | 155 |
| 1943 | 99 | 76 | 96 | 123 | 89 | 56 | 86 | 42 | 106 | 35 | 75 | 239 | 76 | 140 | 75 | 266 |
| 1944 | 80 | 29 | 70 | 59 | 74 | 78 | 62 | 17 | 65 | 35 | 70 | 150 | 73 | 40 | 55 | 78 |
| 1945 | 113 | 53 | 94 | 131 | 107 | 88 | 98 | 38 | 121 | 140 | 104 | 123 | 103 | 95 | 97 | 377 |
| 1946 | 118 | 106 | 106 | 95 | 111 | 47 | 123 | 104 | 159 | 25 | 110 | 80 | 107 | 35 | 19 | 78 |
| 1947 | 118 | 135 | 105 | 84 | 118 | 50 | 107 | 38 | 126 | 25 | 94 | 162 | 100 | 70 | 90 | 72 |
| 1948 | 122 | 206 | 104 | 146 | 110 | 128 | 111 | 42 | 142 | 100 | 99 | 131 | 103 | 15 | 130 | 89 |
| 1949 | 118 | 141 | 115 | 79 | 107 | 44 | 107 | 113 | 128 | 70 | 110 | 96 | 113 | 95 | 98 | 150 |
| 1950 | 146 | 159 | 137 | 125 | 141 | 135 | 139 | 542 | 170 | 75 | 143 | 58 | 135 | 120 | 154 | 100 |
| 1951 | 103 | 94 | 112 | 64 | 96 | 50 | 103 | 138 | 131 | 90 | 87 | 58 | 101 | 80 | 120 | 139 |

Table 4 - Annual low-month streamflows and associated landings of Washington river fisheries.

Salmon in thousands of fish.
Streamflows in thousands of acre feet.

| River- | Nooksack | | Skagit | | Snohomish | | White | | Nisqually | | Skokomish | | Quinault | | Chehalis | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stream flow | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish | Stream flow | Fish |
| 1933 | - | 20 | 746 | 49 | 87 | 52 | 126 | | 43 | 3.3 | 30 | 1.0 | 82 | 45 | 18 | 0.7 |
| 1934 | 48 | 23 | 406 | 25 | 48 | 32 | 79 | | 23 | 0.4 | 12 | 1.3 | 41 | 33 | 12 | - |
| 1935 | 55 | 7 | 294 | 24 | 46 | 58 | 60 | | 18 | 1.8 | 15 | 0.2 | 46 | 14 | 11 | 0.1 |
| 1936 | 40 | 23 | 166 | 65 | 40 | 47 | 49 | | 11 | 0.6 | 7 | 0.2 | 24 | 23 | 13 | 0.2 |
| 1937 | 73 | 14 | 353 | 33 | 47 | 52 | 95 | | 30 | 2.3 | 13 | 4.1 | 38 | 32 | 21 | 1.8 |
| 1938 | 70 | 14 | 353 | 34 | 29 | 46 | 96 | | 22 | 6.6 | 8 | 3.3 | 24 | 8 | 8 | 0.4 |
| 1939 | 73 | 21 | 365 | 58 | 50 | 26 | 82 | | 25 | 4.2 | 9 | 4.4 | 37 | 44 | 10 | 0.8 |
| 1940 | 71 | 2 | 335 | 26 | 31 | 32 | 93 | | 23 | 0.4 | 9 | 1.7 | 30 | 8 | 10 | 0.6 |
| 1941 | 82 | 7 | 380 | 17 | 32 | 10 | 105 | 0.4 | 26 | 1.6 | 14 | 1.8 | 28 | 27 | 13 | 1.3 |
| 1942 | 57 | 30 | 255 | 52 | 34 | 37 | 69 | 0.3 | 19 | 4.2 | 9 | 2.5 | 24 | 11 | 11 | 2.8 |
| 1943 | 77 | 13 | 325 | 48 | 47 | 18 | 88 | 1.0 | 26 | 0.7 | 9 | 6.2 | 28 | 28 | 12 | 4.8 |
| 1944 | 81 | 5 | 397 | 23 | 45 | 25 | 81 | 0.4 | 26 | 0.7 | 9 | 3.9 | 26 | 8 | 9 | 1.4 |
| 1945 | 92 | 9 | 476 | 51 | 38 | 28 | 113 | 0.9 | 22 | 2.8 | 13 | 3.2 | 36 | 19 | 11 | 6.8 |
| 1946 | 74 | 18 | 379 | 37 | 48 | 15 | 82 | 2.5 | 41 | 0.5 | 14 | 2.0 | 44 | 7 | 15 | 1.4 |
| 1947 | 83 | 23 | 409 | 33 | 55 | 16 | 93 | 0.9 | 30 | 0.5 | 12 | 4.2 | 41 | 14 | 11 | 1.3 |
| 1948 | 154 | 35 | 646 | 57 | 115 | 41 | 109 | 1.0 | 48 | 2.0 | 18 | 3.4 | 62 | 3 | 17 | 1.6 |
| 1949 | 129 | 24 | 623 | 31 | 73 | 14 | 89 | 2.7 | 42 | 1.4 | 18 | 2.5 | 75 | 19 | 10 | 2.7 |
| 1950 | 111 | 27 | 576 | 49 | 66 | 43 | 103 | 13.0 | 58 | 1.5 | 16 | 1.5 | 52 | 24 | 12 | 1.8 |
| 1951 | 72 | 16 | 485 | 25 | 36 | 16 | 81 | 3.3 | 29 | 1.8 | 12 | 1.5 | 33 | 16 | 8 | 2.5 |

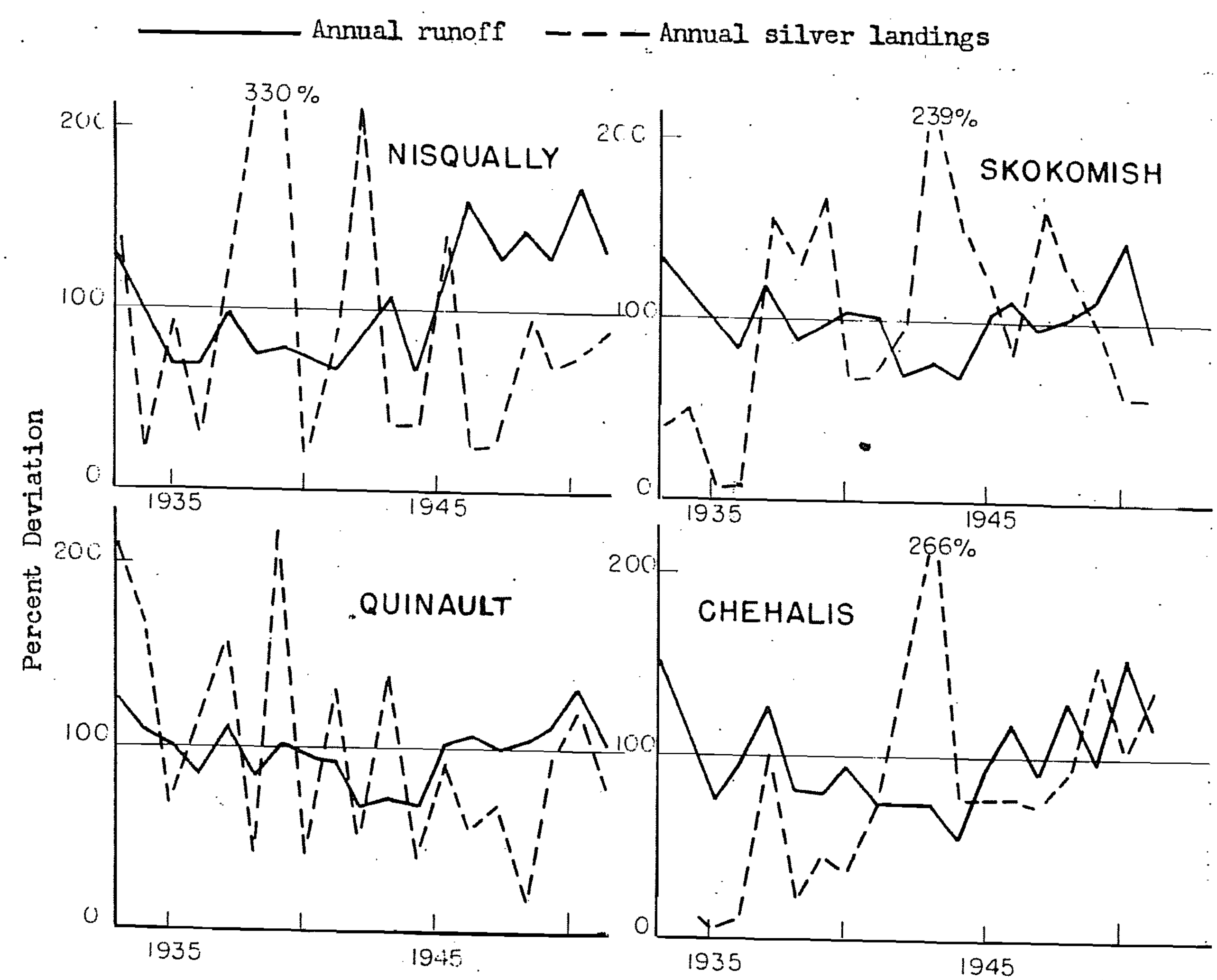



Figure 2-B. Percent deviation from mean of western Washington annual river runoff and associated silver salmon commercial landings.

Quinault and the positive slopes of the Nooksack, White, Skokomish, and Chehalis rivers.

The streamflows, while showing considerable annual variation, do reflect a somewhat similar pattern among themselves, being high at the first year of the period, falling to a low middle period, and rising to a sustained high during the later years. The over-all effect in each case was a slightly positive trend from 1933 to 1951.

It was considered desirable to explore rather thoroughly the interrelationships of the silver and streamflow data of the eight separate systems. River-mouth silver fisheries have been found to be positively related to abundance of specific stream waters in two situations as reported by Neave (1949) and McKernan et al (1950). For the Siletz study, summer low flow was used as an index of streamflow. In the study at hand, both annual runoff and low-month flow (Tables 2 and 3) were considered as indices of water abundance and both the absolute data and deviations from trends were analyzed statistically to determine possible relationships. There is considerable variation in a comparison between annual and low-month flows as shown in Figures 3-A and B. For this reason it was considered necessary to try correlating both streamflow factors with silver production. The study is presented in Figures 2-A to 26-B and Tables 2 to 12.

An inspection of Figures 2-A to 13-B shows a general lack of significant correlation between quantity of river water present and catches of adult silver salmon which, as juveniles, were present in the river during the years indicated. Figures 13-A and B show

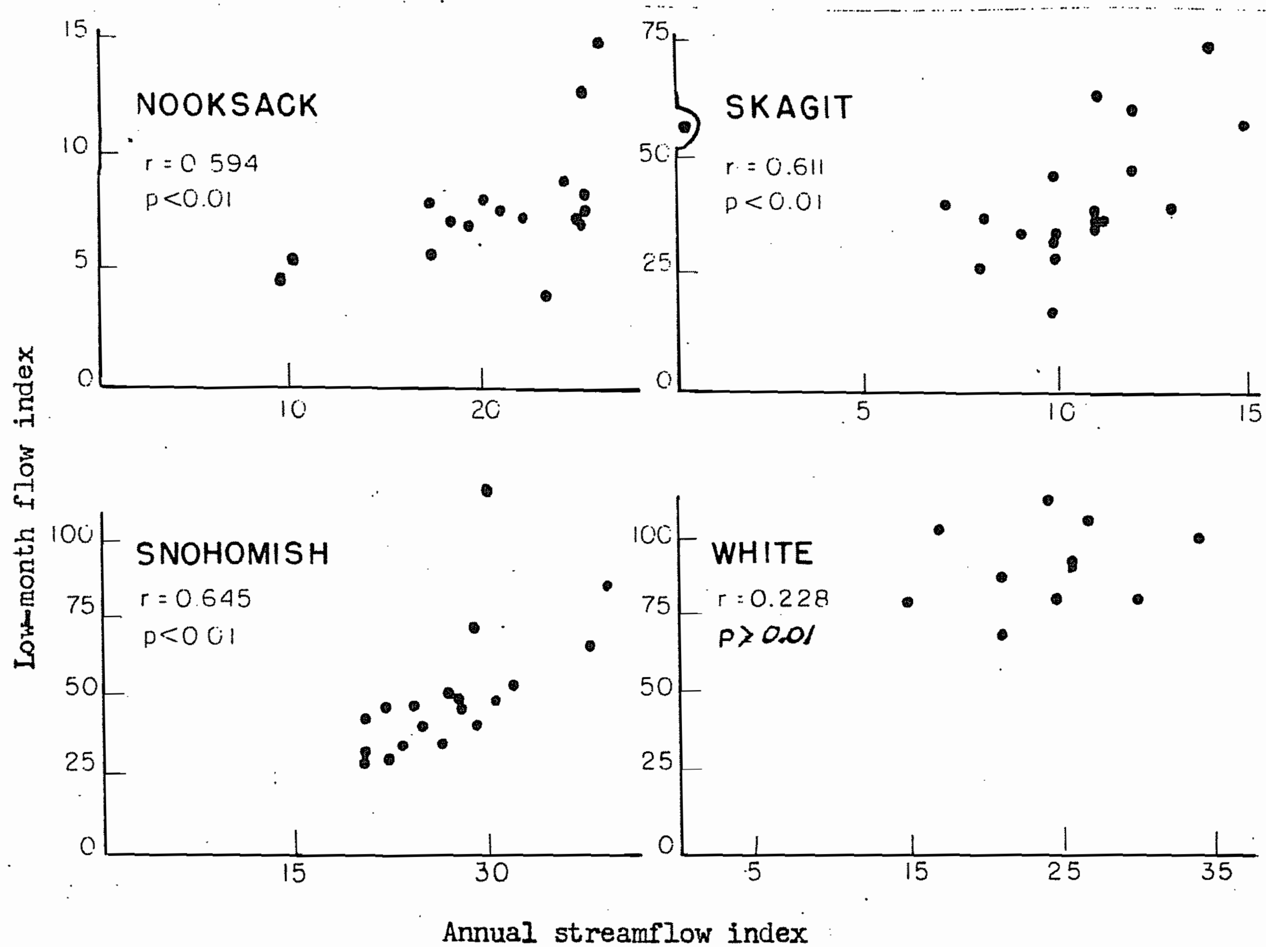



Figure 3-A. Correlation of low-month flow with total annual runoff on watersheds which have associated silver salmon fisheries.

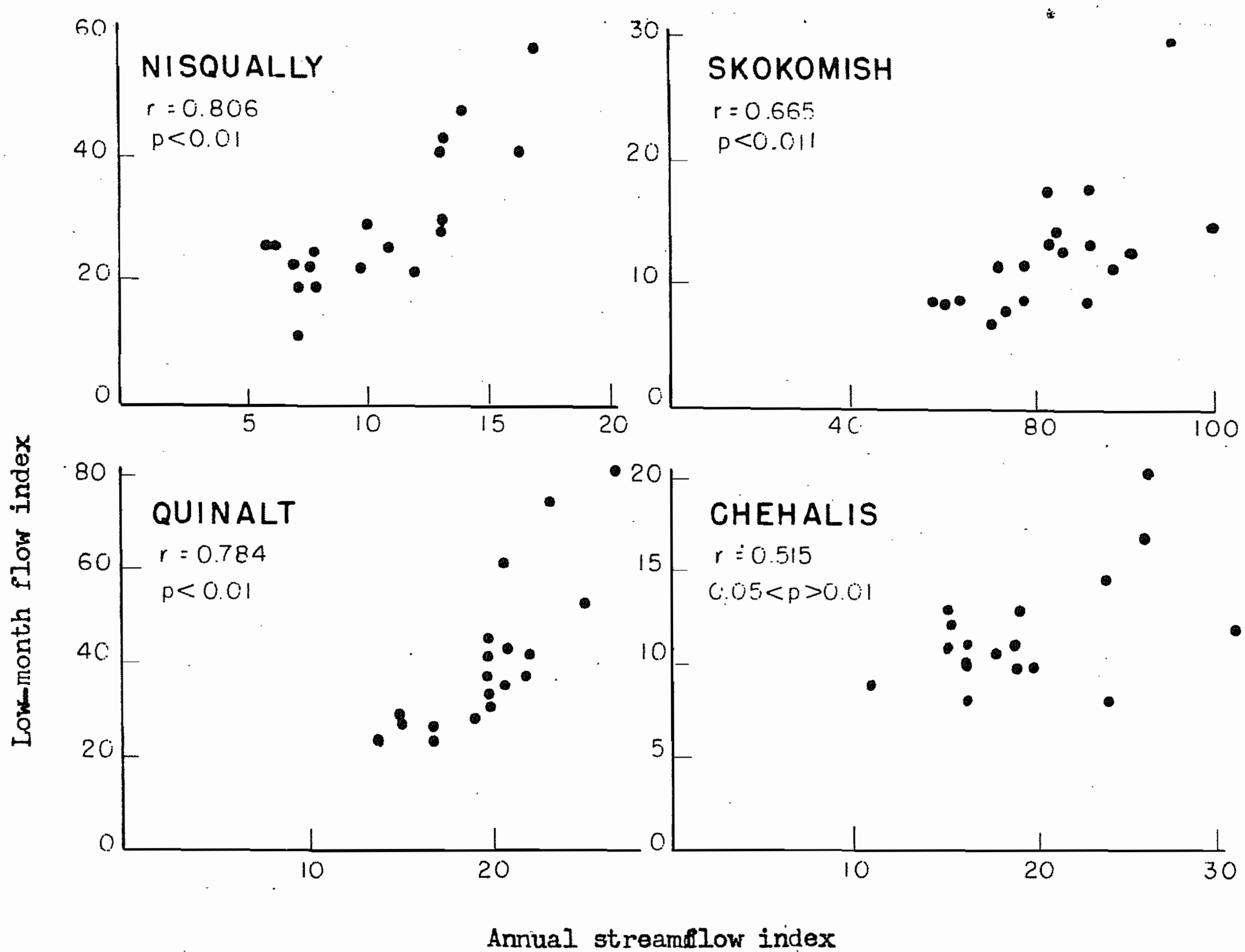


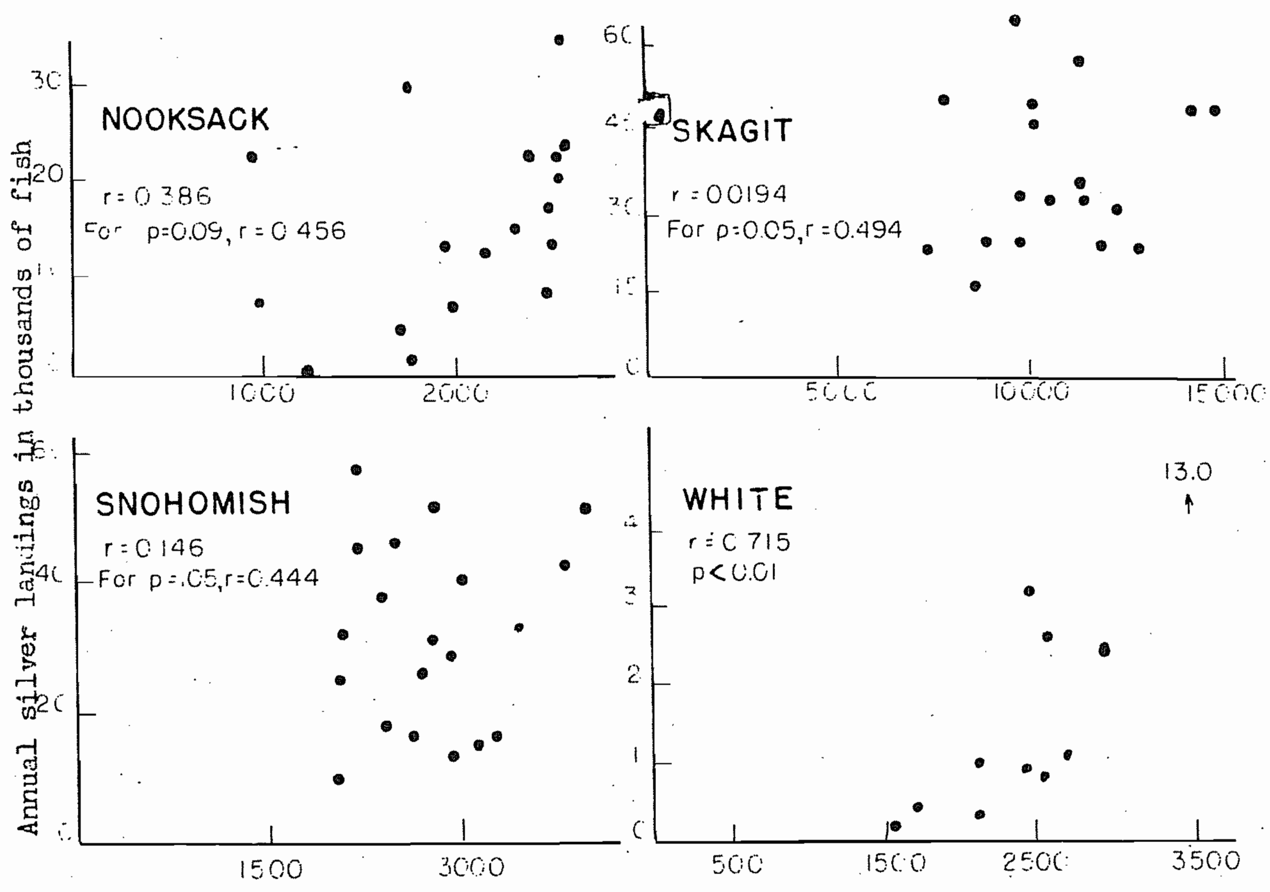

Figure 3-B. Correlation of low-month flow with total annual runoff on watersheds which have associated silver salmon fisheries.

the annual runoff correlation graphs for the eight rivers. Two statistically significant correlations did appear in the study. These were on the White and Quinault rivers (Figures 8-A and 11-B). The basic annual runoff of White River in Figure 8-A shows a positive correlation with catches two years later in the Indian fishery. This may be an unrelated coincidence since the increase in catches are concurrent in time with attempts by the Washington State Fisheries Department, through the stocking of hatchery fish, to build up the almost exterminated upper White River silver runs past Mud Mountain dam. The lack of a significant correlation of deviations from the trend lines in Figure 8-B indicates that variations in streamflow did not completely determine the river catch of silver salmon.

Another positive correlation was derived for the Quinault River between the deviations from the trend lines (Figure 11-B). This is reminiscent of the findings by McKernan et al (1950) on the Siletz where a correlation, significant at the five percent level, was obtained only after the data were corrected for an unknown variable which was causing a pronounced over-all downward trend in fish landings. However, the Quinault fish landings were not correlated with summer low flow as in the case of the Siletz but they were positively related with annual runoff. The degree of significance of this correlation may be because the Quinault silvers have passed only through the troll fishery before entering the river fishery and the numbers available are more likely related to their original abundance. As the location of the fisheries in Figure 1 would indicate, the stocks of silvers harvested near the Nooksack, Skagit, Snohomish, and Quinault rivers may not consist entirely of fish from these watersheds. Transients destined for other tributaries could easily be included among the silvers taken, and the assumption that only discrete stocks are being fished upon is dubious. In addition to having been through previous fisheries, the presence of transient fish in the catches may also explain the lack of correlation between streamflow and fish production. The lack of correlation between silvers and the streamflow in the Coquille and the rather low correlation of five percent on the Siletz reported by McKernan et al (1950) may be due in part to the presence of transients bound for other streams in the river-mouth fisheries. However, Figures 4-A through 12-B show the similarity in runoff patterns among eight major watersheds in Washington; therefore, if the silvers of all watersheds varied according to runoff, in like manner, the net result in any given fishery should be as if the stocks were homogenous, unless the transient stocks were overexploited in their home fishery to the extent that spawning egg deposition was a limiting factor.

1. Nooksack.

There are some interesting periods of positive correlation in the data from the eight river silver fisheries. Figures 4-A and B and Table 5 show an analysis of the Nooksack catches. This fishery consists mostly of gill net gear, operated by the Nooksack Indians. An inspection of Figure 4-B showing the deviations from the trend lines of annual runoff in silver catches indicates similar fluctuations for the water years 1935, 1936, 1938, 1939, 1940, 1941,




Annual streamflow in thousands of acre feet

**Figure 13-A.** Correlation of total annual streamflows and associated silver landings of Washington river fisheries 1933-1951.

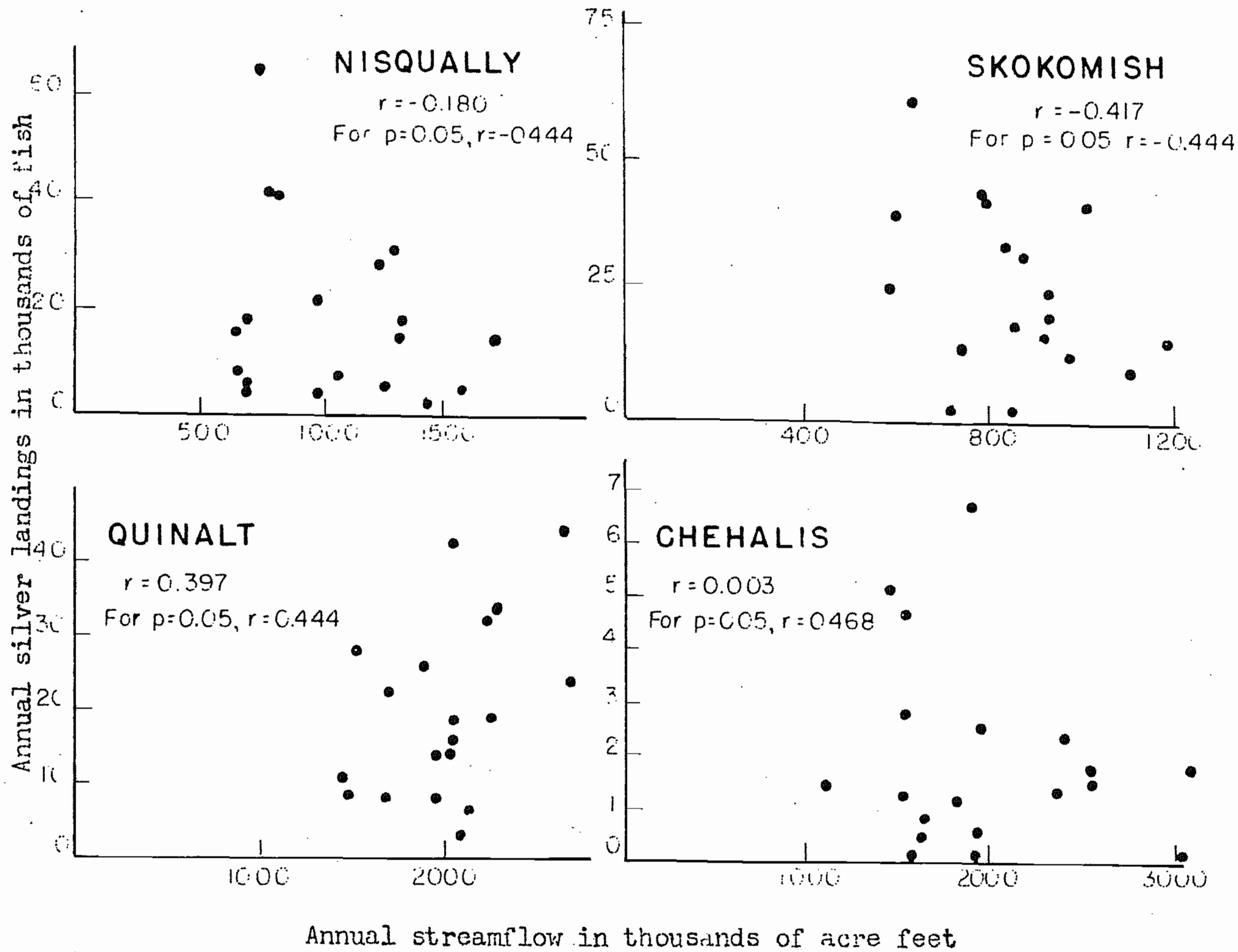



Figure 13-B. Correlation of total annual streamflows and associated silver landings of Washington river fisheries. 1933-1951.

and landed in ports in either district are recorded as part of the landings for that district and listed as outside landings.

Table 15 and Figure 14 show that the majority (69 percent), of silver landings in this study are made in Puget Sound ports and that approximately half of all landings in all ports are from outside or offshore fisheries.

The silver salmon catches demonstrating the annual fluctuations in total commercial landings for the 20-year period are plotted in Figure 15. The initial and largest landing was in 1935. This was followed by an 11-year period of general decline. The lowest catches of silver salmon occurred in 1942 and 1946, which were followed by a sudden increase with four years of sustained production, until finally in 1952 a catch was taken approximating the initial high of 1935. A very fast decline occurred in the final two years of the 20-year period.

Table 16 is a more complete listing of data published by Smoker (1953) and is changed slightly for some of the years, due to recent revisions of the previous catch statistics by the Department of Fisheries.

B. Stream data.

To obtain a measurement of fluctuations in annual, seasonal, or monthly stream runoff, it was necessary to derive a streamflow index that would represent all of the watersheds concerned in the production of silver salmon. The average periodic runoff in inches was computed for this index.

Certain U. S. Geological Survey hydrograph stations located on Western Washington streams served as an excellent source of data

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and landed in ports in either district are recorded as part of the landings for that district and listed as outside landings.

Table 15 and Figure 14 show that the majority (69 percent), of silver landings in this study are made in Puget Sound ports and that approximately half of all landings in all ports are from outside or offshore fisheries.

The silver salmon catches demonstrating the annual fluctuations in total commercial landings for the 20-year period are plotted in Figure 15. The initial and largest landing was in 1935. This was followed by an 11-year period of general decline. The lowest catches of silver salmon occurred in 1942 and 1946, which were followed by a sudden increase with four years of sustained production, until finally in 1952 a catch was taken approximating the initial high of 1935. A very fast decline occurred in the final two years of the 20-year period.

Table 16 is a more complete listing of data published by Smoker (1953) and is changed slightly for some of the years, due to recent revisions of the previous catch statistics by the Department of Fisheries.

B. <u>Stream data.</u>

To obtain a measurement of fluctuations in annual, seasonal, or monthly stream runoff, it was necessary to derive a streamflow index that would represent all of the watersheds concerned in the production of silver salmon. The average periodic runoff in inches was computed for this index.

Certain U. S. Geological Survey hydrograph stations located on Western Washington streams served as an excellent source of data

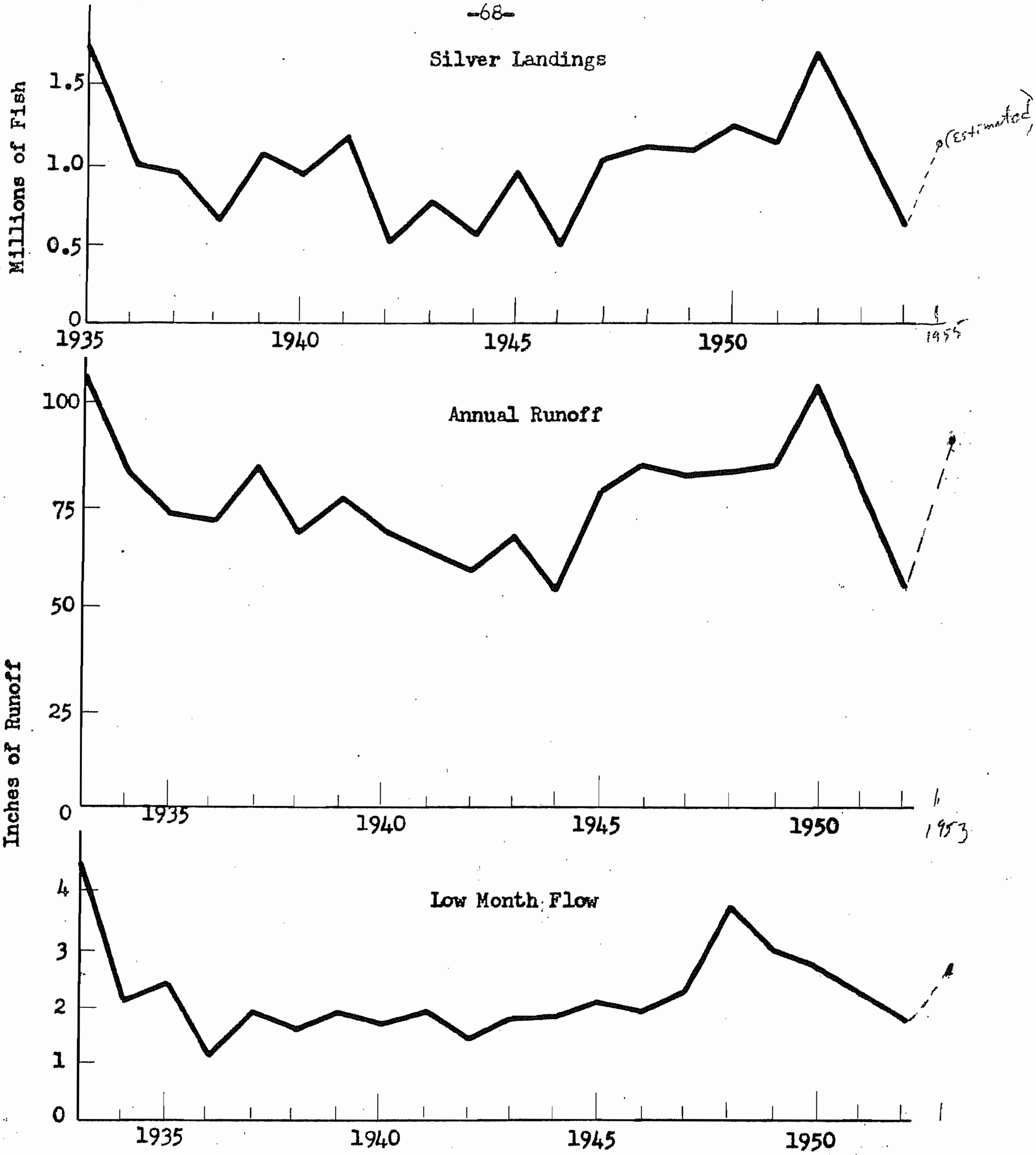


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

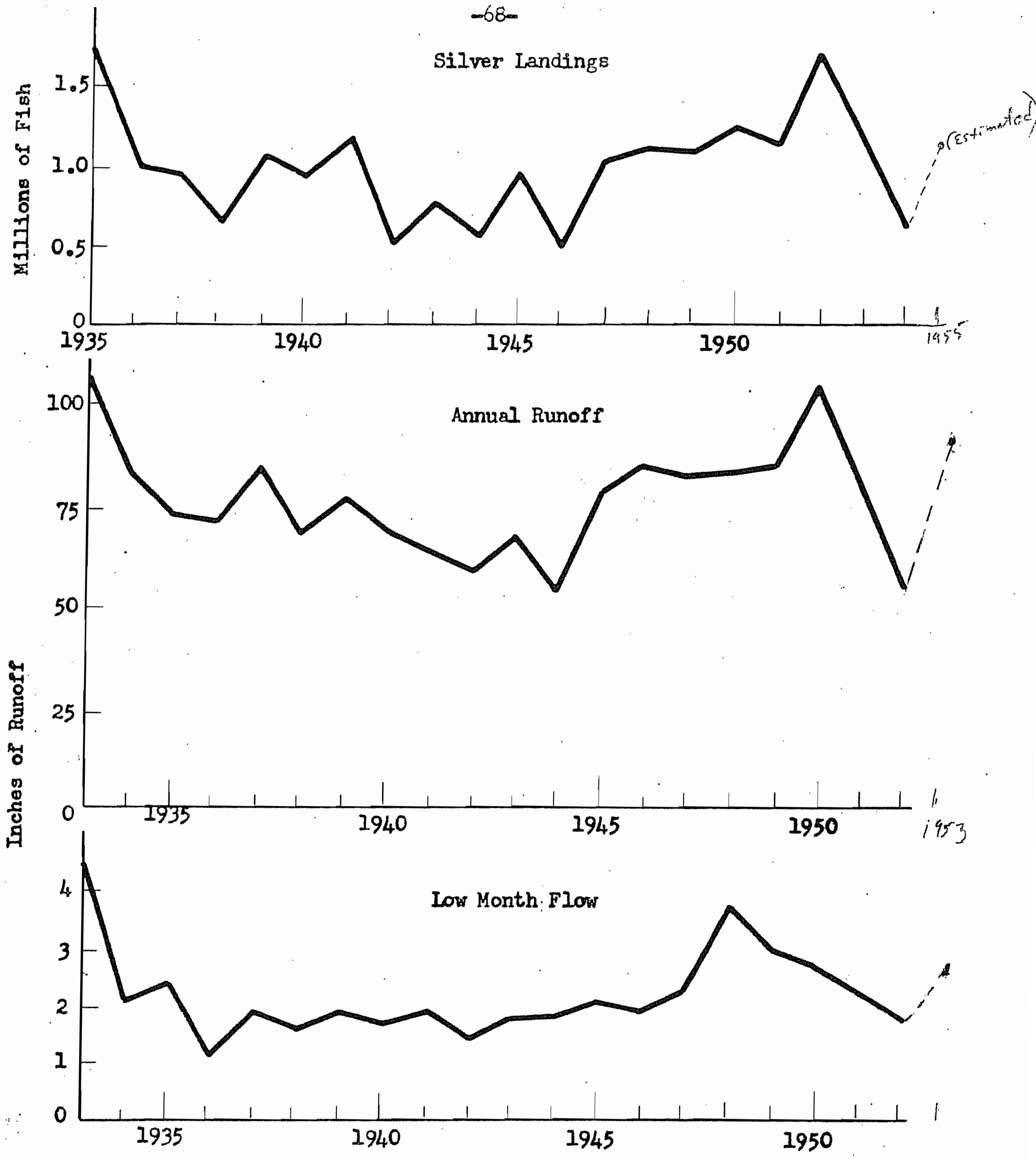


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

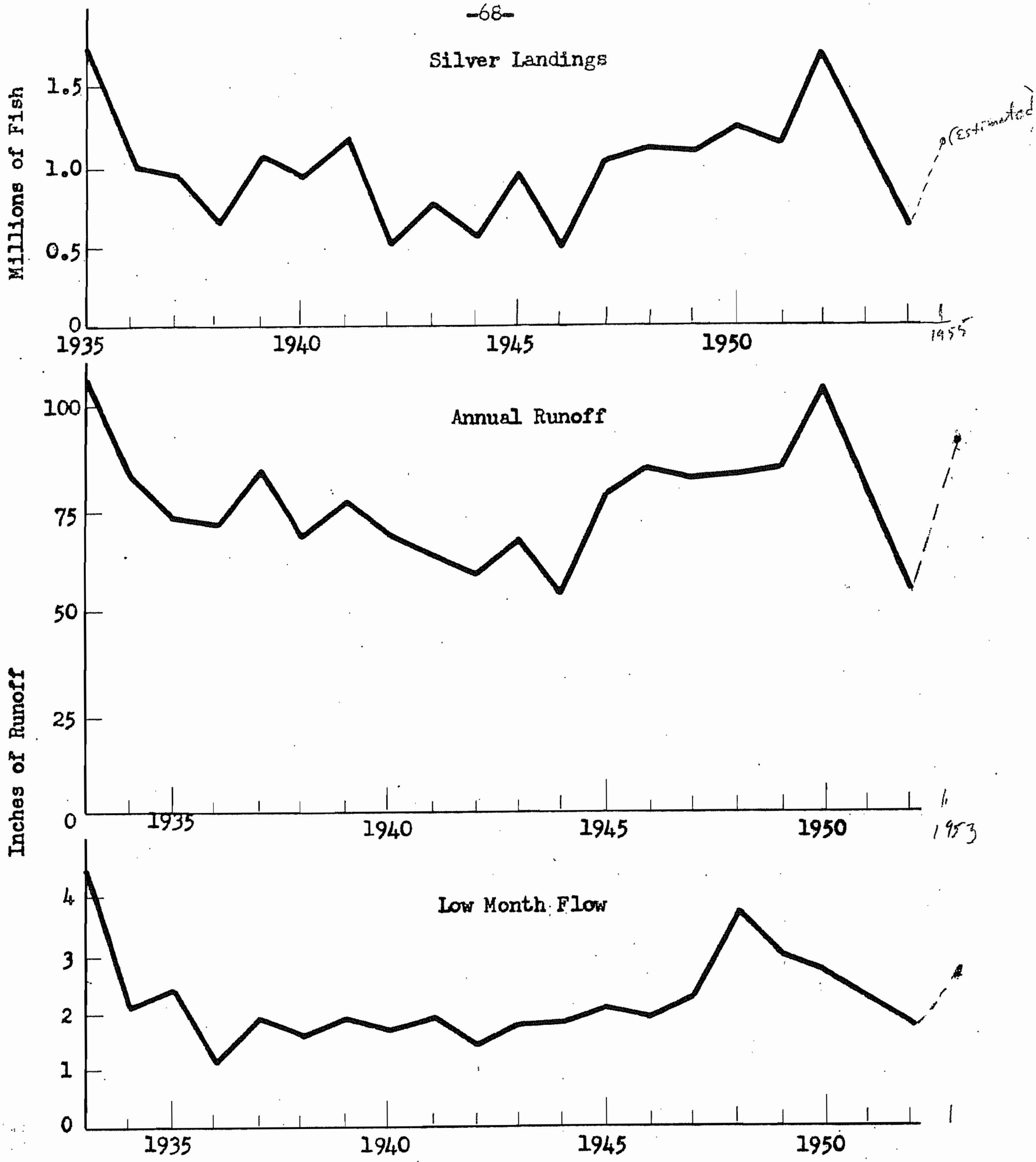


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

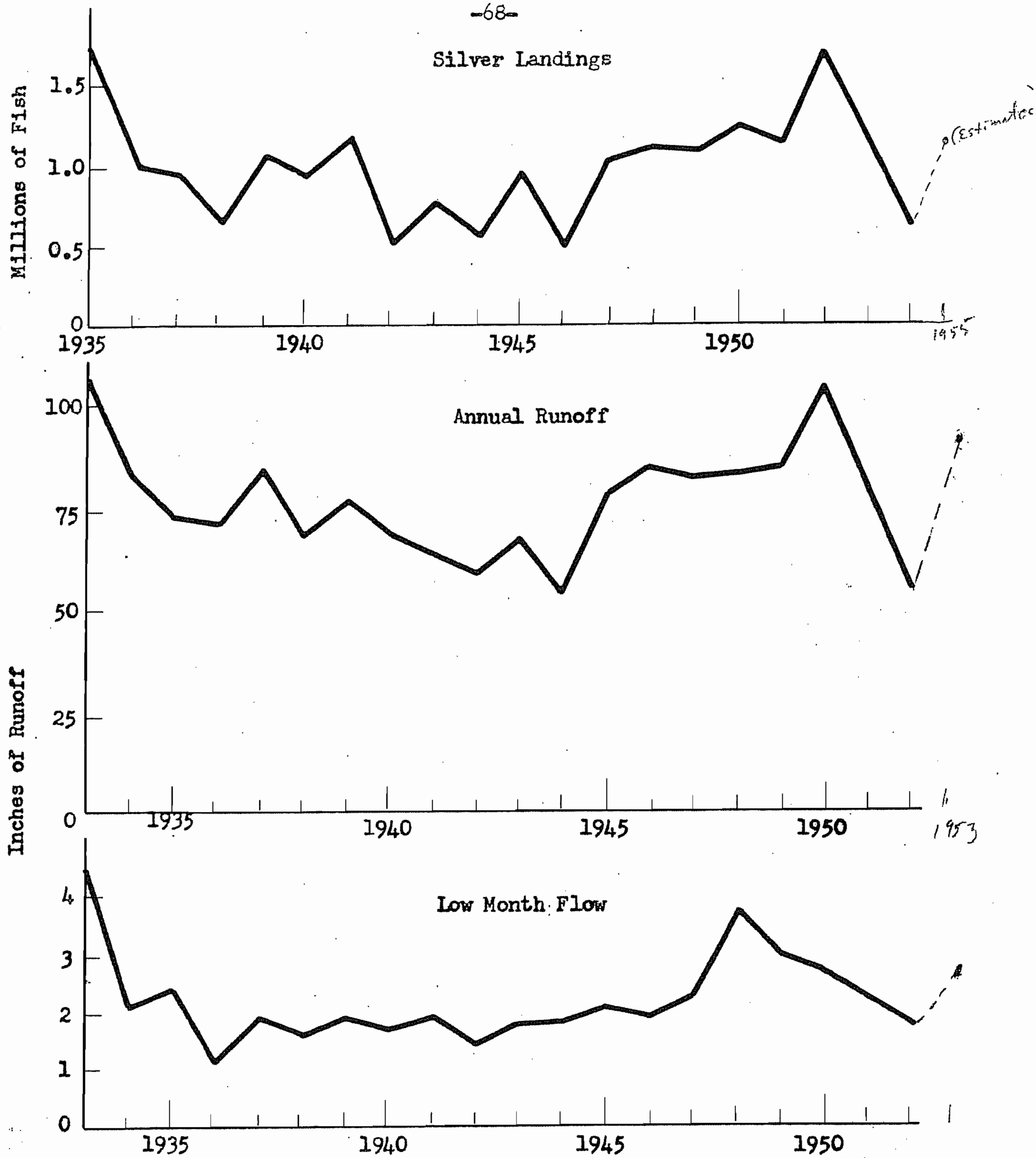


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

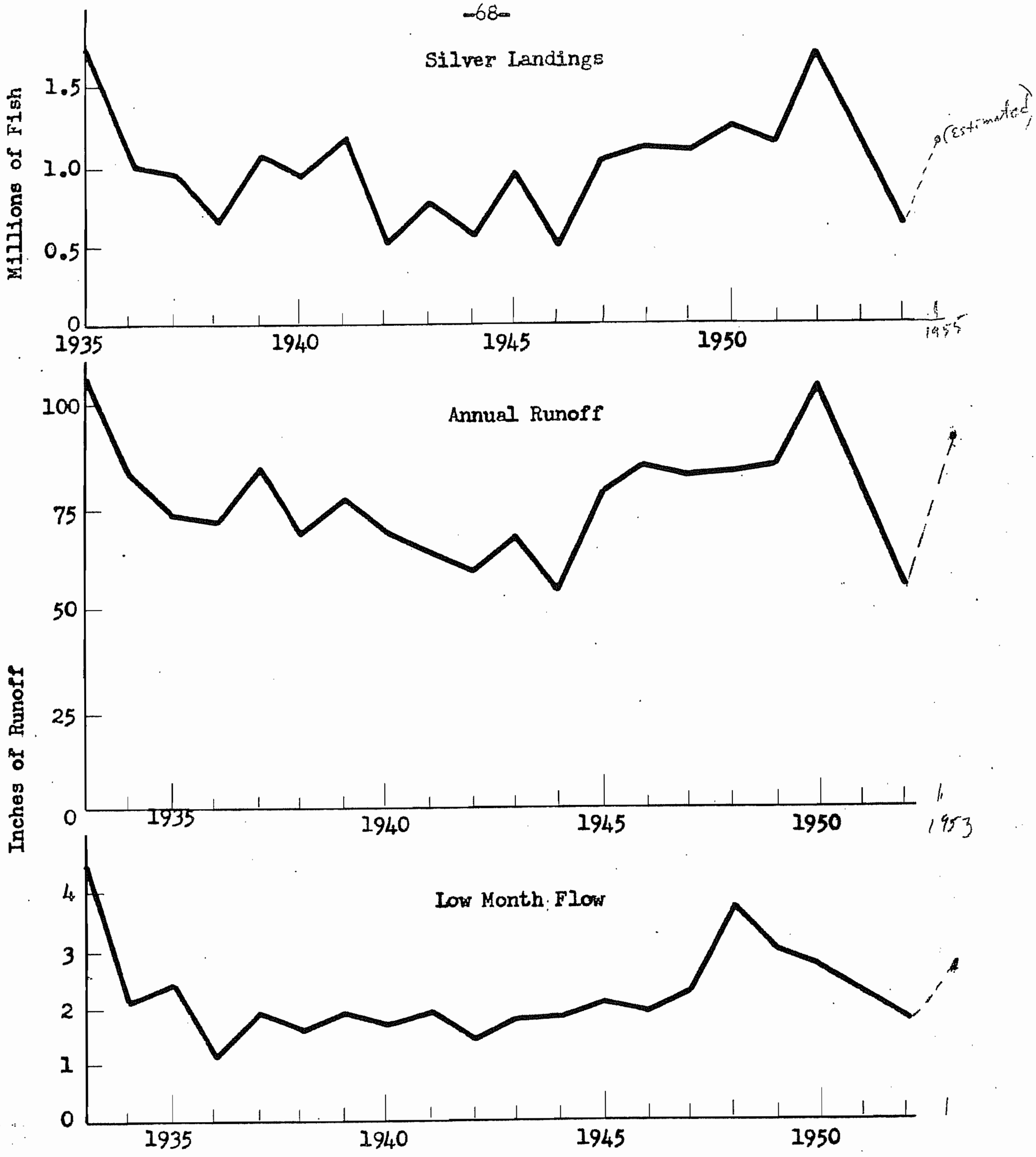


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

from which the desired streamflow indices could be computed. It is interesting to note that the number of gauging stations increased considerably during the period studied and the coverage of smaller tributaries in Western Washington is much greater in 1954 than it was in 1933. When This thesis was started in 1947, data from every major watershed that showed continuous records since 1933 were utilized. Twenty-three such stations were available; however, four of them have been discontinued in recent years. Table 17 presents a list of the river stations with the watershed areas above the gauging positions. The geographical relationship of these watersheds is portrayed in Figure 16. The watershed numbers in this figure are repeated in Tables 17 and 20 to 39, except that rivers number 18 and 19 in the tables designate the Skykomish and Snoqualmie stations respectively. Runoff data from a total of 20 to 23 gauging stations located on major watersheds are combined to give an average annual, summer low month, or seasonal flow for the period 1933 to 1952, inclusive. From the data published in the U. S. Geological Survey "Surface Water Supply" papers, the total monthly runoff in acre-feet for each station from January, 1933 to January, 1953 was added together to obtain the total amount of water that was discharged down the salmon streams.

This total of monthly acre-feet discharges from the combined watersheds was converted to average inches of runoff to provide the runoff index. With such a procedure the index is automatically weighted according to the area of the watersheds. This would seem to be a logical procedure inasmuch as one might expect a large watershed such as the Skagit River to produce more silvers than

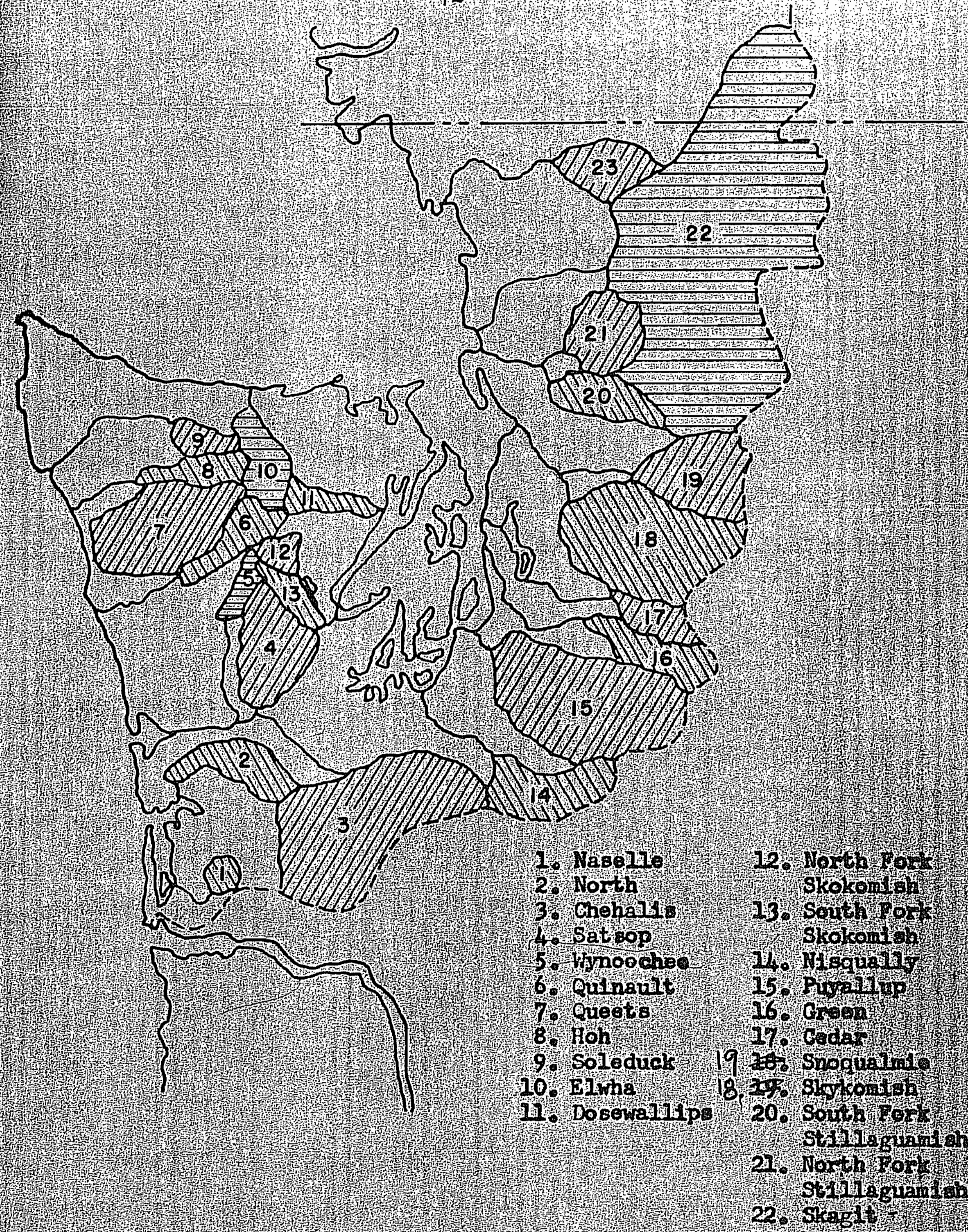


Figure 16. Watershed Areas in Western Washington Used in Compilation of Streamflow Index.

the little Cedar River. The streamflow index, in effect, is the depth of water in inches extending over the total of the watershed area. It is derived by the use of the basic geometric formula for the volume of a solid figure. $V = DA$ or $D = \frac{V}{A}$ where D is depth, A is the area of the base and V is the volume. For this thesis, the volume of water discharged is measured and published in acre-feet units and the area is measured in square miles. It was felt that depths in feet was too gross a unit, particularly when computing summer flows, so a smaller unit of inches of runoff was utilized. To obtain the depth in inches of water drained off a watershed or a number of combined watersheds, the volume in acre-feet is multiplied by twelve to change it to acre-inches. The watershed or combined watershed areas published in square miles are multiplied by 640 to obtain the total area in acres. Finally, the volume of water discharged in acre-inches is divided by the area in acres to obtain the average depth of runoff in inches.

The concept of an annual streamflow index for all of the watersheds concerned in the production of silver salmon in Western Washington was inspired in 1947 by the then unpublished work of McDonald and Riggs on the Columbia River basin. This comprehensive study, published in 1948, presents annual isogrammic comparisons on maps of the entire Columbia basin showing runoff in percentage of the mean for the period 1928 through 1945. The study utilized water year records and was concerned with demonstrating relative regional fluctuations in streamflow. Each stream gauge, regardless of the size of the watershed contributing its runoff, possessed equal weight with all other hydrograph stations in determining the over-all relative streamflow changes from year to year.

In demonstrating the relationship of streamflow to silver salmon production an index was desirable that applied to an adjoining but basically different basin area. The Puget Sound and coastal watersheds show a much different runoff pattern than the Columbia River which is dominated by its upper tributaries east of the Cascade Mountains. These do not produce significant runs of silver salmon. It was also desirable that the runoff index be based upon calendar year periods where annual comparisons are to be made, as well as upon monthly units when the effects of summer low flows are to be analyzed. The calendar year rather than the water year corresponds more closely to the time actually spent by the young silver salmon in the streams. The U.S.G.S. water year runs from October of one year through September of the next year. Finally, it was felt that for this thesis the streamflow index should be quantitative rather than expressed as a percentage, and that it should be weighted to reflect the influence of dominant watersheds.

Table 18, taken from Table 19, is a revised and more complete listing of the streamflow indices published by Smoker (1953:8). Low month flows have been added and the annual runoff for some years appears slightly different. This is due to recent revisions by the U.S.G.S. in their estimations of the areas of the watersheds whose discharges were measured. Some of the areas were not completely surveyed in 1933. Revisions are published from time to time as this information is brought up to date. It is of interest that some areas in Western Washington are still not completely mapped as to watershed delineation and revisions will undoubtedly continue to

Table 18 - Annual and low-month flow indices for Western Washington.

| Year | Average total annual runoff in inches | Low month flow in inches |
|---|---|---|
| 1933 | 107 | 4.5 |
| 1934 | 89 | 2.1 |
| 1935 | 73 | 2.4 |
| 1936 | 71 | 1.1 |
| 1937 | 84 | 1.9 |
| 1938 | 67 | 1.6 |
| 1939 | 77 | 1.9 |
| 1940 | 68 | 1.7 |
| 1941 | 63 | 1.9 |
| 1942 | 59 | 1.4 |
| 1943 | 67 | 1.8 |
| 1944 | 53 | 1.8 |
| 1945 | 78 | 2.1 |
| 1946 | 85 | 1.9 |
| 1947 | 82 | 2.3 |
| 1948 | 83 | 3.8 |
| 1949 | 85 | 3.0 |
| 1950 | 104 | 2.7 |
| 1951 | 79 | 2.3 |
| 1952 | 54 | 1.7 |
| [illegible] | 93 | 2.6 |
| | (89)1/ | (3.8) |
| 1955 | (81) | (2.5) |

1/ Figures in parentheses estimated; based upon 5-watershed correlated – 20 watershed values.

appear. The annual runoff and low month flows are plotted chronologically in Figure 29.

In this study it was thought that the lowest recorded flow for a given summer was perhaps in itself not too significant in the life of a juvenile salmon. The lowest flow condition exists only for a single day, or less. Hatchery techniques demonstrate that silver fingerlings can take considerable crowding and abuse in a rearing pond without significant mortalities. Certainly they can go for several days without feeding and suffer no untoward effects. It did seem logical, however, to suspect that sustained periods of low flow would limit silver salmon survival. After considerable study of U.S.G.S. hydrograph records for Western Washington streams it was decided that the lowest monthly flow for a given year would be a satisfactory unit. Figure 17 shows a typical hydrograph for the summer months in a coastal stream, the Chehalis River. The year presented, 1945, is an average year and shows that during the lowest month, August, there are a few minor daily fluctuations. The lowest-flow month is typically the most stable month.

Utilizing the monthly runoff for an index of low flow for silver salmon relationships has two advantages; the minor daily fluctuations are averaged and the volume of discharge is conveniently published in monthly units by the United States Geological Service.

Table 19, based upon Tables 20 to 39, shows the monthly runoff for Western Washington for the 20-year period. This is also portrayed graphically in Figure 18 which shows an annual pattern with a consistent rise and fall. At first glance the observer wonders that there are actually annual variations that determine silver survival. Figure 18 includes a graph of the average for each month listed at the bottom of Table 29 which shows the existence of two annual low flow periods: one around March when 8.46 percent of the annual flow is discharged and the other around September when 3.28 percent of the annual flow is discharged. The calculation of the runoff in inches for Western Washington for each month and year from 1933 through 1952 is shown in Tables 20 to 39. The conversion factor for giving proper weight according to watershed area involved each month is derived in Table 17 and applied in the calculations in Tables 20 to 39.

The silver landings in Figure 20 for Western Washington show a pattern rather like Cole's (1954) presentation of strictly random numbers as a time series. Although the twenty years of data available for this silver salmon study are far too few to establish the presence of periodic cycles it is interesting to note that there are seven peaks in the twenty years, or 2.85 years between peaks. This is close to the 3.0 years designated by Cole as the average time between peaks of a random time series of great length. Figure 20 also shows that annual runoff and low-month flow patterns for the same 20 years have five and six peaks respectively which are within the frequency expected for a random occurrance of a short 20-year time series. It would be expected that streamflow, being the product of precipitation which occurs in a random manner, would itself exhibit a random pattern. Further, the annual catch of silver salmon should occur in a random manner when presented as a time series if their numbers are related to streamflow.

Since amounts of streamflow and numbers of silvers have occurred as random values in time, the probability of their fluctuations being related can be expressed by their correlation coefficient.

## VI. ANALYSIS OF WESTERN WASHINGTON SILVER AND STREAMFLOW DATA.

The statistical analysis of the 20 years of data covering streamflow and silver salmon landings for Western Washington, while revealing several definite relationships between streamflow and the production of silver salmon, also emphasize the complex nature of their relationships and the numerous factors still to be defined.

### A. Annual runoff and silver production.

The variable providing the highest correlation coefficient with silver salmon was total annual runoff. The catches of silvers in numbers of fish and the occurance of streamflow in inches during the year of stream residence of those fish demonstrated a correlation coefficient of 0.912 (Table 40 and Figures 19 and 19-A). Correlating the same twenty pairs of data, but using the deviations from the twenty-year trend lines, a coefficient of 0.924 (Figure 21) is obtained showing a slight improvement over the elimination of possible unrelated trends in landings and stream discharge. For the 18 degrees of freedom these ocrrelations according to Snedecor (1946: p.149) could be accepted at the 99 percent confidence level with a correlation coefficient of only 0.561. Table 40 demonstrates that the trends of streamflow from 1933 through 1952, and from 1935 through 1954 for fish landings, show rather small deflections from zero. The trend line for annual runoff dropped only 5.8 percent in the twenty-year period while that of the silver landings rose 5.4 percent. However, eliminating these small effects increased the correlation coefficient slightly. The deviations are shown in Figures 20 and 21. Correlation coefficients for silver catch and annual runoff with time were only 0.048 and -0.099 respectively.

Figure 15, based upon Tables 16 and 18, shows a very similar

Table 40 - Correlations of silver and streamflow basic data and trend line deviation data for Western Washington.

| Year | Basic flow & fish data | | | Calculation of trend line | | | Trend line values | | | Deviations from trend lines | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | annual x | low month x | silvers y | annual y | low month y | silvers y | annual | low month | silvers | annual x | low month x | silvers y |
| 1933 | 107 | 4.5 | 179 | x = No. of years | | | 78.70 | 2.133 | 99.26 | 28.30 | 2.37 | 79.74 |
| 1934 | 89 | 2.1 | 102 | y = a + bx | | | 78.46 | 2.139 | 99.55 | 10.54 | -0.04 | 2.45 |
| | | | | $a = \bar{y} - b\bar{x}$ | | | | | | | | |
| 1935 | 73 | 2.4 | 97 | $b = \frac{\Sigma xy - \bar{x}\Sigma y}{\Sigma x^2 - \bar{x}\Sigma x}$ | | | 78.21 | 2.146 | 99.83 | -5.21 | 0.25 | -2.83 |
| 1936 | 71 | 1.1 | 68 | | | | 77.97 | 2.153 | 100.11 | -6.97 | -1.05 | -32.11 |
| 1937 | 84 | 1.9 | 110 | | | | 77.73 | 2.159 | 100.39 | 6.27 | -0.26 | 9.61 |
| 1938 | 67 | 1.6 | 95 | $\Sigma xy$ = 15883 | 465.3 | 21598 | 77.49 | 2.166 | 100.68 | -10.49 | -0.57 | -5.68 |
| 1939 | 77 | 1.9 | 119 | $\bar{x}$ = 10.5 | 10.5 | 10.5 | 77.25 | 2.172 | 100.96 | -0.25 | -0.27 | 18.04 |
| | | | | $\Sigma x$ = 210 | 210 | 210 | | | | | | |
| 1940 | 68 | 1.7 | 51 | $\Sigma x^2$ = 2870 | 2870 | 2870 | 77.00 | 2.179 | 101.24 | -9.00 | -0.48 | -50.24 |
| 1941 | 63 | 1.9 | 81 | $\Sigma y$ = 1528 | 43.9 | 2039 | 76.76 | 2.185 | 101.52 | -13.76 | -0.29 | -20.52 |
| 1942 | 59 | 1.4 | 59 | $\bar{y}$ = 76.40 | 2.195 | 101.95 | 76.52 | 2.192 | 101.81 | -17.52 | -0.79 | -42.81 |
| 1943 | 67 | 1.8 | 98 | a = 78.94 | 2.1263 | 98.98 | 76.28 | 2.198 | 102.09 | -9.28 | -0.40 | -4.09 |
| 1944 | 53 | 1.8 | 51 | b = -0.242 | 0.00654 | 0.2827 | 76.04 | 2.205 | 102.37 | -23.04 | -0.41 | -51.37 |
| 1945 | 78 | 2.1 | 107 | | | | 75.79 | 2.211 | 102.66 | 2.21 | -0.11 | 4.34 |
| 1946 | 85 | 1.9 | 113 | | | | 75.55 | 2.218 | 102.94 | 9.45 | -0.32 | 10.06 |
| 1947 | 82 | 2.3 | 110 | | | | 75.31 | 2.224 | 103.22 | 6.69 | 0.01 | 6.78 |
| 1948 | 83 | 3.8 | 126 | | | | 75.07 | 2.231 | 103.50 | 7.93 | 1.57 | 22.50 |
| 1949 | 85 | 3.0 | 116 | | | | 74.83 | 2.238 | 103.79 | 10.17 | 0.76 | 12.21 |
| 1950 | 104 | 2.7 | 175 | | | | 74.58 | 2.244 | 104.07 | 29.42 | 0.46 | 70.93 |
| 1951 | 79 | 2.3 | 119 | | | | 74.34 | 2.251 | 104.35 | 4.66 | 0.05 | 14.65 |
| 1952 | 54 | 1.7 | 63 | | | | 74.10 | 2.257 | 104.63 | -20.10 | -0.56 | -41.63 |
| N = | 20 | 20 | 20 | | | | | | | | | |
| r = | 0.912 | 0.756 | | | | | | | | 0.9238 | 0.7575 | |
| DF = | 18 | 18 | | | | | | | | 18 | 18 | |
| For p = 0.01, r = | 0.561 | 0.561 | | | | | | | | 0.561 | 0.561 | |

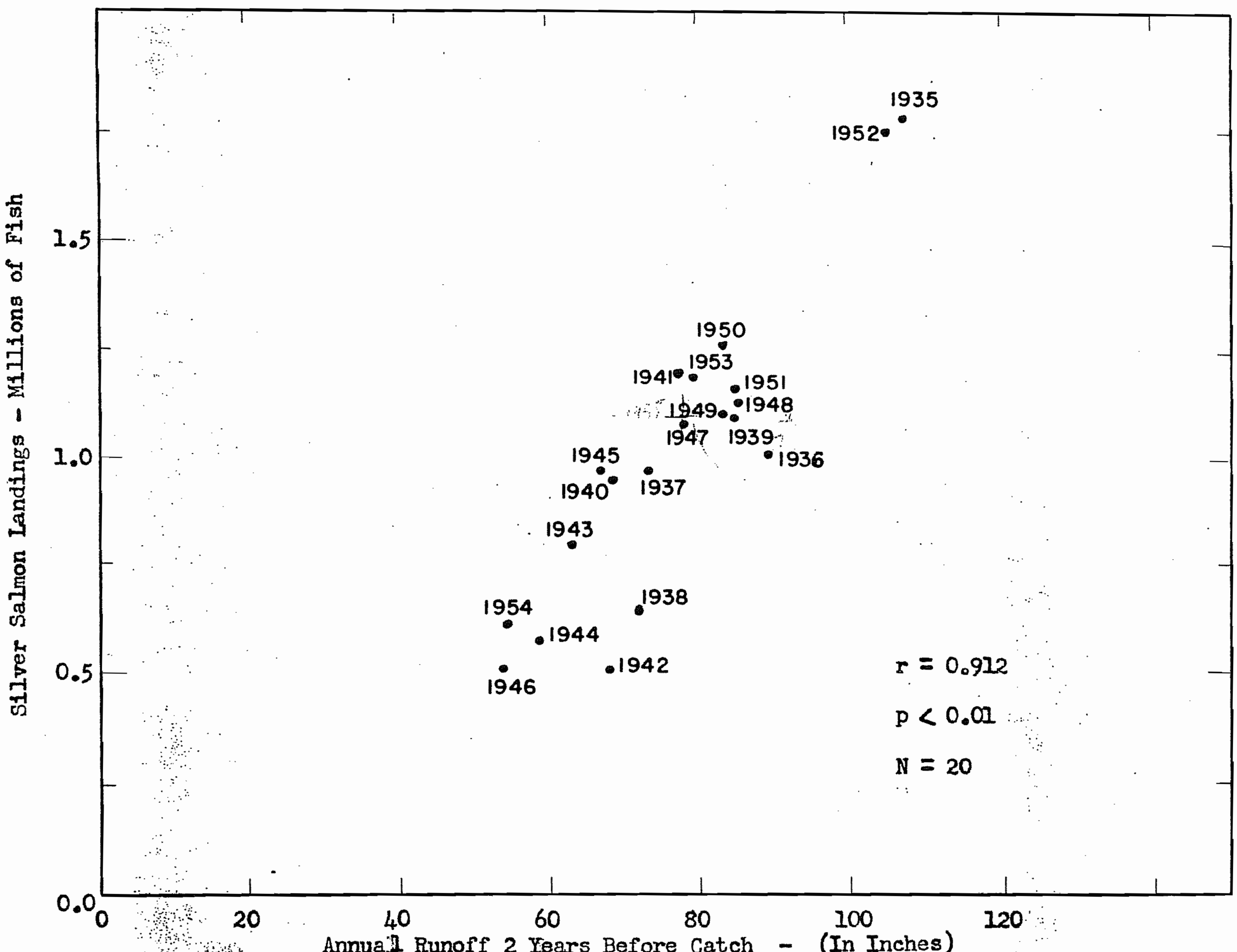


Figure 19-A
Correlation of Total Commercial Silver Landings With Annual Runoff in Western Washington
Dates Refer To Year of Silver Catch

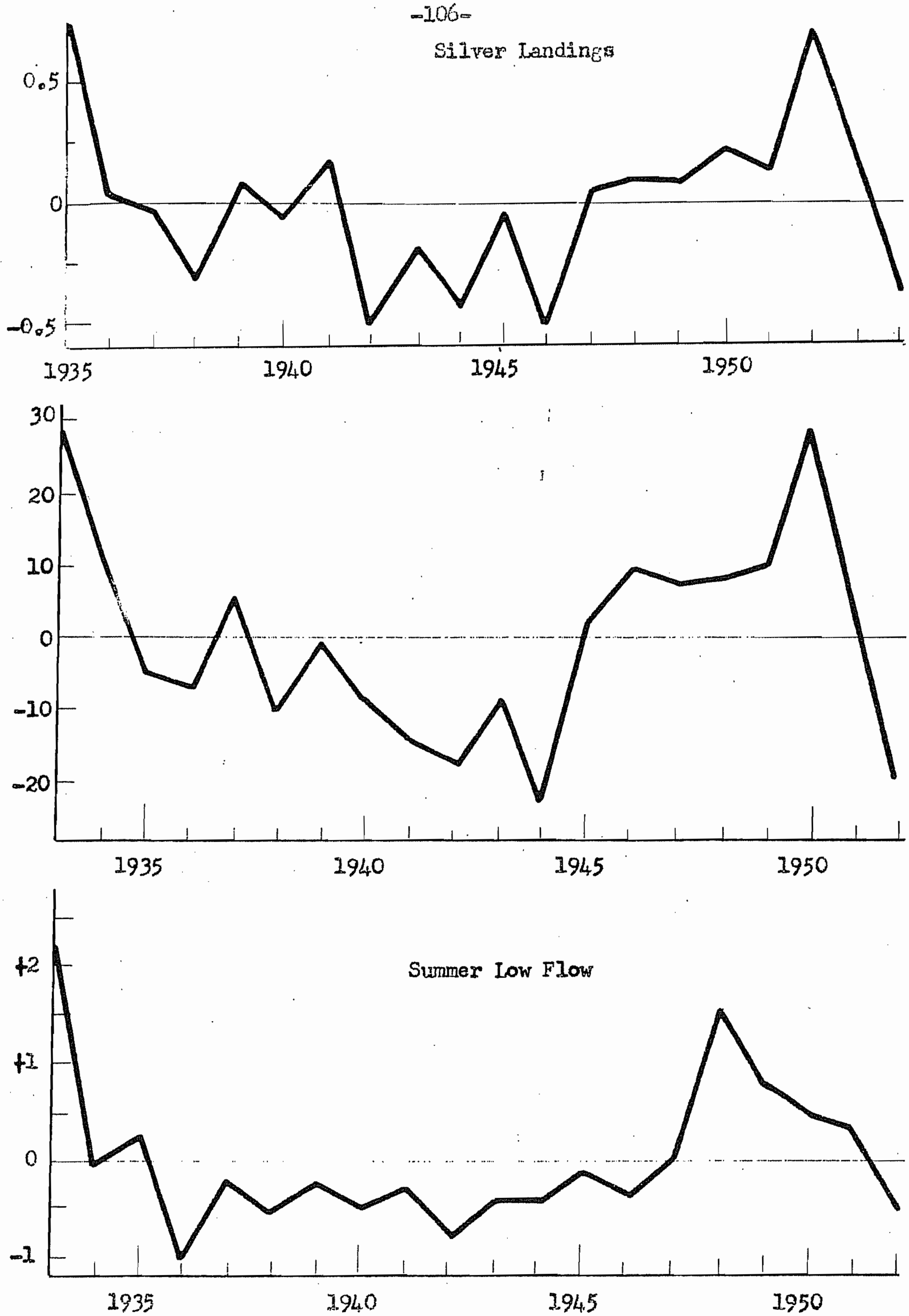


Figure 20. Comparison of Deviations From Trend Lines of Annual Silver Landings With Annual Runoff and Summer Low Flows

pattern of rise and fall in the annual fish landings and water flow data. However, anomalies are apparent for the fish produced by the water years 1936 and 1940. In both of these years the silver landings were somewhat less than would be expected from the annual abundance of stream water. For the water year 1936 the silver landings in 1938 were about 270,000 fish below expectations or about 28 percent low. For 1940 the landings in 1942 were about 400,000 silvers or 44 percent low. It seems logical that merely passing certain amounts of water down the streams within a given year did not answer all the requirements for successful silver production. Trusting that there might not be some unknown marine factor involved, either in the natural environment, or in shifts in fishing effort, a further examination of the water year and its possible effects on silver landings was made. It was readily observed that the monthly summer and fall runoff patterns for 1936 and 1940 were different from the general patterns of the other years. This can be seen by comparing the monthly runoff figures for 1936 and 1940 with the average in Table 19, and inspecting Figure 18.

In 1936 the summer runoff was below average but not excessively so until the month of October. Then, due to lack of rainfall, the stream discharges dropped severely and remained so into November providing the only year in which the lowest-month flow fell in November in the twenty-year period (Figure 22). By contrast, 1940, although showing the most frequently occurring lowest month of September, and also a normal flow pattern for the fall, shows a considerably reduced runoff for early summer in June, July, and August. These anomalies associated with abnormally low silver catches indicated that the low flow pattern was also significant in the survival of silver salmon besides the total yearly abundance of stream water.

B. Summer and monthly streamflows and silver production.

Several analyses were made to explore further the matter of summer and fall runoff patterns. Correlation coefficients were calculated between the streamflow during each month of juvenile residence and total adult landings two years later (Figures 24-A and B). This was also done for the lowest-flow month of each year and for the summer period of June, July, August, and September. The calculations are shown in Tables 40, 41, and 42. A summary in graph form, presented in Figure 23, emphasizes the high degree of correlation of annual runoff as contrasted with the various other breakdowns. When the coefficients for the separate months are plotted they generally do not become significant until after June. Significance above the 95 percent level is maintained from July through December, dropping below a significant level during the following January. Downstream migration studies by the Washington Department of Fisheries on Minter Creek, White River, and Wynoochie River have shown that by January the seaward migration of yearlings has started even though the peak may not occur until late spring. Logically, the stream discharge from the second January through the spring could not be expected to have much effect and the lack of significance is not surprising.

1. Summer streamflow correlation.

The combined flow for the summer period of June through September during juvenile residence shows a high correlation with adult landings. The calculation

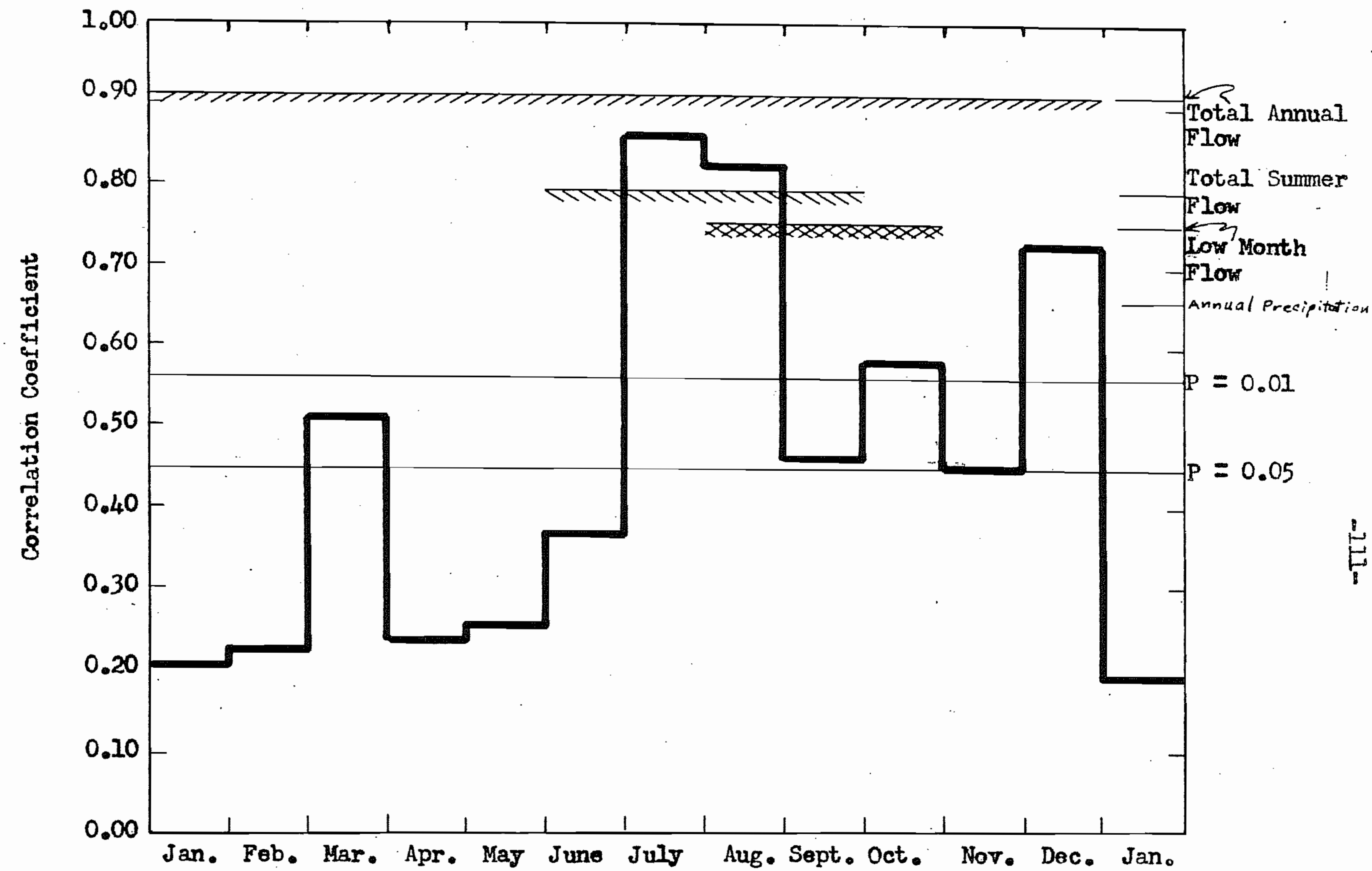


Figure 23. Monthly Flow Correlations for Silver Landings 1935-1954 in Western Washington

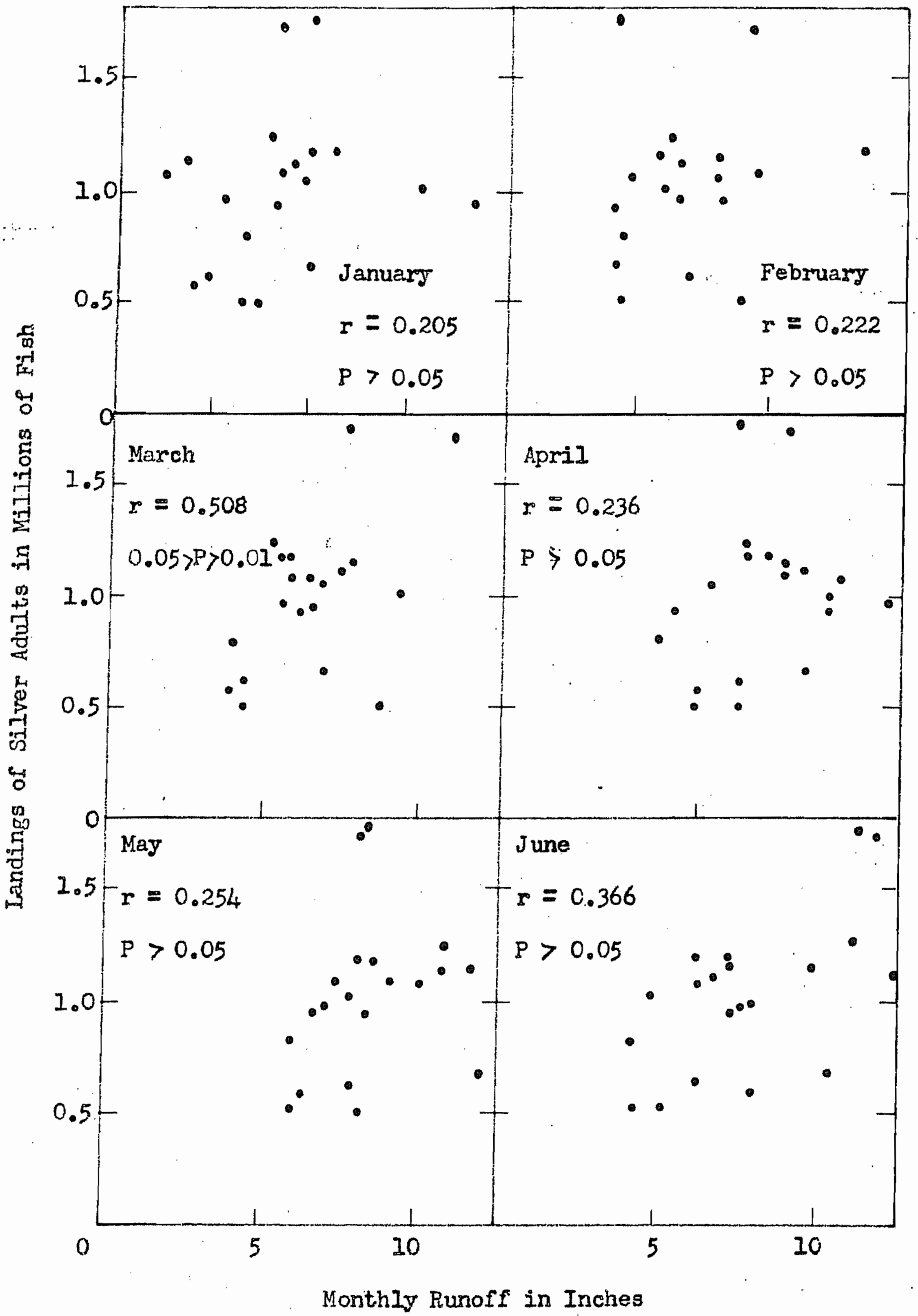


Figure 24-A.
Correlation of Total Silver Landings with Monthly Runoff 1933-1952

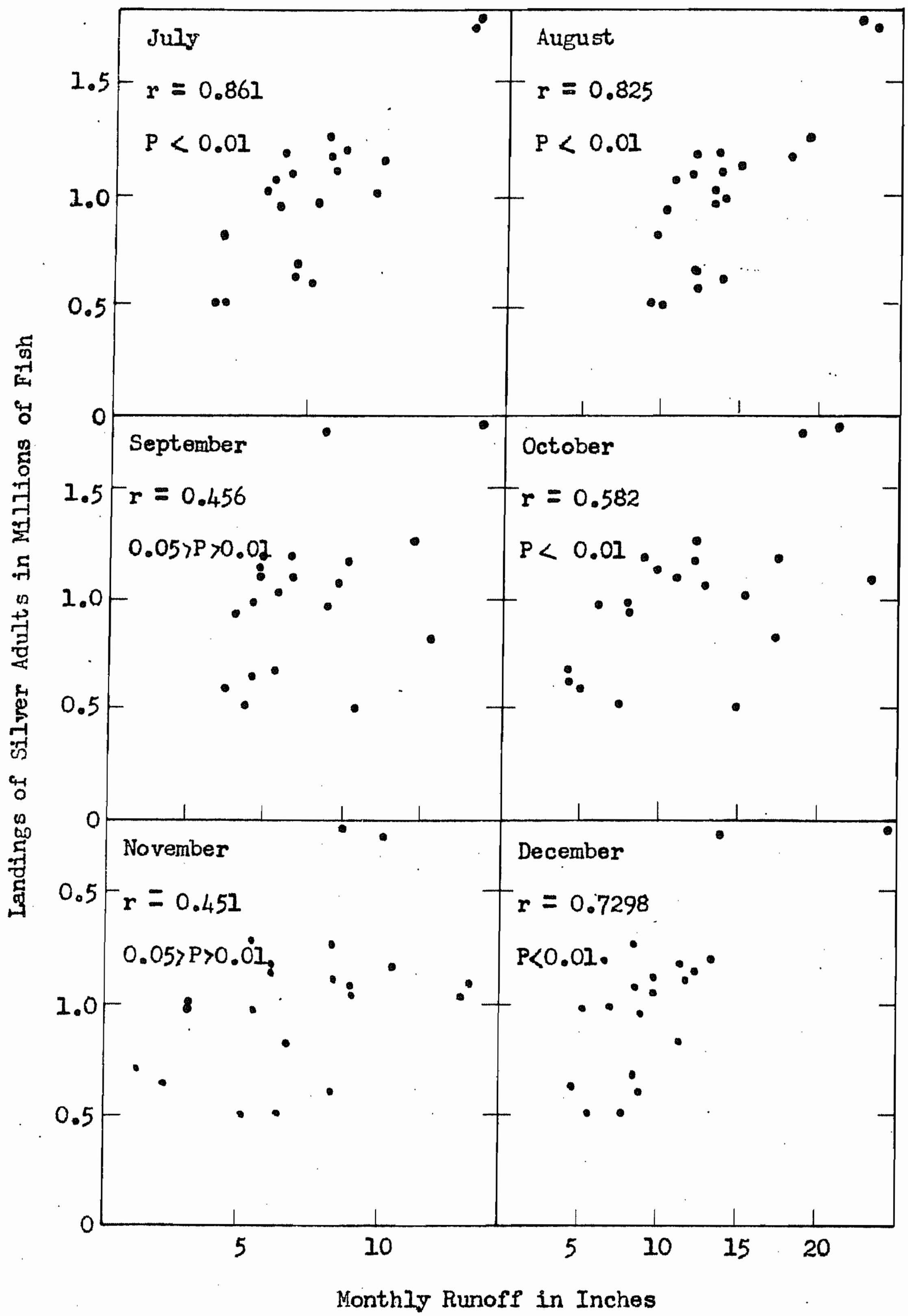


Figure 24-B.
Correlation of Total Silver Landings with Monthly Runoff 1933-1952

presented in Table 42 shows a correlation coefficient of 0.7946 which is considerably above the 0.561 required for 99 percent confidence. The dry early summer of 1940 and its effects on the silver survival is nicely demonstrated in Figure 25. By comparing the positions of the 1942 catch data on this graph and in Figure 33 the abnormally low survival in the latter is explained.

The possibility of correlation due to unassociated trends in summer runoff and silver production was explored by correlating the deviations from the calculated trend lines. As mentioned above, the trend line of silver landing rose 5.4 percent. However, the summer flow data show a negligible trend downward for the twenty years of only 0.3 percent. The correlation coefficient of the basic summer-flow and fish data is changed only slightly from 0.7946 to 0.7970 by correcting for possible trends (Table 42). When summer flow is correlated with time r is only -0.0037.

The question now arises as to which variable is more important in determining the survival of silver salmon. Both annual runoff and summer flow show a very high degree of correlation with silver landings. Does summer flow appear so significant because it actually is the most critical period? Or, is the yearly flow primarily the important variable while summer flow is merely reflecting annual runoff?

The very high correlations of 0.8610 and 0.8254 between July and August streamflows, during juvenile residence, with total landings of adults (Figures 23 and 24-B) may merely indicate that these two months may be the most stable flow months of the year which would consistently reflect the general level of water abundance determined by previous precipitation and snow and glacial melt. Since the summer period analyzed in Table 42 includes July and August, the high correlation coefficient of 0.7946 with silver production may in large part be a measure of its agreement with the annual runoff pattern rather than indicating a significant role in silver survival. However, the one extreme pair of observations, 1940 summer runoff and 1942 silver catch, shows that this period can be limiting on occasion.

To test the hypothesis that generally summer flow did limit silver production, a partial correlation coefficient was calculated according to the procedure set forth by Snedecor (1946:p.357). In order to complete the partial correlation formula it was necessary to correlate summer runoff with annual runoff. The derivation is shown in Table 43, and the scatter of points in Figure 26. In this technique, annual runoff in effect is held constant and the degree of correlation with summer flow is determined. Using Snedecor's symbols:

Variable 1 = Silver landings.

Variable 2 = Summer flow.

Variable 3 = Annual runoff.

$r_{12}$ - 0.7946 (Table 42).

$r_{13} = 0.9120$ (Table 40).

$r_{23} = 0.7266$ (Table 43).

According to Snedecor, (1946:p.358):

$$r_{12.3} = (r_{12} - r_{13}r_{23}) \left[(1-(r_{13})^2)(1-(r_{23})^2)\right]^{-\frac{1}{2}} = 0.4683$$

For 17 degrees of freedom P is greater than 0.05. This should justify a rejection of the hypothesis that the summer flow is generally limiting in the natural production of silver salmon. However, the very low silver catch associated with the very low summer flow of 1940, plus the fact that the partial regression coefficient of 0.4683 is approaching the 95 percent level and might actually be considered as a borderline case, leads one to further exploration of possible limitations in silver salmon production due to low flow.

2. Lowest-month flow correlation.

Instead of using a fixed period such as was done for the summer flow correlation, the extreme in the low flow pattern which shifts from year to year (Figure 22) might provide more significant information. For the period 1933 to 1952 the low-flow month in Washington streams (Figure 22) occurred 30 percent of the time in August, 55 percent in September, 10 percent in October, and 5 percent in November.

Figure 15 shows the basic similarity in the twenty-year patterns of the low-flow month streamflow during silver juvenile residence and the total landings of adults two years later.

Table 40 and Figure 27 show that the basic data of low-flow month streamflows in inches and the total silver landings in numbers of fish provide a correlation coefficient of 0.756 ($^{r}.99$ = 0.561 for d.f. = 18). The position of this coefficient, compared with those of other possible variables indicated in Figure 23, shows that it ranks lower than total annual flow and lower than summer flow in significance but higher than the other single-month comparisons except for July and August discussed above.

As in the case of the annual and summer runoff comparisons with fish landings, the possible effects of unassociated trends were explored by correlating deviations from trend lines of the low-month flow streamflows and the silver salmon landings for the twenty-year period. In Table 40 the low-flow month shows a rise of only 5.8 percent. When the low-flow month streamflow is correlated with time, r is only 0.097. Correlating the deviations of from the trend lines provides a coefficient of 0.758 which is only slightly higher than the coefficient of 0.756 obtained by using the basic data. The deviations from trend line data for the lowest-flow month streamflows are shown in Figures 20 and 28.

Again the question arises: Is the high correlation between the low-flow month streamflows and the catch two years later merely coincidental because it reflects annual runoff or does it actually account for some limitations in the production of silver salmon? The very dry late summer and fall of 1936 culminating in the low-flow

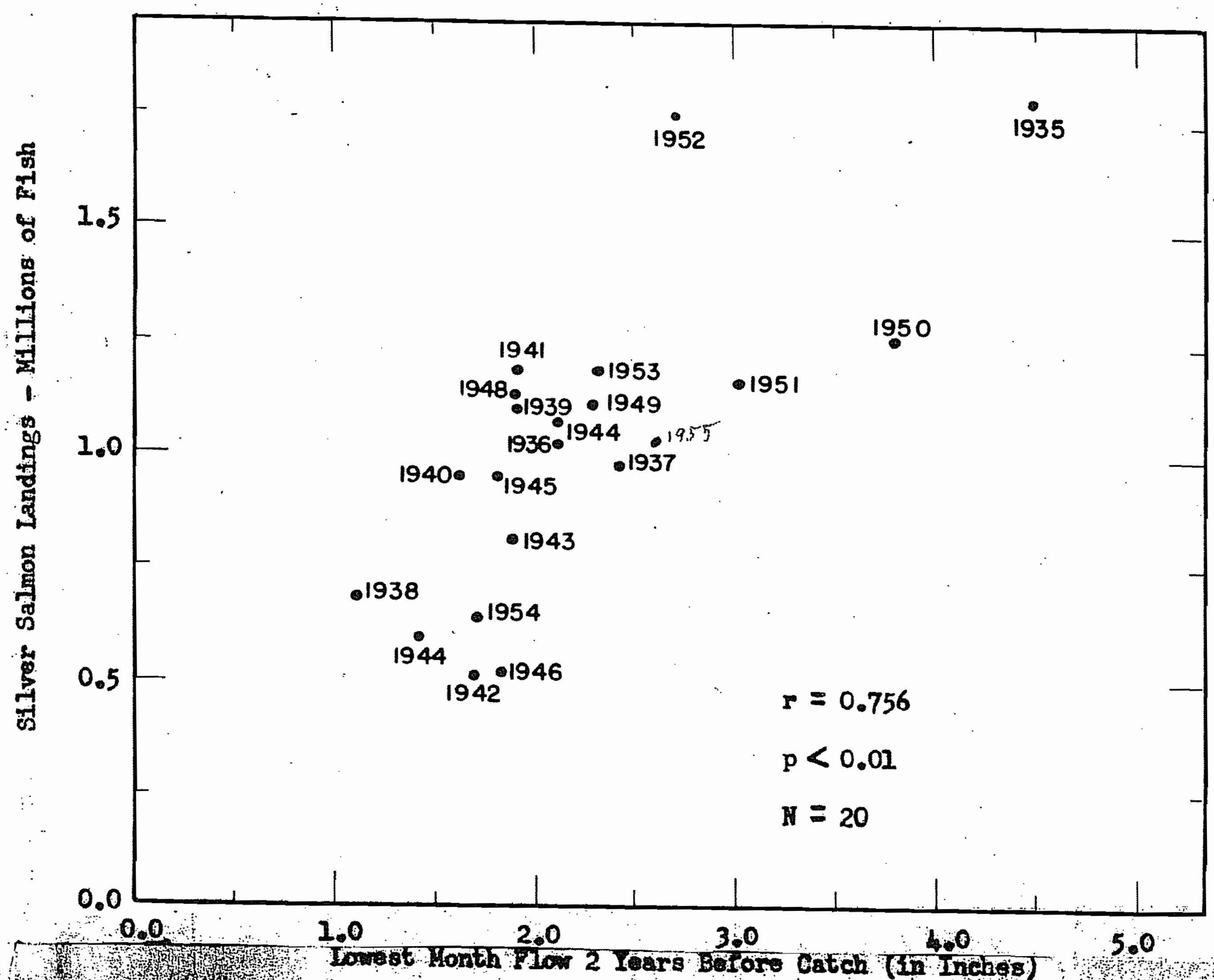


Figure 27. Correlation of Lowest Month Flow and Total Commercial Silver Landings in Western Washington
Dates refer to year of silver catch.

month of November (Figure 22) would lead one to suspect that such extremes do play a part in determining silver salmon survival. It is emphasized again that the catch in 1938 produced by the 1936 water year was about 28 percent lower than it should have been when considering annual runoff alone.

As in the summer flow analysis a partial correlation coefficient was calculated. This time the three variables were:

Variable 1 = Silver salmon landings.

Variable 2 = Low flow month runoff.

Variable 3 = Annual runoff.

$r_{12} = 0.756$ (Table 40).

$r_{13} = 0.912$ (Table 40).

$r_{23} = 0.696$ (Table 44).

the correlation of lowest monthly flow with annual runoff or $r_{23}$ is derived in Table 44 and the considerably dispersed although significant grouping of data is shown in Figure 29. Substituting these values in Snedecor's formula for a partial correlation coefficient: $r_{12} = 0.4117$.

For 17 degrees of freedom with three variables $r_{12.3}$ could be accepted on the 99 percent level of confidence at a value of 0.545.

Again there is cause for rejection of the hypothesis that a low flow variable is generally limiting in the natural production of silver salmon. However, like the summer flow, this is a borderline situation and there is evidence that the low-month flow will influence the survival of salmon, particularly during the years of reduced streamflow.

A close inspection of the basic data in Table 40 and Figure 15 reveals a number of pairs of observations showing the dominant effects of annual runoff but also showing the pronounced effects of the 1936 low-month flow. These are plotted in Figures 30 and 31. In Figure 30 three groups of data have been sorted out of the more inclusive diagram given by Figure 27. These show the effects of changes in stream discharge during the low-flow month at different levels of annual runoff.

Considering that there are only twenty years of data available, the numbers of observations with differences in lowest-month flow but showing the same level of total annual runoff are few in numbers. First, Figure 30 shows that for years of fairly constant annual runoff there is an increase in silver salmon landings which is related to changes in level of the lowest-flow month. Secondly, the effects of changes in water volume during the lowest-flow month are greatest during years of very low total annual runoff and least during the wet years. There are not sufficient data in the three levels portrayed in Figure 30 to derive any formulas and the data will have to be considered merely as information supporting the conclusion presented by the partial correlation coefficient calculated above.

Figure 31 shows that the converse, as might be expected from the high correlation coefficient in Figure 19, is also true and that annual runoff consistently influences silver salmon survival for years of fairly constant lowest-month flow.

The lowest group in Figure 31 has been plotted by itself in Figure 32 and shows still more clearly the strong positive effect that annual stream water abundance has on silver survival.

C. <u>Linear regression of annual flow with silver salmon.</u>

Since a major reason for the significant correlations between summer and low-month flows and silver landings is that they are merely good indices of annual runoff, a final expression is derived for streamflow and silver salmon production using only annual runoff and silver salmon landed.

Using standard methods the linear regression formula is derived:

$$\hat{Y} = -66.4356 + 2.204X$$

where $\hat{Y}$ is the expected landings of adult silver salmon in Western Washington in 10,000's of fish and X is the annual run-off in Western Washington in inches.

The standard error of estimate is found to be $\pm$ 14.317 which means that in estimating silver salmon landings by using this formula, we can expect these calculated values to fall within a range of 143,170 fish above and below the actual landings for at least two-thirds of the years.

## VII. DISCUSSION OF FINDINGS IN RELATION TO ASSOCIATED STUDIES.

### A. Streamflow during salmon rearing period.

Table 45 and Figure 33, based upon Cowichan data from Neave (1949), show the effect of the lowest flows in 1938 and 1944 for that Canadian river. The catches in 1940 and 1946 were the lowest of the 1940 through 1947 period. It is interesting that, as pictured in Figure 33, increasing the lowest runoff from 15 c.f.s. to 80 c.f.s., a 430 percent change, increased the catch per unit of sports effort only about 25 percent. Further increases in summer low flow did not increase the availability of later adults. The Canadian pattern, although based upon considerably less data, is similar to that of the lowest-month flow comparison in this thesis shown in Figure 30 where increasing the lowest month flow about 167 percent increases the adult silver yield to the commercial fishery about 22 percent. Direct comparisons of the two studies are not too meaningful since the measure of abundance of stocks in the Canadian study is catch per unit of effort but in this thesis is total catch. It would appear that after a certain level is attained, further increases in low flow have decreasing effects.

The flow index used by McKernan et al (1950) for Oregon is comparable to the summer flow study in this thesis where the total flow for the months July through September is used. In this study such a significant correlation is due more to the summer runoff being a good index of annual runoff rather than to any specific effect of the period itself. Figures 2-A and B in this thesis also show certain broad similarities in several of the river fisheries. From the standpoint of this problem, however, the most interesting aspect of the catch graphs in Figure 3 of the Oregon study is that, disregarding the downward trend in silver landings, the general peaks and valleys agree with the general peaks and valleys of fish landings and associated annual runoff for Western Washington (Figure 15). The most consistent or prevalent point of agreement between the two studies is the high point of all silver catches and of associated Washington annual runoff in 1935. This is followed by a sharp drop with a succeeding rise for several years about 1940. Next, there is a low in the early 1940's followed by another rise in the late 1940's. This superficial agreement between Oregon silver landings and Washington annual runoff may not be too surprising since the annual weather patterns of Oregon and Washington are similar and the requirements of the silver salmon are the same. As might be expected from Figure 44 similar precipitation patterns would produce similar stream discharge patterns.

The water and silver production data in Table 46 are a reproduction of Table II by Wickett (1951). The data were not shown as a graph in Wickett's paper but are so presented in this paper in Figure 34. Although four pairs of data are too few to determine the relation of fresh-water conditions to silver salmon production, the graph does indicate the limiting effect of "dry" summers. The Nile Creek study, similar to that on the Cowichan River, also indicates that after the summer flow is increased beyond a certain level it has little effect on silver salmon survival. This phenomenon is illustrated in the Cowichan graph in Figure 33 as well as in Figure 34.

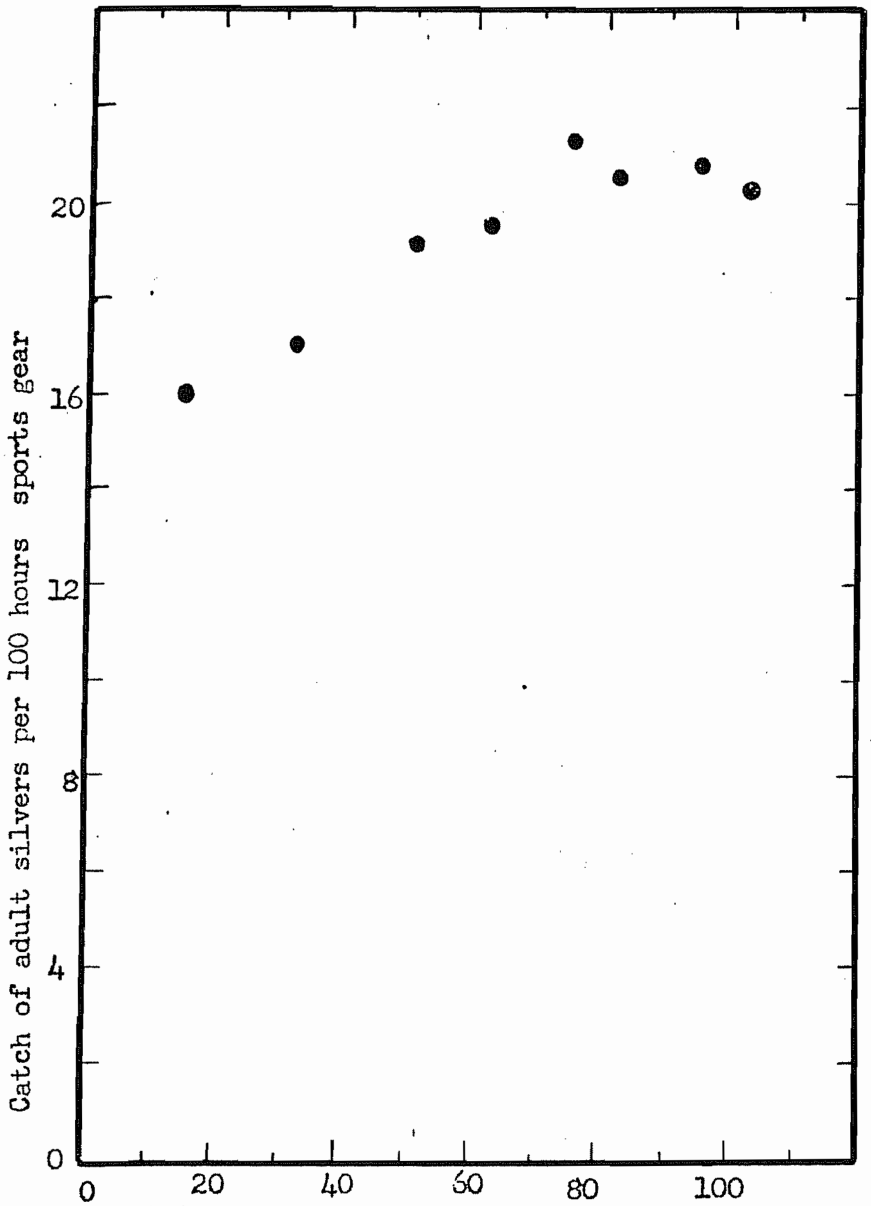


Figure 33. Comparison of silver sports harvest in Cowichan Bay with minimum flow.

problem, however, the most interesting aspect of the catch graphs in Figure 3 of the Oregon study is that, disregarding the downward trend in silver landings, the general peaks and valleys agree with the general peaks and valleys of fish landings and associated annual runoff for Western Washington (Figure 15). The most consistent or prevalent point of agreement between the two studies is the high point of all silver catches and of associated Washington annual runoff in 1935. This is followed by a sharp drop with a succeeding rise for several years about 1940. Next, there is a low in the early 1940's followed by another rise in the late 1940's. This superficial agreement between Oregon silver landings and Washington annual runoff may not be too surprising since the annual weather patterns of Oregon and Washington are similar and the requirements of the silver salmon are the same. As might be expected from Figure 44 similar precipitation patterns would produce similar stream discharge patterns.

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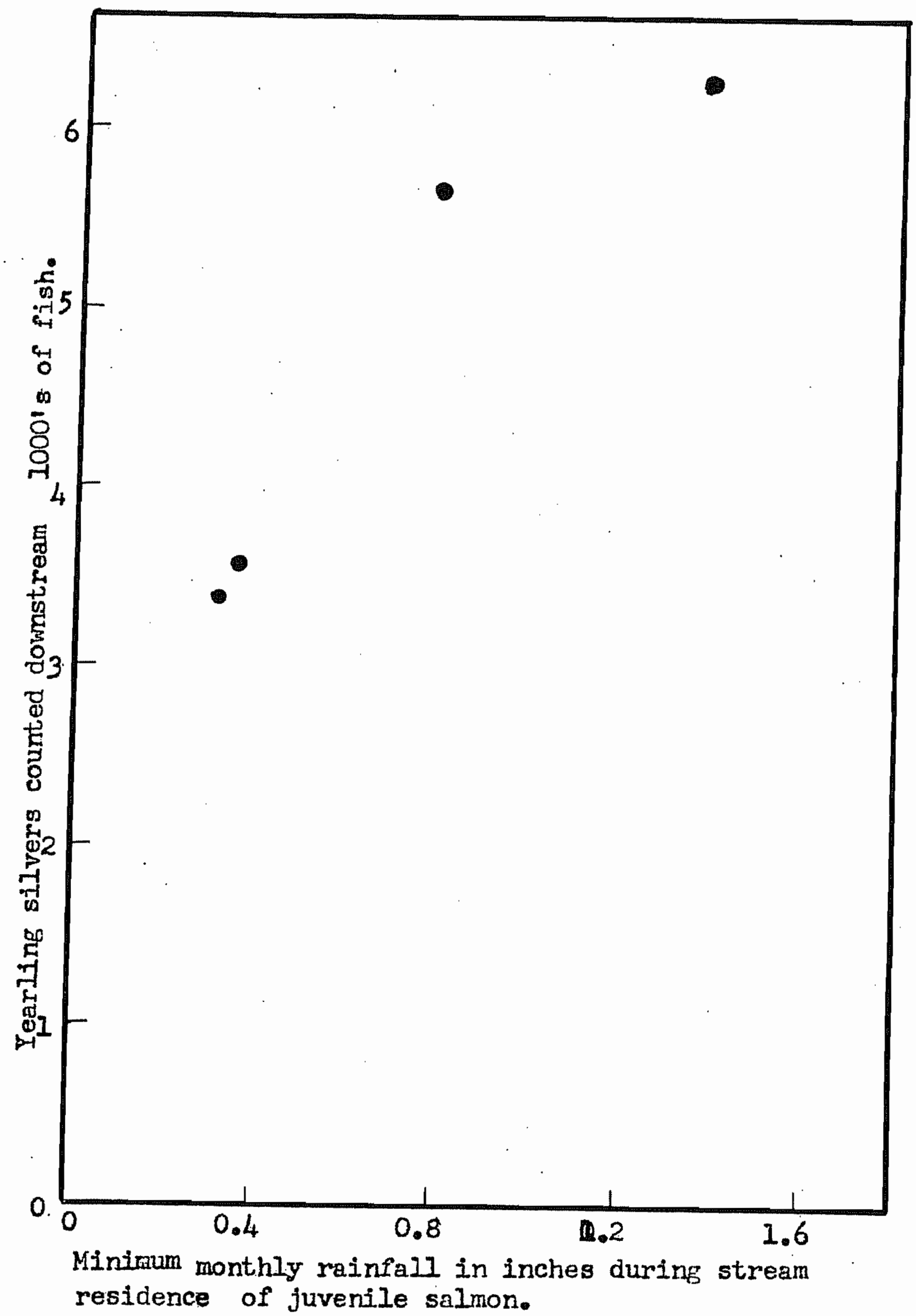


Figure 34. Nile Creek silver yearling production related to minimum monthly precipitation.

It is unfortunate that while the enumeration of upstream and downstream migrations of silver salmon was excellent throughout the seventeen years of continuous operation of the Minter Creek station there was a very poor continuity and at times a complete lack of stream discharge measurements on Minter Creek. An official U.S.G.S. gauging station has been in operation on the watershed since 1948 but data are lacking to compare with the silver salmon production measured in earlier years. It was determined, however, by this author, that for the earlier years when Minter Creek stream discharges were measured by the Department of Fisheries and in later years after the U.S.G.S. installation, there was good agreement between annual fluctuations in Minter Creek discharges and annual fluctuations in the general Western Washington stream discharges (Figure 35 and Table 47). The Western Washington streamflow index derived for this thesis was applied with some confidence to the Minter Creek silver data with fairly positive results.

Figure 36 based upon Table 48 shows the results of these comparisons. The information was presented previously by Smoker (1954), however, several additional years of data have become available and are incorporated into this thesis in Figure 36.

The Minter Creek comparisons show rather well that adult escapement at sufficiently low levels will result in low yearling production in spite of favorable water conditions. Smoker (1954) stated that at least 500 female silvers were required to produce the maximum number of downstream migrants to the ocean. Since then, the results of an escapement of 400 females into Minter Creek have been compiled and are plotted in Figure 36. It appears that the number of young produced by 400 females is also above the maximum number that can be reared efficiently in the stream.

Ignoring streamflow effects, Figure 37 shows that when spawning escapements are cut sufficiently low, a level is reached below which yearling production depends upon numbers of eggs deposited. However, Figure 36 emphasizes that regardless of the level of spawning escapement the effects of annual streamflow continue to influence the survival of the juvenile salmon.

In 1954, Shapovalov and Taft published data on Waddell Creek in California which has some application to this general problem. The Waddell Creek study covers the period 1932 to 1942, and although the subject of silver production and streamflow abundance was not discussed as such, a few interesting items of relevant information did occur in separate parts of the report. The authors make the statement on page 101"-----within the limits of conditions encountered during the above four seasons (1933-1936 brood years) the number of downstream migrants is approximately proportional to the number of eggs deposited."

The numbers of females put upstream to spawn are listed in their Table 9 which includes both fish taken in the trap and counted over the dam and fish which jumped over the dam unassisted. The numbers of downstream yearling migrants from these escapements were calculated by counting and marking part of the downstream migrants and then observing the marked to unmarked ratio among the adult escapement two years later and back calculating to estimate the probable numbers of downstream migrants that had occurred. The number of yearling downstream migrant silver salmon are listed by the authors in their Table 12. Pectoral fin marks were used in all of the four brood years. Table 1 of the California

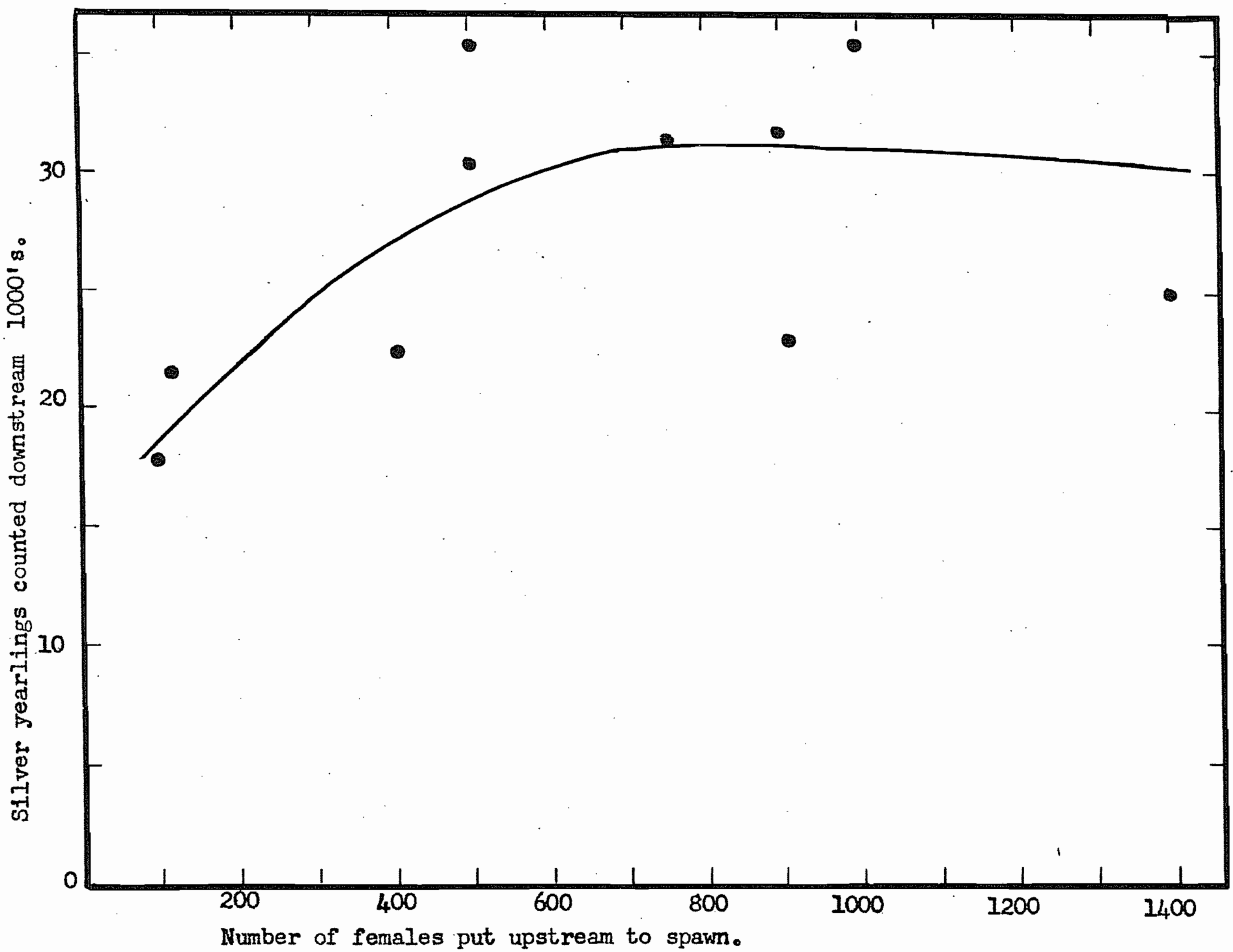


Figure 37. Minter Creek silver salmon yearling production related to spawning escapement.

report gives the minimum flows for these years when the juveniles lived in the stream. The combined information is presented in Table 49 of this thesis and plotted in Figure 38.

The almost perfect straight-line relationship between eggs deposited and yearlings produced is remarkable in view of the considerable variation in streamflow which has been found to be an important factor in Minter Creek studies. The lowest flows in Waddell Creek are extreme when compared to Minter Creek and should have influence on survival. The number of adult silver salmon spawning Waddell Creek is very low, and when the length of available channel is considered it may be that egg deposition is completely dominant in determining numbers of yearlings. The silver stocks may have been reduced to a level below optimum watershed use.

B. Streamflows during salmon egg incubation period.

The straight line relationship between egg deposition and yearling production for the 1933 - 1936 brood years of silvers in Waddell Creek (Shapovalov and Taft, 1954) has been approached at Minter Creek for chum salmon (Figure 39). Data completed for fifteen brood years (1939 - 1953) of chum salmon show a close approximation to a straight line relationship between numbers of females put upstream to spawn and numbers of chum fry counted downstream.

The time spent by chum fry in the stream is very short in comparison with silver juveniles and the annual and low streamflows would not be expected to be correlated with chum fry survival. However, at times in Minter Creek, streamflow conditions did limit the production of chum fry migrants. During incubation periods,

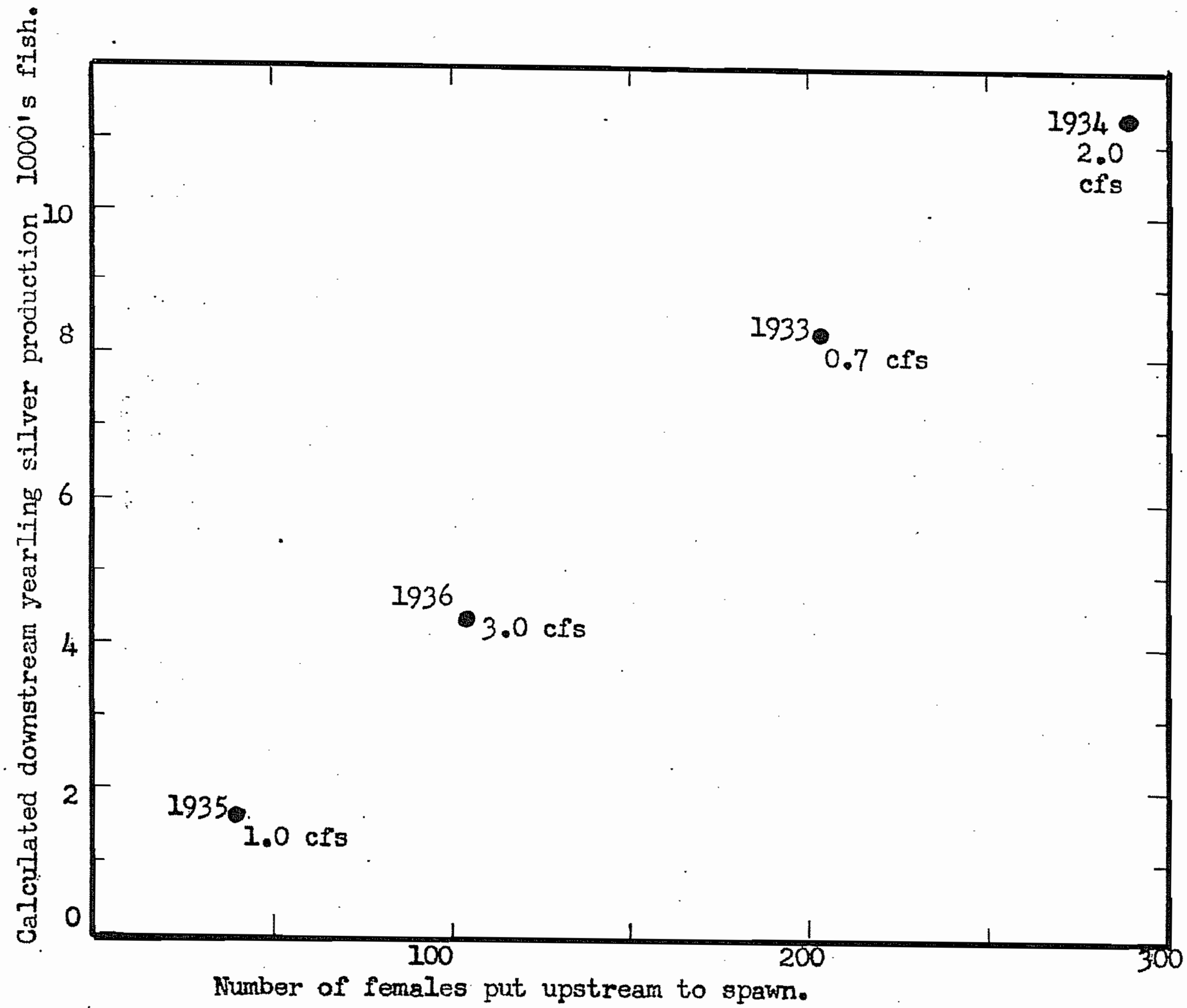


Figure 38. Waddell Creek calculated yearling production related to spawning escapement. Dates refer to brood years. Flows are minimum daily rate during stream residence.

excessive freshets drastically reduced the survival of chum fry. Such freshets occurred for 1946, 1949, and 1950 brood years (Figure 39 and Table 50). In the spring of 1949 and 1950 dead chum fry, many in the yolk sack stage, were observed to collect on the screens at the mouth of Minter Creek during the floods. Figure 39 indicates that during years of heavy stream freshets, the production of fry remained at about 200,000 fish regardless of egg deposition. It would almost seem that under flood conditions only eggs in certain limited protected areas would survive and that these areas were always fully utilized by spawning females.

Since severe stream conditions have such a pronounced effect on chum salmon the silvers might be expected to show some reaction to these conditions also. One would not expect the effects would be entirely smoothed over by the extra year of stream residence by the silvers. However, there is no evidence in the Washington data to show that severe floods limit the number of silvers produced. In fact, it may be noted that in Table 48 where equal escapements of 500 females were allowed upstream at Minter Creek for the 1944 and 1946 broods, the 1946 brood, which experienced a severe winter flood condition, actually produced more yearlings than the 1944 brood which had a normal winter. The annual runoff indices for these two years were in reasonably close agreement.

It would seem that, in Western Washington streams of the lowland type such as Minter Creek, silver juveniles find a limiting survival factor, or complex of factors, in the total volume of streamflow which dominates all other variables while chum salmon with their comparatively short stay in fresh water find streamflow of no

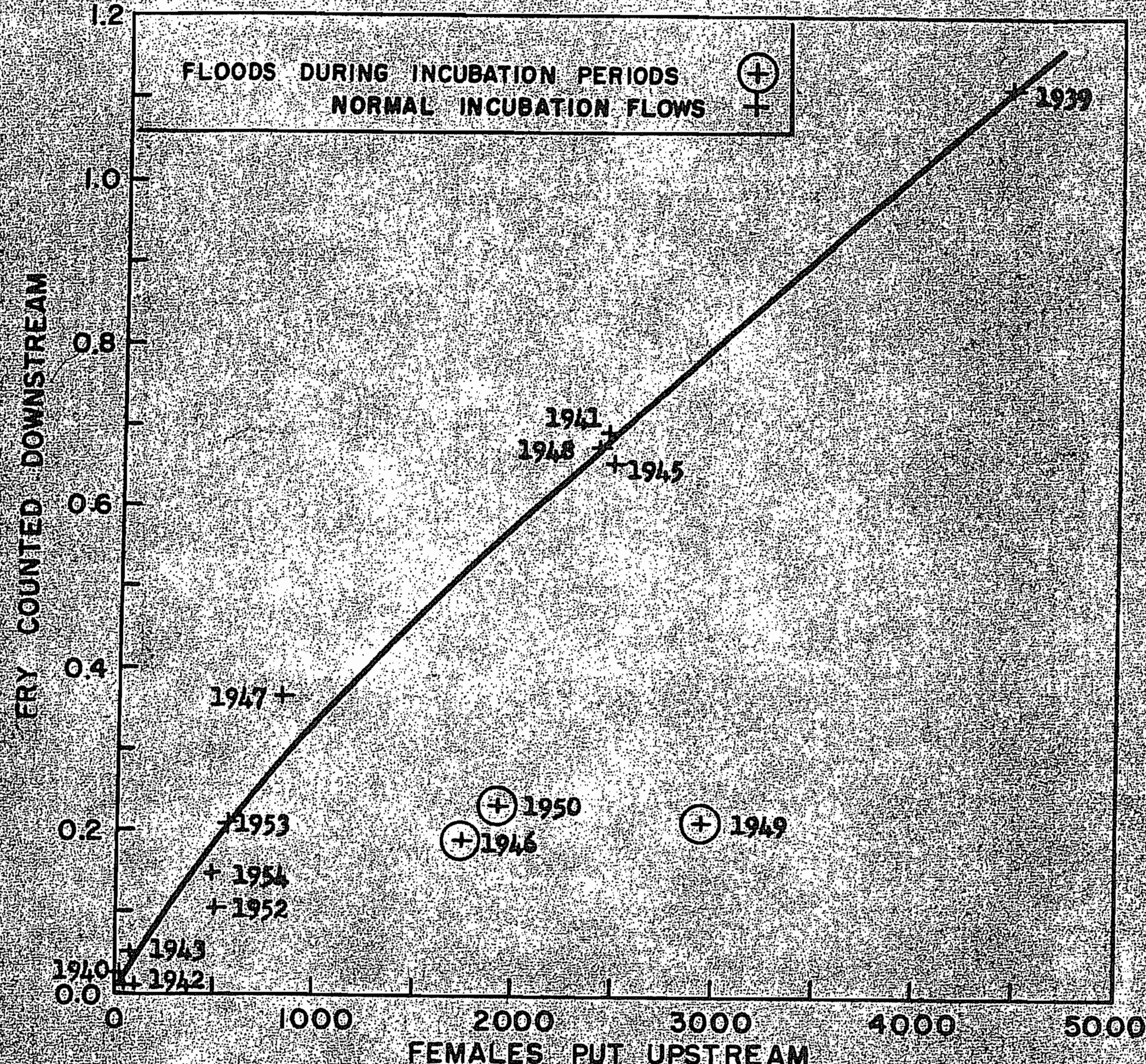


Figure 39. Relationship of chum fry production in Minter Creek to adult female spawning escapement and to floods during incubation periods. Years refer to brood years.

concern unless certain flood intensities occur.

Henry (1953) compares in chronological order chum landings from the Tillamook commercial fishery with minimum flows in the Wilson River during the incubation period of the fish. If the data are accepted at face value and presumed not to be modified by such variables at the numbers of fish in the spawning escapements, changing ratios of age groups taken each year in the fishery, and inclusion of other chum stocks in the fishery, the adverse effects of too little water can be shown by replotting Henry's data as in Figure 40 which is based upon Table 51. The low production of the 1945 brood indicated by the lower right hand point is explained by Henry as due to the excessive delay in appearance of adequate spawning flows on the more desireable spawning grounds. Considering the rest of the points in Figure 40 it appears that when streamflows during the chum egg incubation period drop below about 650 c.f.s. in the river at the gauging station, the commercial yield will not exceed one million pounds. Between flows of 300 to 650 c.f.s. there is considerable variation in chum production but no definite trend. In fact, Figure 40 would indicate that there is more of a ceiling affect for this range of flows rather than a gradient. After the bottleneck of 650 c.f.s. is exceeded, the greater the abundance of water during incubation the greater the yield or survival of fry.

Summarizing the subject of incubation period streamflows, it seems the effect varies with species and with watersheds. The production of downstream migrant silvers in Washington does not appear to be affected by the volume of flow during the incubation

Table 51 - Comparison of commercial chum landings on Tillamook Bay with incubation period low flows. 1/

| Year | Minimum incubation flow 15 Jan. to 20 March | Chum landings three years after incubation period |
|---|---|---|
| 1932 | 5.6 | 5.7 |
| 1933 | 7.9 | 11.9 |
| 1934 | 3.8 | 4.4 |
| 1935 | 6.4 | 7.3 |
| 1936 | 5.1 | 4.3 |
| 1937 | 6.3 | 4.4 |
| 1938 | 8.1 | 17.6 |
| 1939 | 9.2 | 26.5 |
| 1940 | 4.7 | 3.8 |
| 1941 | 3.4 | 3.6 |
| 1942 | 4.6 | 7.8 |
| 1943 | 3.4 | 4.8 |
| 1944 | 6.4 | 3.7 |
| 1945 | 5.7 | 9.0 |
| 1946 | 9.3 | 4.4 |
| 1947 | 5.0 | 2.0 |

1/ Data compiled from Figure 5, Henry's report 1953.

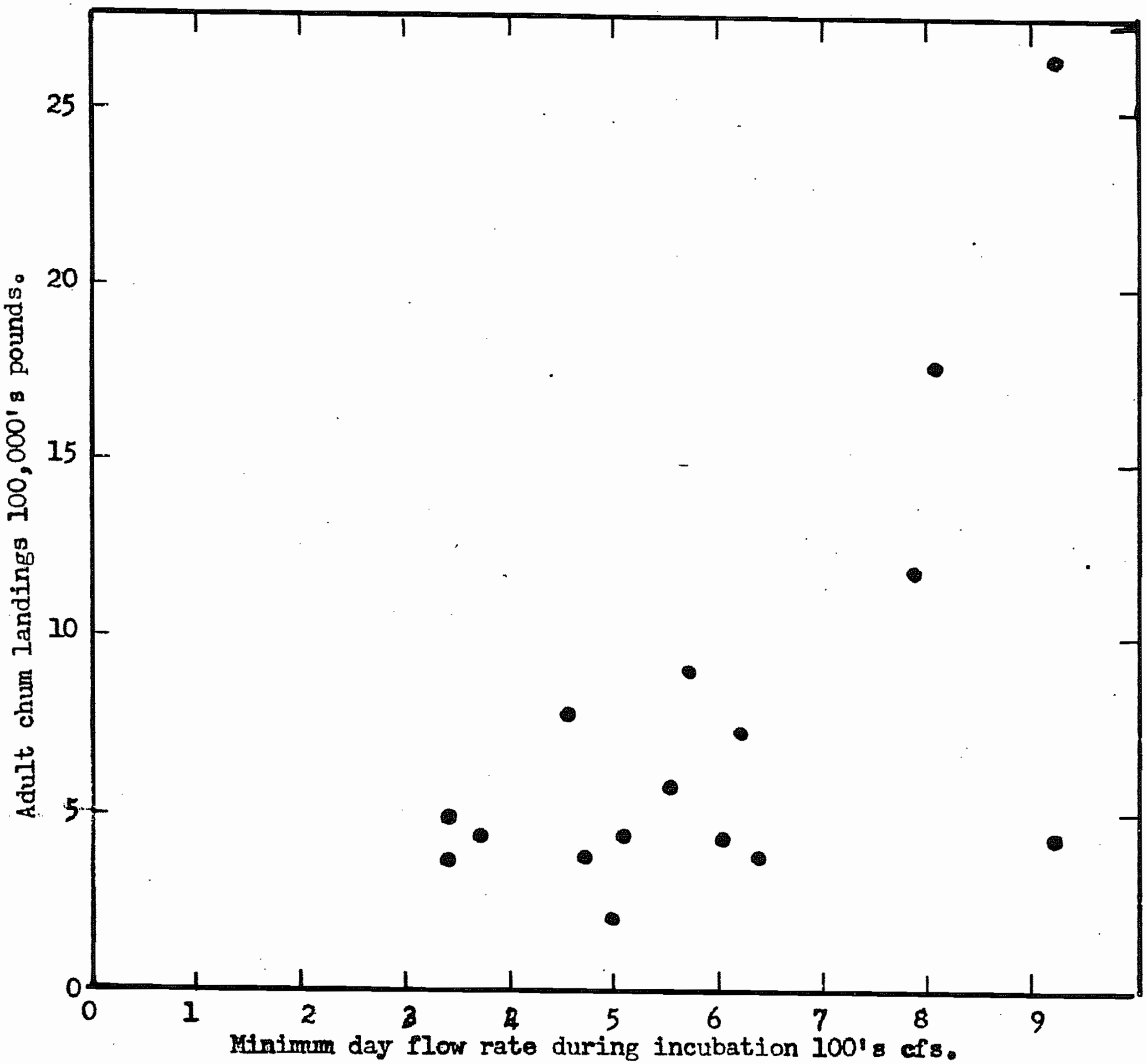


Figure 40. Comparison of commercial chum landings on Tillamook Bay with incubation low flows.

period. Chum salmon in the Minter Creek type of watershed are limited by incubation period flows only when they occur as severe freshets; on which occasions juvenile production is held below a certain ceiling. Chum salmon fry production in the Wilson River type of watershed is held by incubation period flows below a ceiling until the streamflows exceed a certain level at which time the chum survivals increase.

C. Washington rainfall during stream rearing period of silver salmon.

Further evidence supporting the thesis that the volume of stream water available to juvenile silver salmon has a positive relationship with their survival is found when certain comparisons are made between silver landings and preciptiation in the State of Washington. The U. S. Department of Commerce Weather Bureau, in Climatological reports, provides annual precipitation data that correlates with silver production on a highly significant level. However, precipitation is statistically of less significance than either annual or low flow stream runoff when correlated with silver production. Figure 41 and Table 52 present data showing the relationship between annual precipitation for the entire state of Washington from 1933 through 1952. The annual precipitation figures are derived from about 220 gauging stations distributed throughout the state. The correlation coefficient of 0.6618 with 18 degrees of freedom is greater than the 0.561 required for 99 per-cent confidence. However, it is considerably less than the 0.912 value obtained for annual runoff or even the 0.756 obtained for lowest flow month (Table 40). Its general relationship to other correlations obtained in this thesis is indicated on the right hand

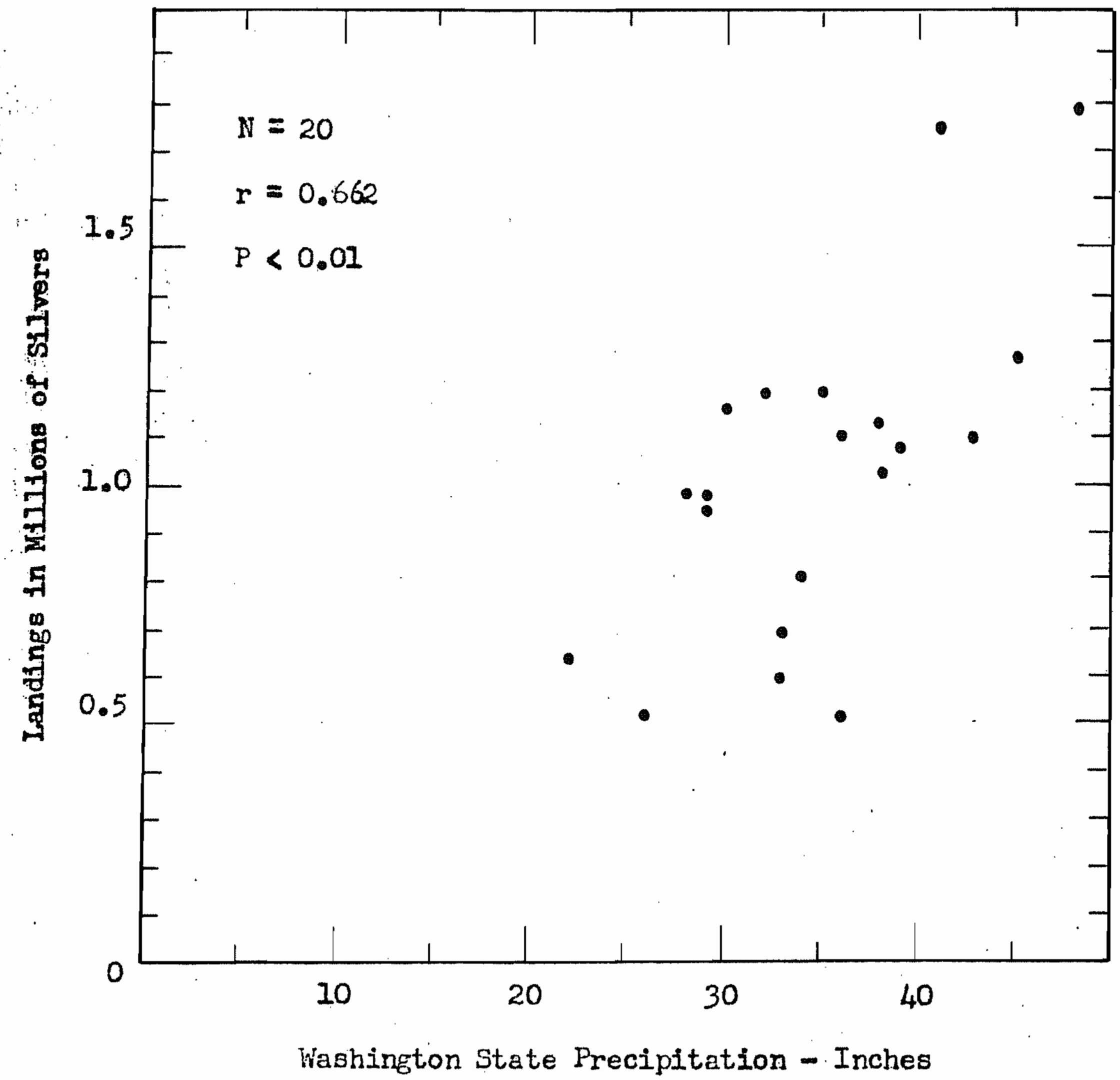


Figure 41. Correlation of Annual Western Washington Silver Landings With Washington State Annual Precipitation

margin of Figure 23.

The weather bureau, for many years, published a summary of annual runoff for the western division of Washington but discontinued the practise after 1947. However, the data available for the years 1933 through 1947 are correlated with the corresponding silver catches in Figure 42 and Table 52. The correlation coefficient of 0.7378 for 13 degrees of freedom is significant at the 99 percent level. ($r_{.99}$ at 13 d.f. = 0.641)
For almost the same period of time Smoker (1953) published an annual runoff correlation coefficient of 0.889. These are comparable figures in the the water data used in both correlations are limited to areas west of the Cascade mountains and to a similar time period, although the study by Smoker in 1953 included the water year 1948. The western division rainfall summary included about 130 stations.

A third annual precipitation summary published by the Weather Bureau for Washington that might apply to this study concerns the data from the single gauging station in Seattle, Washington (Figure 43). This might be accepted as sort of an index station for Western Washington precipitation fluctuations on a yearly basis. The data listed in Table 52 shows that the Seattle precipitation is considerably less than that of the western division of Washington. The former has an average of about 34 inches per year and the latter about 62 inches. It is also interesting that the Seattle precipitation has about the same annual average as the whole state of Washington. Figure 43 shows a correlation coefficient between Seattle precipitation and

Western Washington silver salmon landings of 0.7026 which is acceptable on the 99 percent confidence level. Figure 44 and Table 53 show a high significance between Western Washington streamflow and annual precipitation as measured at Seattle. It reveals, however, the considerable scattering of points which probably explains the scatter in Figure 43 and restricts the application of precipitation as an index of silver abundance to qualitative levels of use.

D. Steelhead seaward migrant production at Minter Creek related to rearing-period streamflows.

The question naturally arises as to whether or not species other than silver salmon are limited by streamflow during their residence in fresh water. Data on steelhead trout, Salmo gairdneri, from the Minter Creek station presented in Table 54 and Figures 45 and 46 show a significant correlation between stream water abundance during the two years of juvenile residence and downstream migrant production. For sixteen years of available data (+DF), a correlation coefficient of ~~0.6324~~ 0.577 is obtained which is significant at the ~~99~~ 95 percent level of confidence. For $P_{95}$ r = 0.497 and for $P_{99}$ r = 0.623. Figure 46 shows that there is considerable variation in steelhead production for the periods of higher runoff. No explanation can be offered at the present for this dispersion. It may be due to unknown factors associated with the relationship of steelhead to higher stream discharges or it may be due to some inherent weakness in the flow data. For example, by using the Western Washington runoff figures for two years, the effects of unknown disagreements with Minter Creek runoff may be increased.

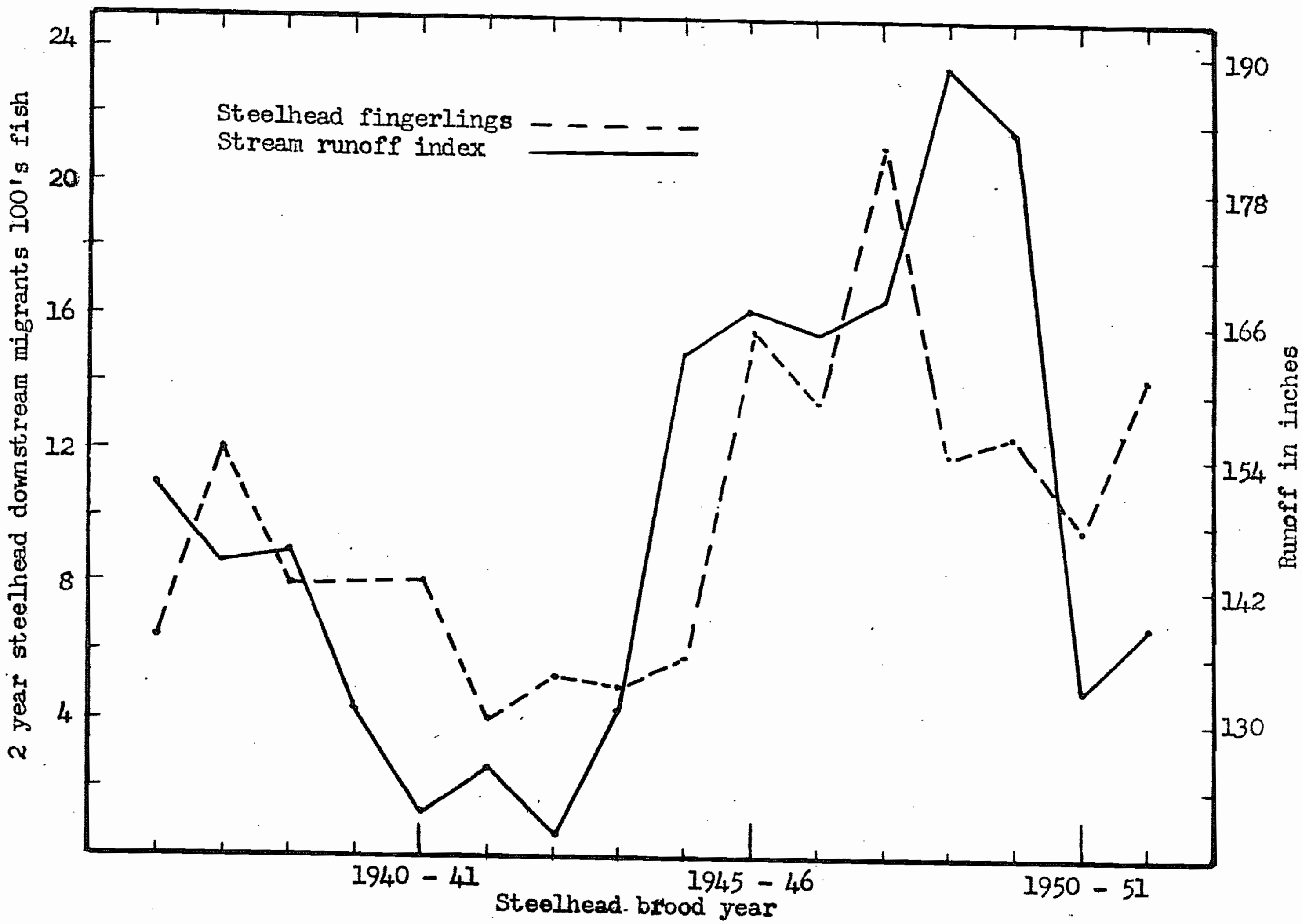


Figure 45. Comparison of downstream steelhead counts at Minter Creek with Western Washington runoff during the two years residence of the juveniles.

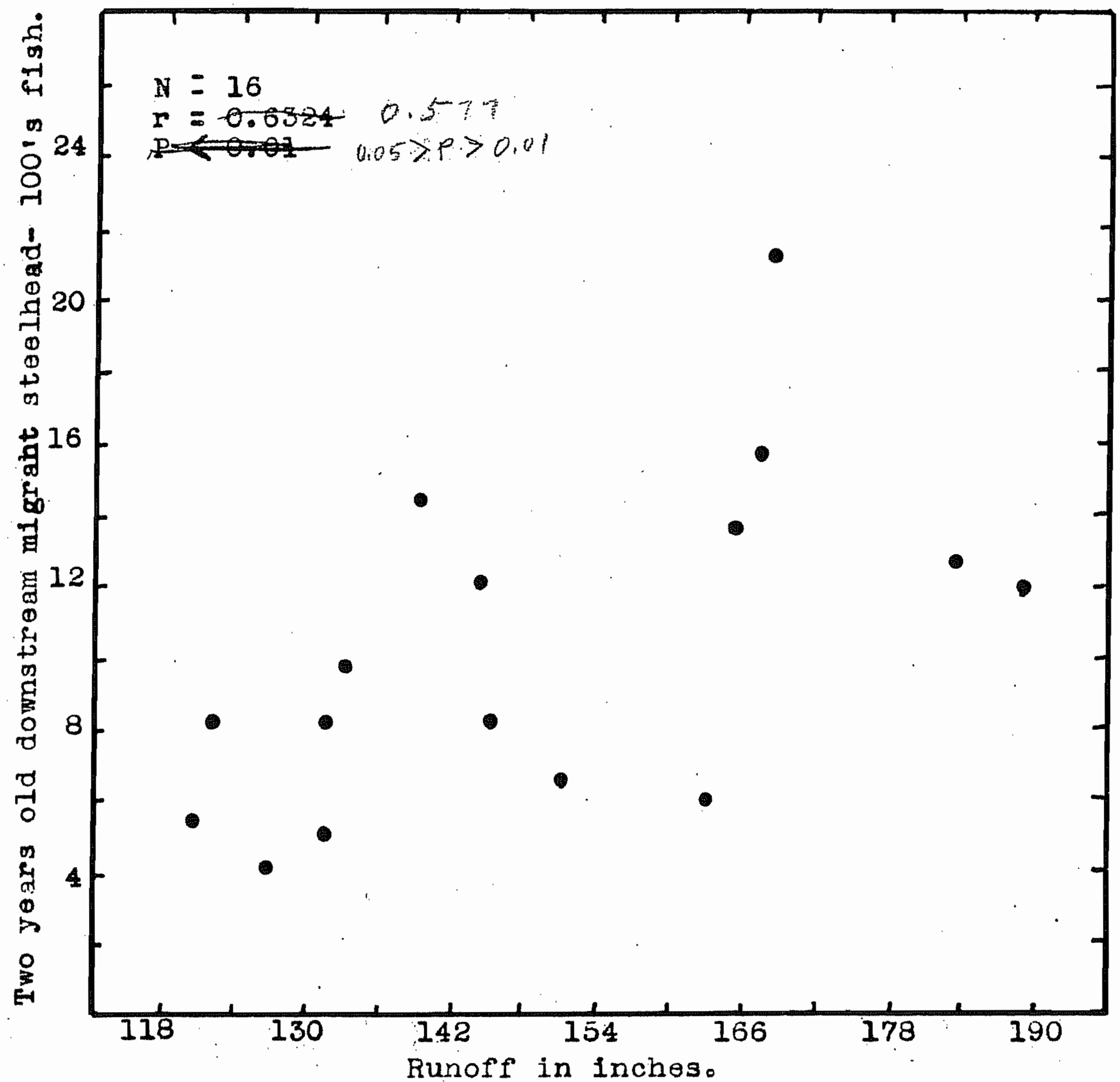


Figure 46. Correlation of downstream steelhead counts at Minter Creek with western Washington runoff during the two years stream residence of the juveniles.

It is apparent that the relatively low counts of downstream migrant steelhead for the 1948 and 1949 brood years (Figure 45) are not associated with the escapement of relatively small numbers of adults for spawning. Table 54 shows that the spawning escapement for both the 1945 and 1947 brood years were less than for 1948 and 1949 and yet more downstream migrants were produced in the former years and under less favorable water conditions. The low production from the 1944 brood, however, may have been due to a small escapement of adult spawners since only 76 adults were put upstream.

The above Minter Creek steelhead data can only be used as general evidence supporting the thesis that stream water during juvenile residence of salmonoids with a long stream-rearing period plays a major part in their survival. Unfortunately, the lack of a detailed history of Minter Creek streamflows precludes the measurement of the significance of the lowest-month flows, or of the first-year flow compared to the second-year flow, etc.

## VIII. APPLICATIONS TO MANAGEMENT.

A tempting but risky aspect of the silver-streamflow relationship is the possibility of forecasting the abundance of silver salmon stocks two years in advance or as soon as the streamflow pattern during juvenile residence is known. Or, since this often takes as much as a year to compile, the immediately available figures of annual precipitation will serve as a rough index and it can be stated with some confidence that the abundance of stocks will be average, or less than average, or above average. After this relationship was derived in 1947 eight silver harvests occurred which were privately forecast each time a year in advance. Actual landings coincided closely with predicted values. The last four years of landings 1951, 1952, 1953, and 1954 (Figure 15) were watched with particular concern since, in quick succession, the annual runoff two years before the catches, had passed from a little better than average, to very high, back to average, and finally to very low. For each year in turn the commercial landings fell close to expectations thus providing an excellent test of the thesis at all levels of streamflow.

However, the use of the index for forecasting abundance should be applied with caution and only as a basis for management. It should not be released to the fishing fleet yet as a firm basis for their activities. The chance of error is sufficient so that considerable deviations from the anticipated can be expected with some frequency and such errors would be detrimental to the welfare of the fishery. The 1934 and 1940 water years caused negative deviations far in excess of expectations.

The dry water year of 1952 and the subsequent results provide a good illustration of intelligent use of this thesis with the Puget Sound silver stocks. The Washington Fisheries Department was alerted by early 1953 that the 1954 silver stocks would probably be very low and that the fishery should be watched carefully and curtailed if it became apparent that spawning escapements were in jeopardy from overfishing. The industry was notified informally of the possibilities. The troll fishery in June, 1954 started briskly but soon fell off and by mid-summer when the fish started to appear in the inside gill net fisheries it became apparent that the stocks were quite low. As a result of the previous explanation a complete closure of inside fisheries in the Puget Sound was made in early October. At that time most of the returning adult silvers were moving to their respective river mouths. Thus a good escapement of silvers was permitted as indicated by the spawning ground surveys in the late fall of 1954.

It is of interest that due to a concurrent heavy chum run in the inside fisheries of Willapa Harbor and Grays Harbor a compromise was made with those fishermen and a complete closure did not occur until late November when a majority of the silver movement was past. As a result the silver spawning ground counts in that area were the lowest of a four year record.

The most valuable use of the streamflow-silver production relationship has been in stream management. It is positive evidence that when stream waters are reduced by irrigation diversions or watershed denudations or made unavailable to the fish by dams, salmon production is sacrificed. This in turn has illustrated the need for curtailing such watershed practices where they affect adversely Washington salmon streams. It is the basis for future plans by the Department of Fisheries to build dams in headwaters of selected silver streams for the purpose of storing spring runoff and increasing the flows during the lowest month.

# IX. SUMMARY

Little information has been available relating streamflow during fresh-water residence and the production of salmon. Previous studies on silver salmon were concerned with specific streams whereby low-water flows during the stream residence of the juveniles were related to production of silvers.

Analyses of separate streamflow measurements and silver catches from eight Western Washington streams demonstrate that river or river-mouth catches generally cannot be used as a relative measure of silver production by the streams concerned.

The total landings of silver salmon in Western Washington ports from 1935 through 1954 were combined under the assumption that they were related to their general abundance as downstream migrants.

An index for the monthly streamflow in Western Washington was obtained by computing the monthly over-all average runoff for 23 major rivers. The silver landings were related to various streamflow factors based upon the streamflow index. For the water years 1933 through 1952 annual, summer, monthly, and lowest-month flows were correlated with total commercial silver landings. Very high correlation coefficients were obtained for all but some of the winter and spring months.

None of the streamflow factors approached the annual runoff in degree of significance. After considerable study it was determined that the high correlations of summer flow and low-month flow were obtained merely because they were good indices of annual runoff.

A linear regression formula was derived: $\hat{Y} = -66.4356 + 2.204X$, where $\hat{Y}$ is the total annual silver landings in 10,000's of fish for the Western Washington areas of Puget Sound, Grays Harbor, and Willapa Harbor. For the streamflow variable, X is the Western Washington annual runoff in inches during the stream residence of the silver salmon as juveniles. The average annual catch of silvers for the twenty-year period was 1,019,500 fish, while the average annual runoff was 76.40 inches.

The correlation coefficient for annual runoff and silver salmon landings is 0.912, which is considerably in excess of the 0.561 required for 99 percent confidence. The standard error of estimate was found to be ± 143,170 fish.

At the Minter Creek Research Station data have been compiled which demonstrate the interaction of annual runoff and parent egg deposition on the production of silver seaward migrants. Steelhead trout downstream migrant production was significantly related to the total streamflow during their residence in Minter Creek. Also from Minter Creek there is evidence that excessive streamflows during the incubation period do not effect the production of silver salmon which have a long fresh-water residence but do have a limiting effect on chum salmon which spend only a short time in the stream.

Various annual rainfall data for Washington, Western Washington, and Seattle are also correlated significantly with silver salmon landings.

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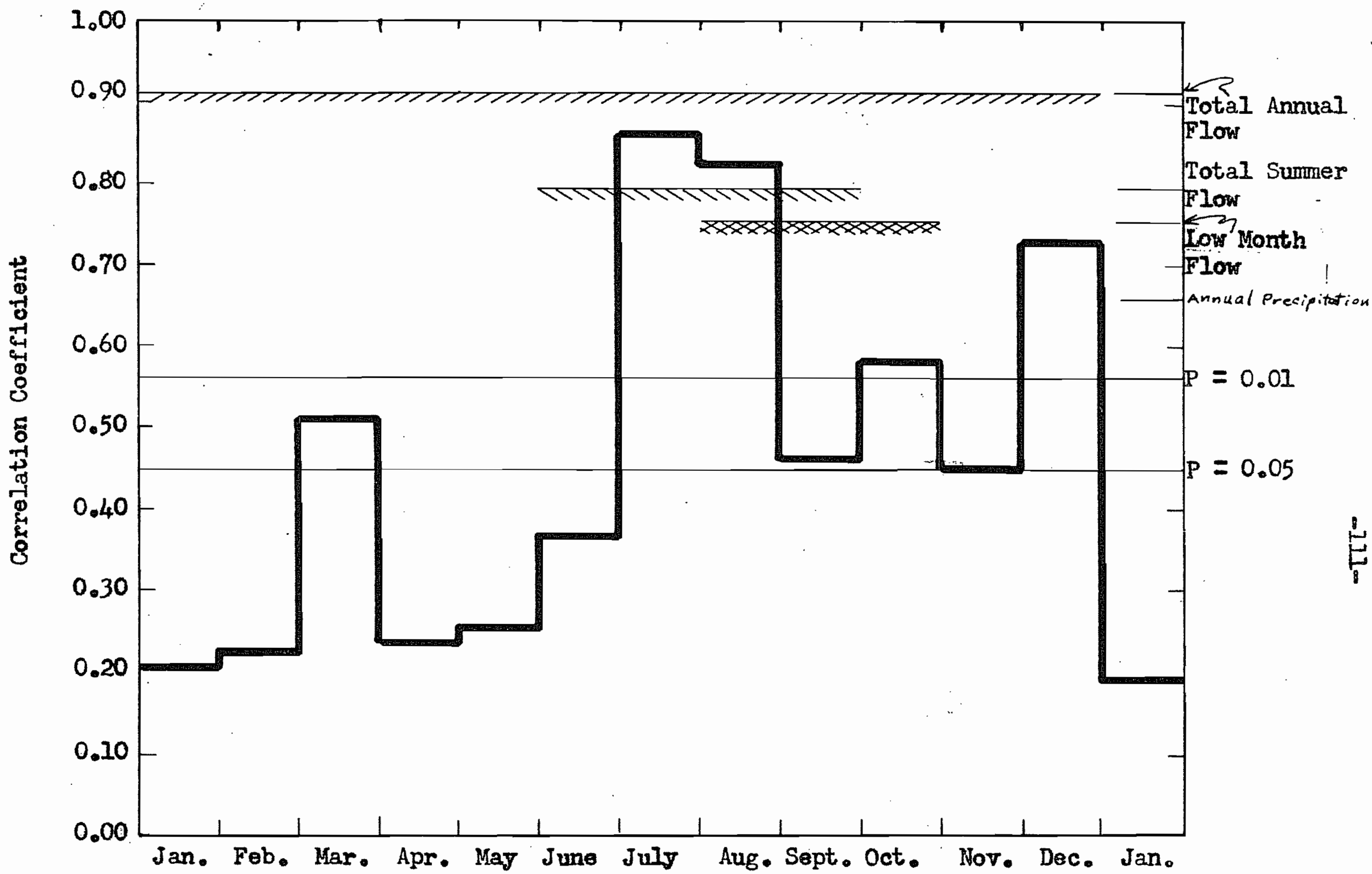


Figure 23. Monthly Flow Correlations for Silver Landings 1935-1954 in Western Washington

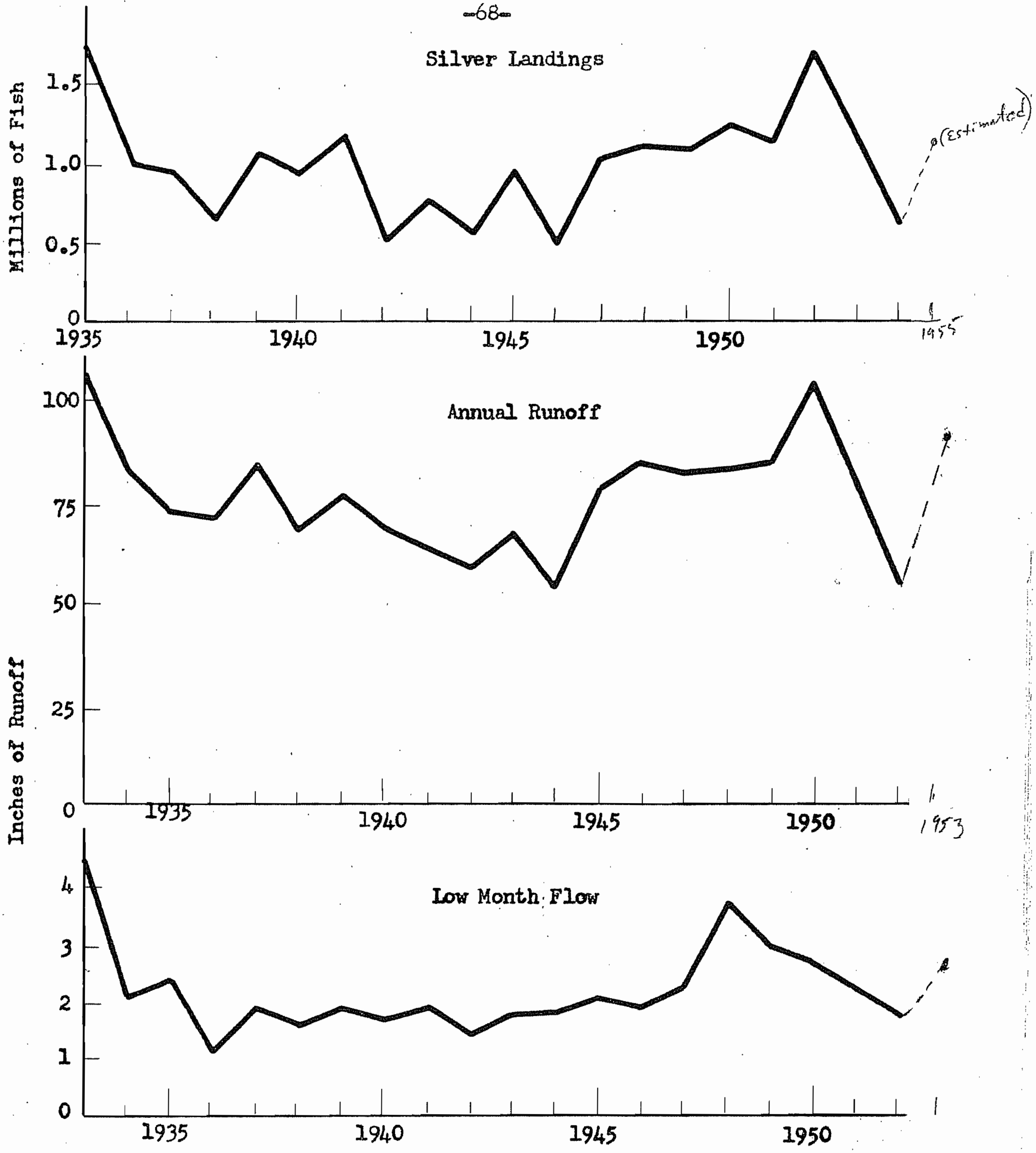


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

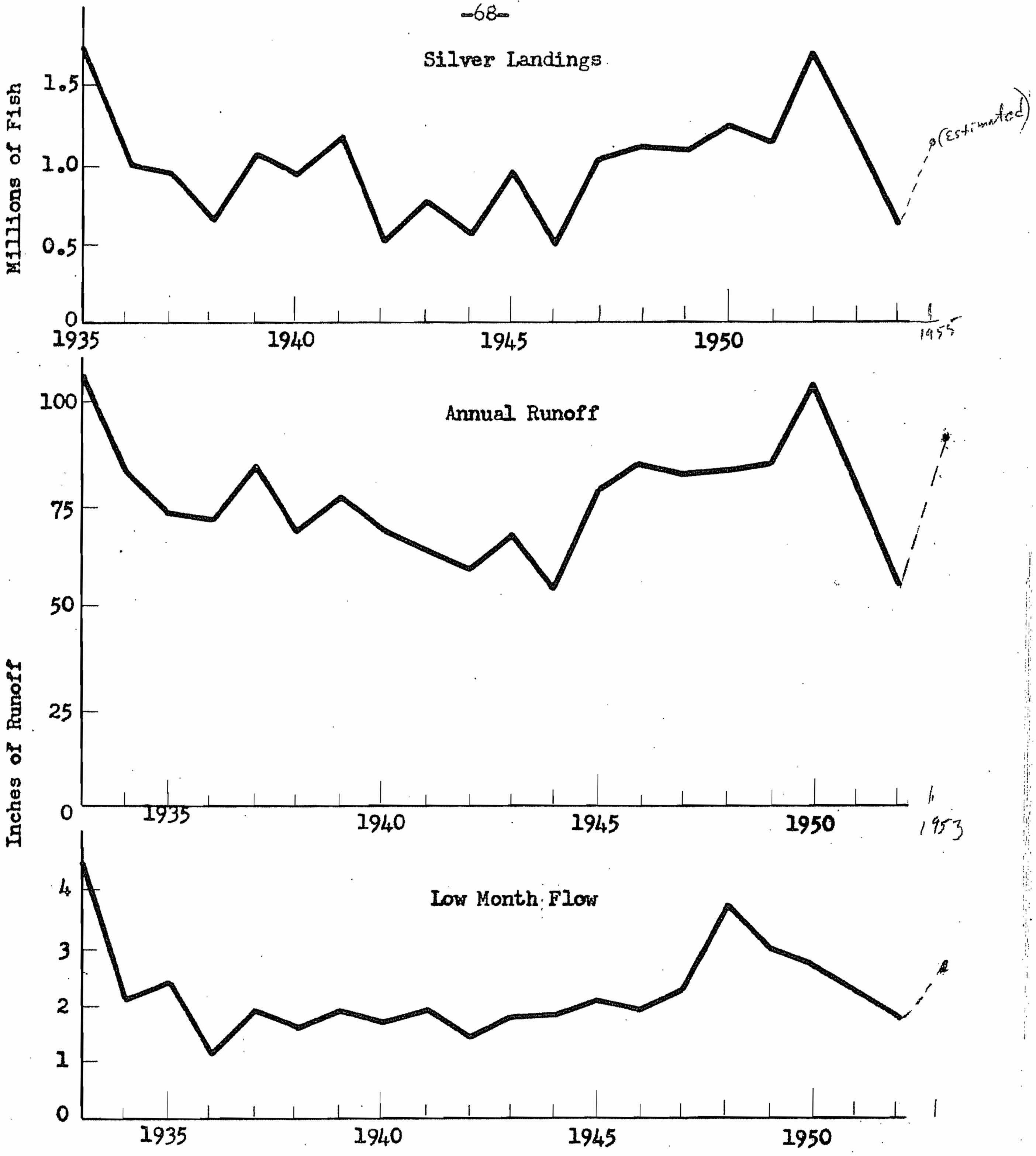


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

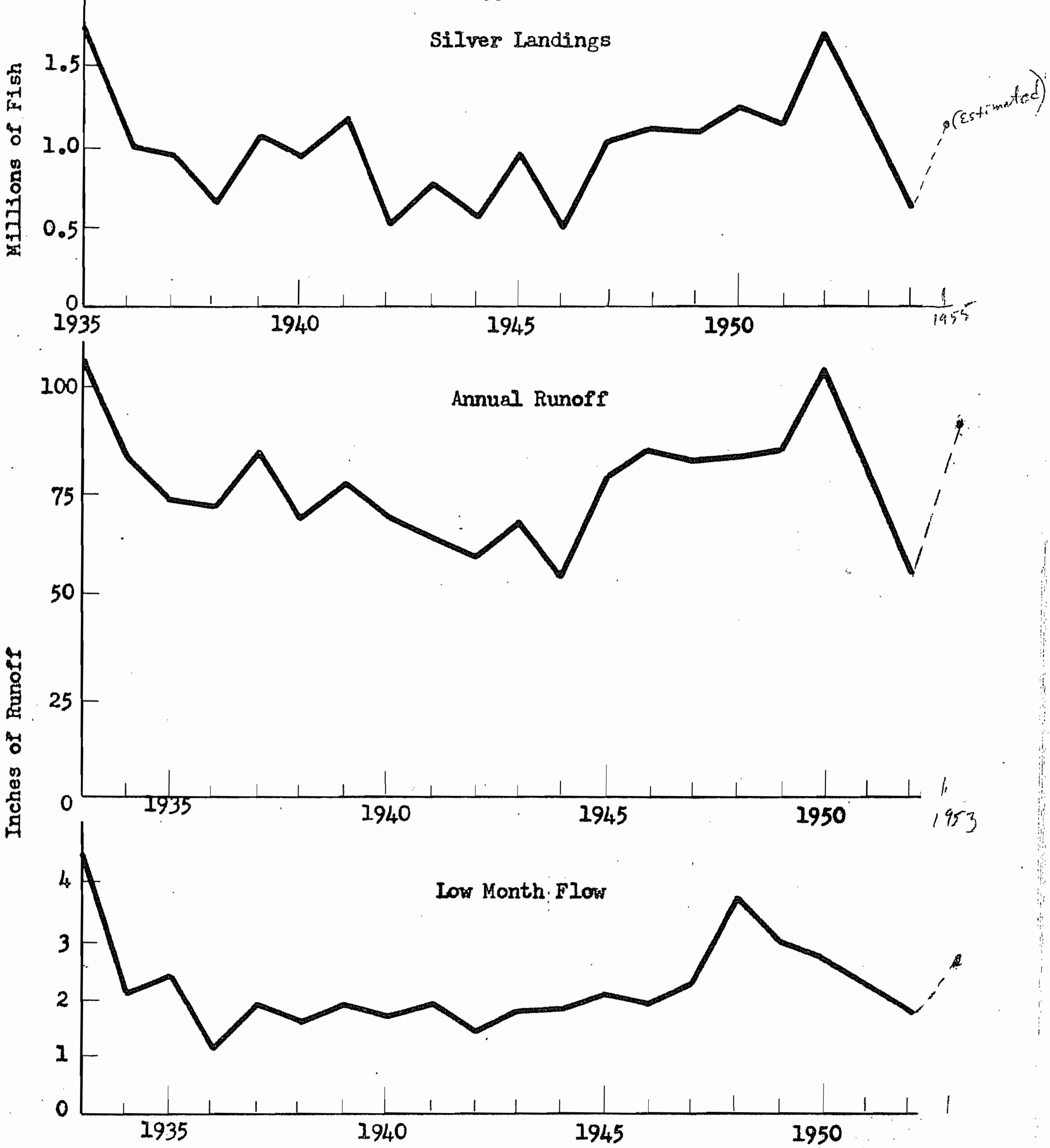


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

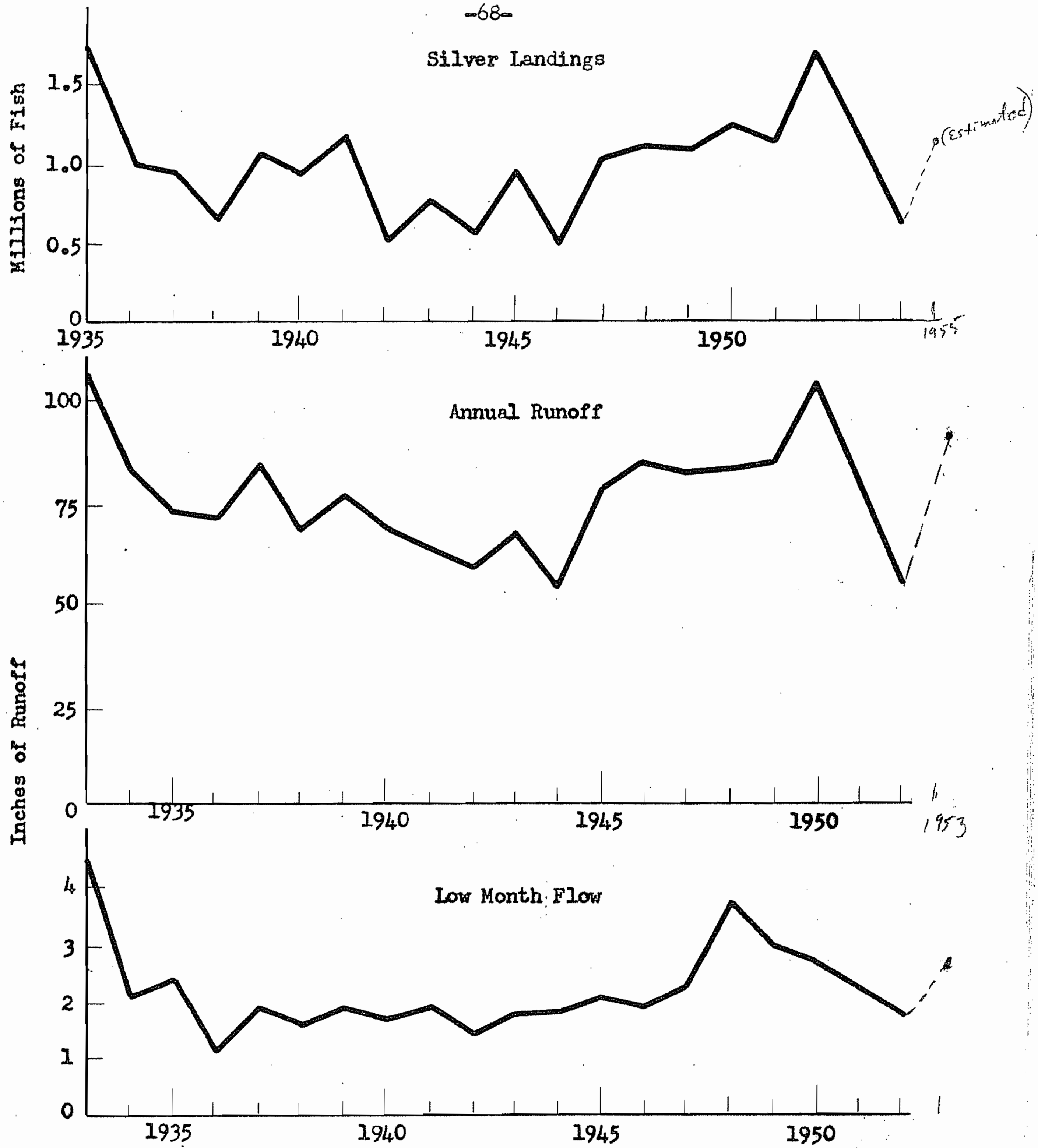


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.

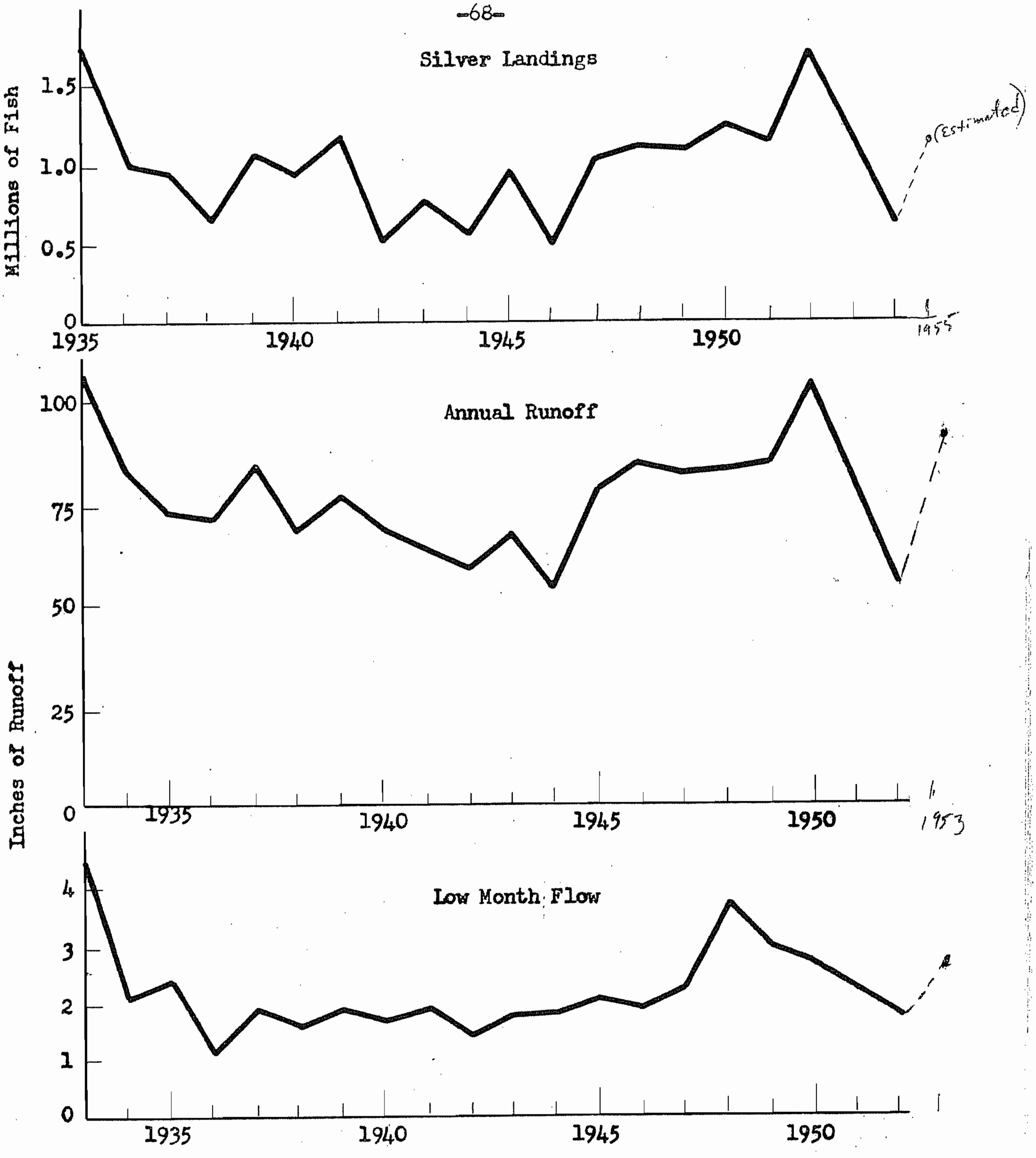


Figure 15. Comparison of Fluctuations in Annual Silver Landings With Annual Runoff and Low Month Flows.