PASSAGE OF SHAD AT THE BONNEVILLE FISHWAYS

SPECIAL SCIENTIFIC REPORT: FISHERIES No. 94

UNITED STATES DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

Explanatory Note

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Washington, D. C.
March 1953

United States Department of the Interior, Douglas McKay, Secretary
Fish and Wildlife Service, Albert M. Day, Director

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In the last 50 years the catch of shad (Alosa sapidissima) on the Atlantic coast has dwindled to less than a fifth of its former size. Because of concern about the shad fishery, the Atlantic States Marine Fisheries Commission sponsored legislation that provided for a 6-year study of this valuable natural resource. The Fish and Wildlife Service, as the primary research agency of the Commission, began this study in 1950.

An evident factor in the decline of the shad was the erection of dams that prevented the fish from ascending streams to reach their natural spawning grounds. Although many of these dams had fish ladders intended to pass fish upstream, the shad generally did not use the ladders. Consequently, a part of the investigation of the Atlantic-coast shad has been a search for suitable methods of passing shad over obstructions. At the beginning of the study the only fishways we knew of that were utilized by shad were those at Bonneville Dam on the Columbia River in the Pacific Northwest, and a special study was made of the passage of shad by those fishways. This paper is a report of that study.

In the study, William H. Rees (now with the State of Washington Department of Fisheries) made the observations at Bonneville Dam and compiled and analyzed part of the data; C. J. Burner and K. G. Weber made many helpful suggestions during the progress of the study; R. A. Fredin and C. H. Walburg helped prepare the statistical analyses; C. E. Atkinson helped plan and carry out the study; and Harlan B. Holmes gave special help in obtaining unpublished records, supplied much of the factual information, and suggested methods of analyzing the data. I am indebted to Ivan Donaldson, resident biologist at Bonneville Dam, for his help and suggestions, and to the Corps of Engineers for the use of unpublished records and for the map and photographs.

Description of Bonneville Fish Ladders

Bonneville Dam is on the Columbia River 140 miles from the ocean. At this site (fig. 1) the river is divided into two channels by Bradford Island. The spillway dam is in the north channel, and the powerhouse, which also functions as a dam, is in the south channel. The normal pool level above the dam is at elevation 72 (feet above mean sea level), but during the flood season in spring and summer (the time of shad migration) the level may reach elevation 82.5. During the first 5 years of operation, the pool was never raised above the normal 72-foot level. Tailwater below the dam fluctuates from around elevation 8 to as high as elevation 53 during flood stages. The level at the time of peak shad migration, usually varies between elevations 15 and 30. The total head on the dam, that is, the height to which shad must climb in the fishways, ranges from 40 to 60 feet, but most commonly is about 50 feet.

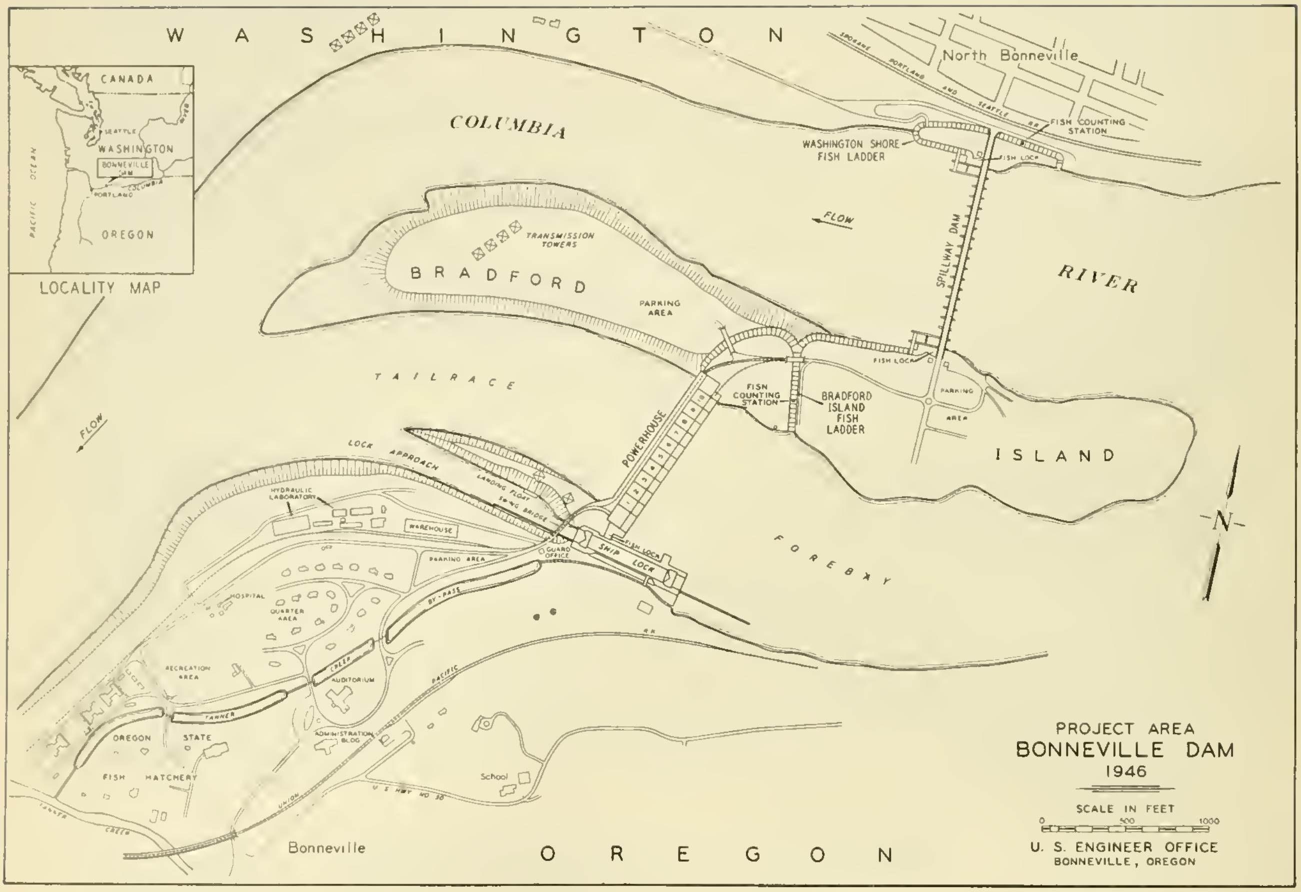

Fig. 1.--Site map of Bonneville Dam and fish-passing facilities. (Courtesy of Corps of Engineers)

Fish-passing facilities include the Washington Shore fish ladder at the north end of the spillway dam and the Bradford Island fish ladder with entrances on the south end of the spillway dam and on the north end of the powerhouse. Fish locks are located at each end of the spillway dam and on the south end of the powerhouse; these have not been used extensively, but are available in case of emergencies.

The Washington Shore ladder is 37 feet wide, and the Bradford Island ladder is 40 feet wide. Both ladders narrow to 30 feet in the lower sections where they are usually flooded by tailwater. Each ladder circles around the end of the dam from the lower to the higher water level. At 16-foot intervals there are cross partitions 6 feet in height (fig. 2). The top of each successive cross partition, or weir, is 1 foot higher than the one next below. These weirs continue up the ladder to the elevation level of 70 feet. Above this point the ladders are like a level-floored flume. At 16-foot intervals along this upper section there are guides in which stop logs can be added to form weirs. In this way additional pools can be added to extend the steps up to the high forebay level of 82.5 feet.

Water flows down the ladder, spilling over each successive weir, and forms a series of pools, each one a foot lower than the one above (fig. 3). In each weir between pools there is at the bottom a submerged opening (fig. 2) 2 feet square, through which fish may pass without coming to the surface. These openings alternate from near one side to near the other in successive weirs.

At both sides of the spillway dam at the lower end of the fishways are expanded entrances to the ladders which are supplied with auxiliary water through gratings in the floor. These are called collecting systems. Their purpose is to supply sufficient attraction water so that the fish can find the ladders. A collecting system extends all across the lower face of the powerhouse, and the flow within this system can be directed to orient the fish to the fish-passing facilities on either side or both sides of the powerhouse.

The 40-foot-wide ladder usually carries approximately 200 second-feet of flow from headwater. Approximately 20 second-feet of this passes through the 2-foot-square orifice in each weir; the remainder flows over the crest of the weir. This quantity of flow causes the water level in each pool to be about 12 inches higher than the crest of the weir below it. The water surface "draws down" as it passes over the weir, to give a depth of approximately 10 inches over the crest of the weir (fig. 3).

The Washington Shore collection system is designed to supply an additional 1,000 second-feet of water. A similar set of facilities at the south end of the spillway is designed to supply the spillway branch of the Bradford ladder with 1,000 second-feet. Two auxiliary water intakes which supply the powerhouse collection system have a combined capacity of 2,400

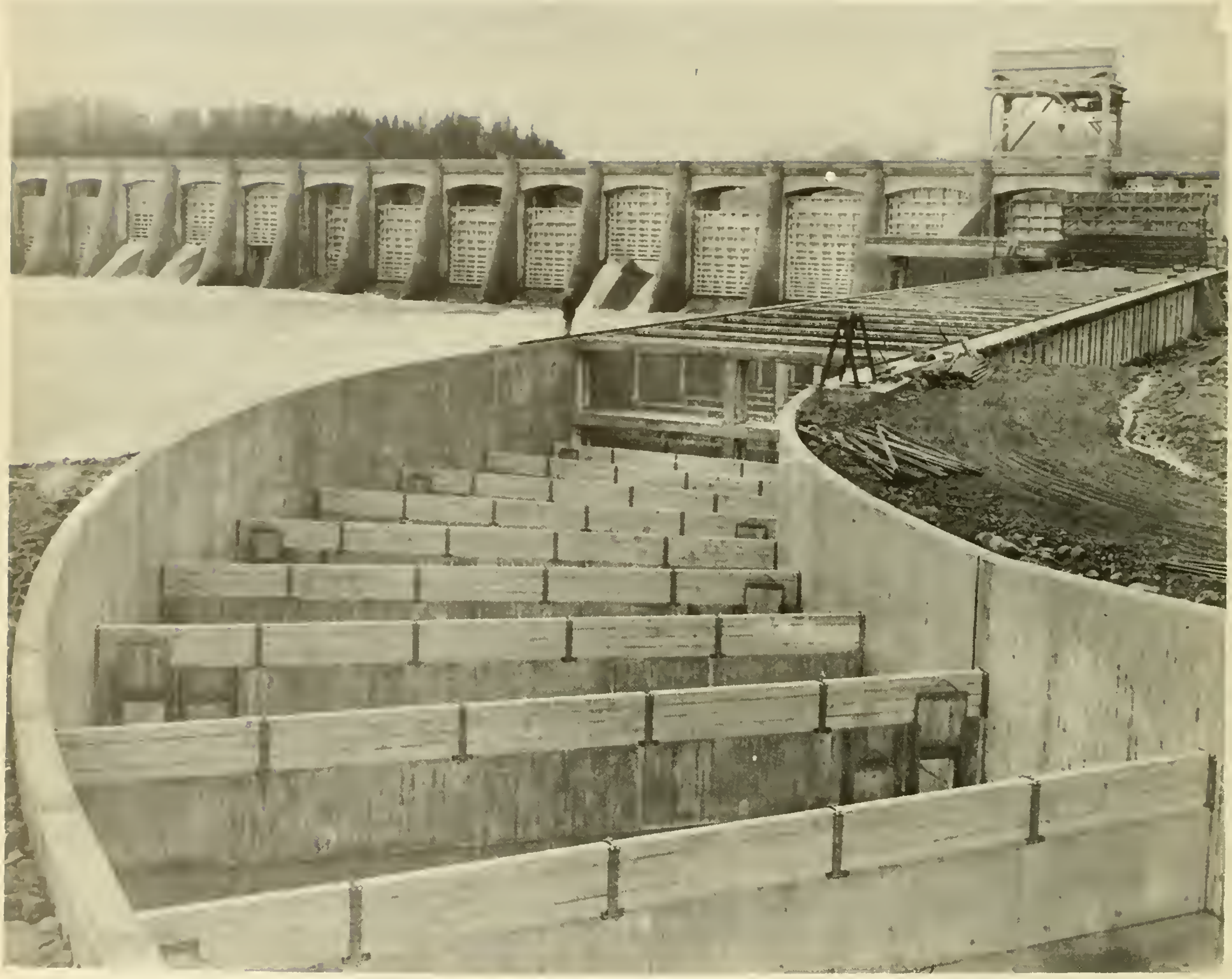

Fig. 2.--Lower end of the spillway branch of the Bradford Island fish ladder.
(Photo by Corps of Engineers)

Fig. 3.--Upper section of Bradford Island fish ladder just below counting station. (Photo by Corps of Engineers)

second-feet. Picket barriers across one spillway gate adjacent to each of the fishway entrances on the spillway dam also furnish attraction water for the fishways. Each of these supplies approximately 3,000 second-feet of water.

Counting stations are located near the upper end of each ladder so that the number of fish ascending may be counted (fig. 4). At each station there is a picketed barrier in which is a 2-foot-wide opening through which the fish can pass. A submerged white board is located under the opening as an aid in identification of species. Before 1950, both counting stations were at weir elevation 70. Early in 1950 the Washington Shore counting station was moved to the head of the ladder, where it is at headwater level and where the fish, after being counted, pass directly into the forebay. In 1951 the Bradford Island counting station was also moved to the head of the ladder.

In the design of the ladders no provision was made for the counting stations. Their installation at weir 70 caused complications in adjustment of the ladder. As there is no significant drop in water level at the counting barrier, one weir, and hence 1 foot of elevation was lost. To provide a large pool immediately below the counting station, a weir was omitted there. Similarly to create a large pool above the counting station a third weir was omitted. After 1942, when the pool level was allowed to rise above elevation 72, adjustments were made to compensate for the loss of 1 foot (of a total of 3) of ladder elevation by adding 4 inches to the rise at the three weirs immediately below the counting station. At normal forebay levels no additional weirs were needed, but at the highest forebay level the 2 feet lost through the elimination of weirs 70 and 71 had to be regained by increasing the height of the weirs between the counting station and the upper end of the fishway.

The shad is considered a relatively unimportant species on the Columbia River; the fishways were constructed and are operated mainly for the passage of the more valuable salmonoid fishes whose spawning grounds are above the dam. A record is kept, however, of the miscellaneous species using the fishways, and counts of shad passing up the ladders have been made each year since 1938 when the fish-passing devices were completed. As shown in table 1, the number of shad using all fish-passing facilities at Bonneville Dam each year has varied considerably, from 2,848 in 1943 to 94,526 in 1945 (U. S. Army, Corps of Engineers, 1950). Shad have been counted at Bonneville as early as May 13 and as late as October 30, but the bulk of the run usually passes the dam during the month of July. The one exception is the year 1940 when a larger percentage was taken in June than in July.

Fig. 4.--Counting station on Bradford Island fish ladder.
(Photo by Corps of Engineers)

Bonneville Dam is 140 miles above the mouth of the river and much of the stream below the dam is available and suitable for shad spawning purposes. In the natural river before Bonneville Dam was built there was a drop of approximately 26 feet in water surface in the 4-mile stretch between Bonneville and the head of Cascade Rapids. It is not known how many shad migrated past this point before 1938, but for practical purposes this may have been the upper limit of spawning. The incentive for surmounting the dam, therefore, may not be so great for shad as it is for the runs of salmon whose spawning grounds are many miles upstream. Some of the shad that pass the dam are known to ascend at present at least to Celilo Falls which is about 60 miles above the dam (Oregon Fish Commission, 1948).

Table 1.- Annual shad count at Bonneville Dam

Year	Count	Year	Count
1938	5,273	1945	94,526
1939	4,803	1946	20,383
1940	22,230	1947	26,041
1941	18,675	1948	8,422
1942	12,859	1949	22,579
1943	2,848	1950	7,816
1944	17,103		

Time of Passage Compared with Flow and Temperature

Since variation exists both in the numbers of shad passing the dam each year and in the time of passing, an examination was made of the water temperature and water flow to determine their relations to number and passage time. A graph for each year was made showing the count of shad by days, the corresponding water temperature, and the combined rate of flow (c.f.s.) for the powerhouse and spillway. The graphs for 1940, 1946, and 1950 are shown in figures 5, 6, and 7 and depict runs that are early, average, and late, respectively.

From a study of figures 5, 6, and 7 and the graphs for the other years, it appeared that the later the peak flow was reached at the dam, the later the fish began to appear in numbers in the fishways. The shad, as measured by the counts, appeared to be early when the river flow dropped early and when the water temperature warmed early. When the water flow was high and temperature low the runs tended to be later in passing through the fishways.

To test this hypothesis, table 2 was prepared, showing for each year the date when the water flow dropped below and stayed below 325,000 c.f.s. (arbitrarily selected), the date the water temperature raised to and stayed above 60° F. (also arbitrarily selected), and the time of run as indicated by the date when half the run was counted.

Table 2. - Time of Bonneville shad passage compared with flow and temperatures (figures in parentheses give number of days after May 31).

Year	Date flow below 325,000 c.f.s.		Date Temp. 60° F. and above		Date half of run counted	
1938	July 17	(47)	June 24	(24)	July 24	(54)
1939	June 12	(12)	June 26	(26)	July 7	(37)
1940	June 16	(16)	June 9	(9)	June 30	(30)
1941	All season	(0)	June 5	(5)	July 5	(35)
1942	July 1	(31)	June 28	(28)	July 21	(51)
1943	July 24	(54)	June 29	(29)	July 20	(50)
1944	June 21	(21)	June 21	(21)	July 17	(47)
1945	July 4	(34)	June 18	(18)	July 13	(43)
1946	July 13	(43)	June 29	(29)	July 8	(38)
1947	July 4	(34)	June 16	(16)	July 4	(34)
1948	July 13	(43)	July 19	(49)	July 18	(48)
1949	June 22	(22)	July 13	(43)	July 11	(41)
1950	July 28	(58)	July 7	(37)	July 21	(51)

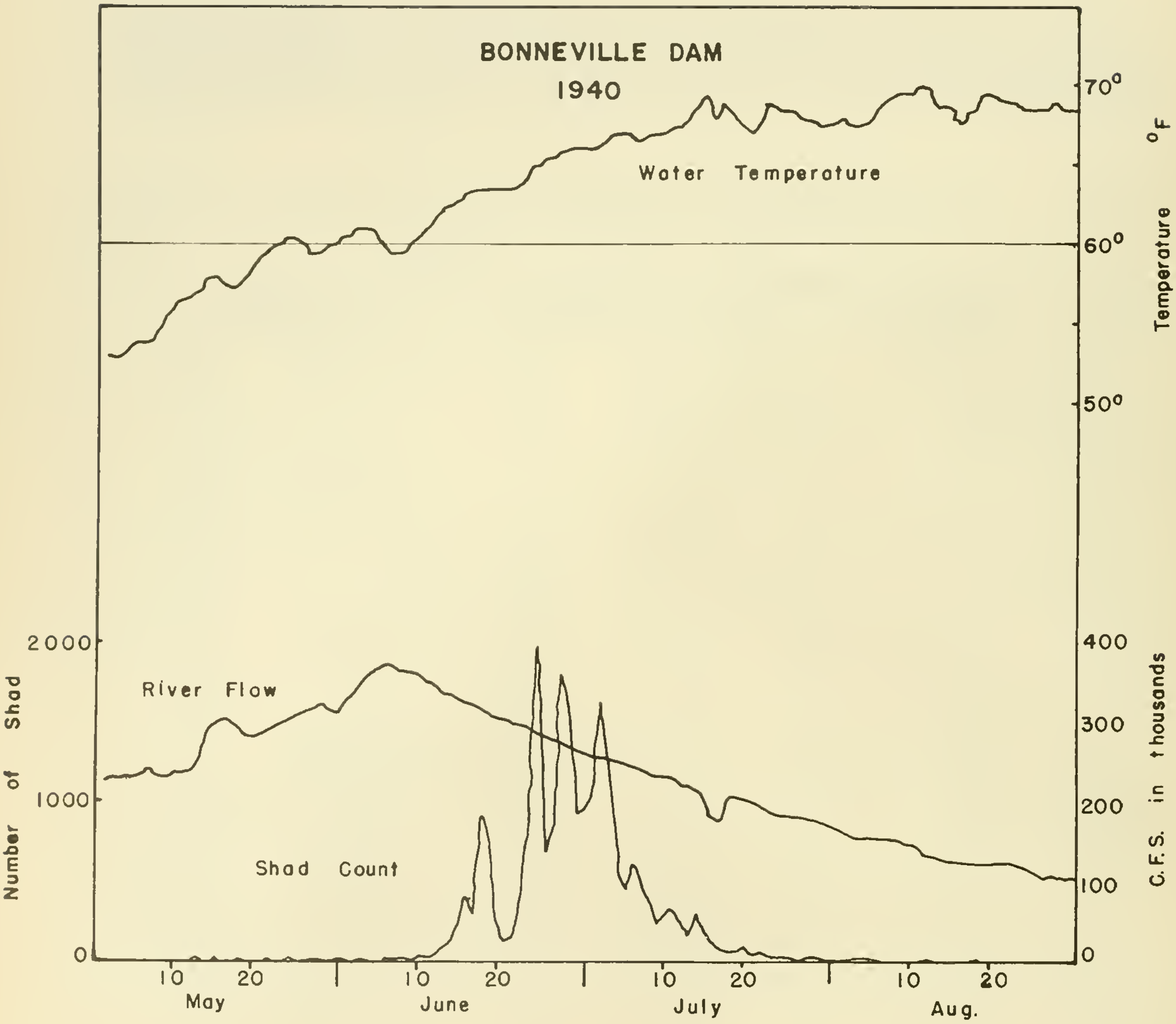

Fig. 5 - Comparison of water temperature, river flow and daily shad count through fishways at Bonneville Dam, 1940

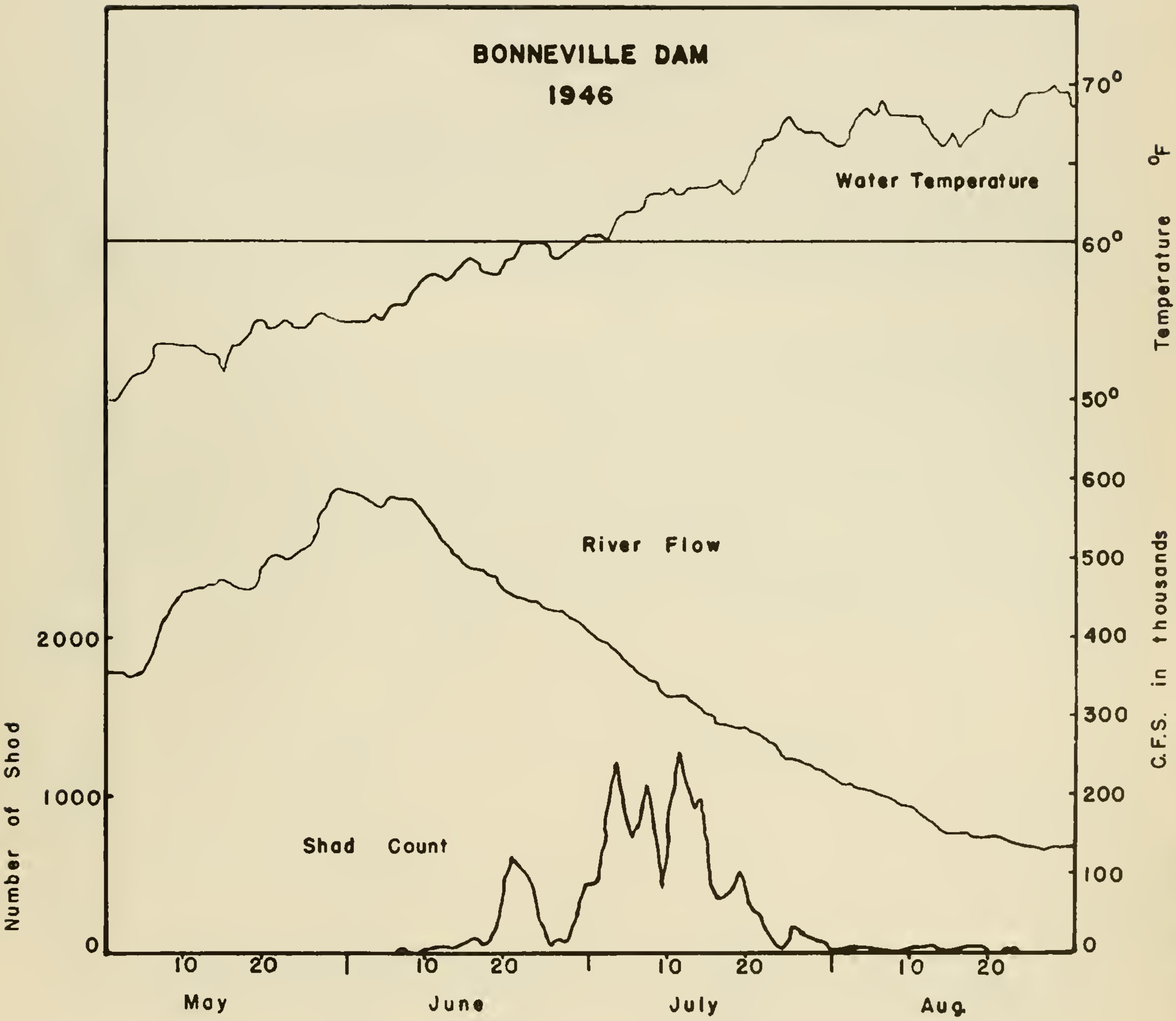

Fig. 6 - Comparison of water temperature, river flow, and daily shad count through fishways at Bonneville Dam, 1946

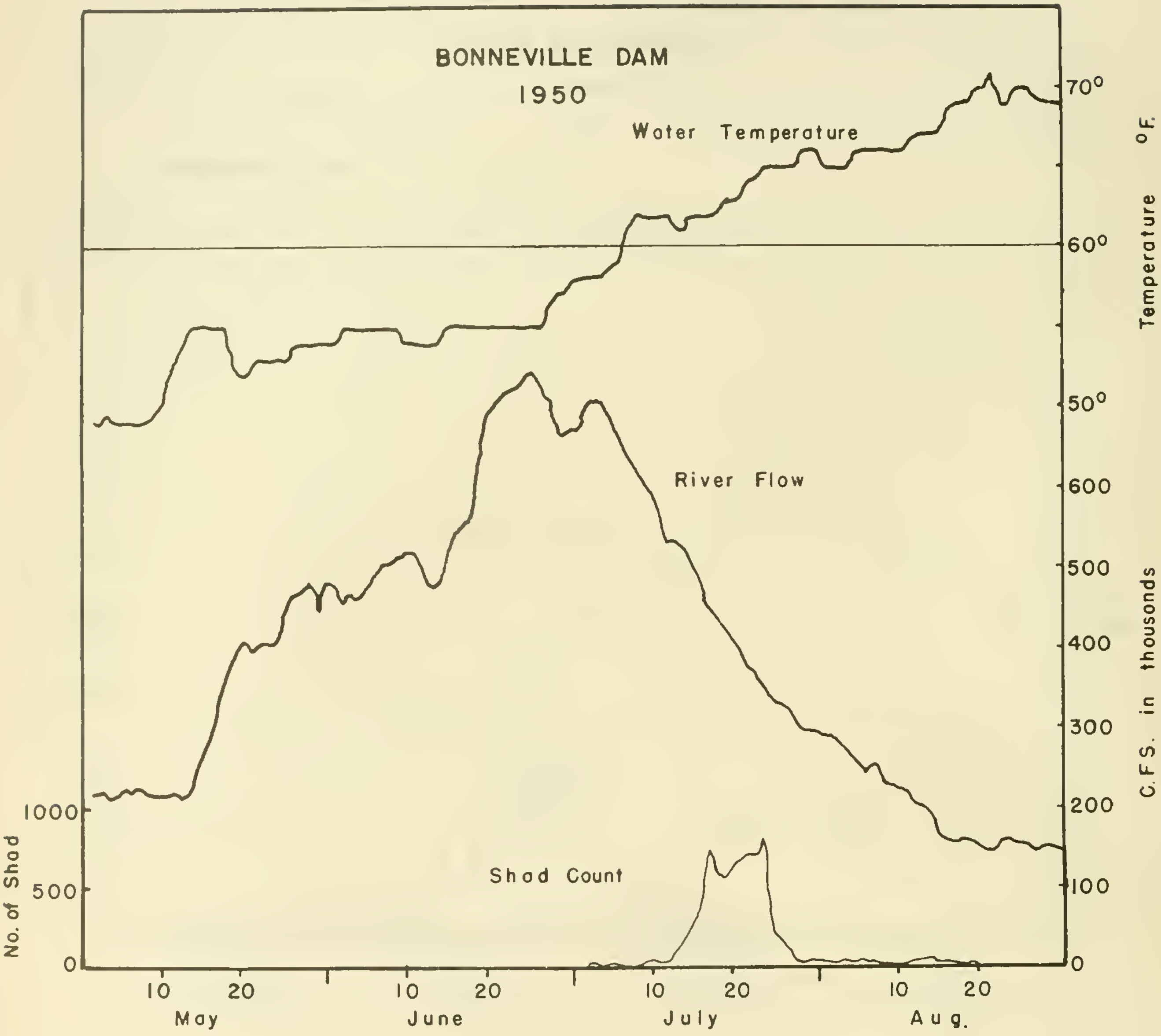

Fig. 7.--Comparison of water temperature, river flow, and daily shad count through fishways at Bonneville Dam, 1950

The effects of river flow and temperature upon the time of run were evaluated by a multiple-regression analysis using the figures shown in parentheses in table 2. The following subscripts were used in expressing the results: R = time of run, F = time of low river flow, and T = time of high temperature. A value of $R_{R.TF} = 0.70$ was obtained, which is significant at the 5-percent level. A value of $R^2 = 0.49$ was obtained, showing that approximately half of the variation in time of arrival of run at Bonneville can be attributed to the variation in flow and temperature (Snedecor, 1946).

A linear-regression analysis showed that there was a significant correlation at the 5-percent level between flow and time of run, ($r_{RF} = 0.666$). The correlation coefficient for temperature and time was not quite significant at the 5-percent level ($r_{R.T} = 0.54$). Similarly, the correlation coefficient for flow and temperature was not quite significant at the 5-percent level ($r_{FT} = 0.545$). A value of 0.553 for both of these correlations is necessary for significance at the 5-percent level (Snedecor, 1946).

It was desired to know whether the factors influencing the time of run at Bonneville also affected the time the shad were in the river below Bonneville. Statistics of the monthly landings for each year from 1938 through 1949 were available from the Oregon Fish Commission (1950). Preliminary figures for 1950 were obtained from the Oregon Fish Commission and the Washington Department of Fisheries. Catches of shad in the Columbia River were recorded as early as February, but the first month that they were caught in numbers was May. The percentage of shad caught up to and through the month of May each year was calculated, and this was used as an index of the time the shad runs arrived in numbers in the river. The percentages are as follows:

Year	Percentage caught through May
1938	34
1939	52
1940	56
1941	41
1942	30
1943	21
1944	22
1945	19
1946	21
1947	28
1948	19
1949	21
1950	12

In correlating the above index figures of the time of run in the commercial fishery with the time of run at Bonneville it is necessary to note that the earlier the run in the commercial catch for any year the larger the figure; conversely the earlier the count at Bonneville, the smaller the figure. Thus if the two variables are positively correlated the correlation coefficient using the designated indices will be negative. Using the figures from Table 2 and the list above, a correlation of $r = -.584$ was found, which is significant at the 5-percent level.

The correlation between the size of run and the time of run each year at Bonneville was not significant, nor was a significant correlation coefficient found between size of run at Bonneville and size of commercial catch each year. Since the commercial catch of shad on the Columbia is incidental and supplemental to the salmon fishery (Oregon Fish Commission 1950), the size of catch probably does not represent the population present.

The catch of shad above Bonneville Dam, most of which is caught at Celilo Falls, 60 miles above, is directly proportional to the numbers passing Bonneville Dam. A significant correlation was obtained between the shad catch for zone 6 (which includes Celilo Falls)(Oregon Fish Commission 1950) and the Bonneville shad counts for each year from 1938 through 1949.

It can be concluded from the above correlation analyses that flow and temperature do affect the times of entry of the shad into the river and of passage through the Bonneville fishways. The river discharge appears to be the more important of the two factors.

Bradford Island Ladder Counts Compared with Washington Shore Ladder Counts

The total number of shad counted in the Washington Shore ladder for all years from 1938 through 1950 was 90,937; during the same period 167,285 were counted through the Bradford Island ladder. The Bradford ladder has entrances in both channels of the river (fig. 1). If these two entrances are considered as separate ladders and equal shares of the Bradford count are assigned to each, their counts do not differ greatly from that of the Washington Shore ladder.

In some years (1939, 1940, and 1946) more shad were counted in the Washington Shore ladder than in the Bradford ladder. No reason for this has been ascertained. Several factors may influence the counts at each ladder. When the forebay level changes, it is necessary to adjust the weir heights between the counting gate and the water level behind the dam. If the forebay level fluctuates rapidly the efficiency of the ladder may be impaired for several days. Other things, such as repairs to the ladders, rain-squalls, people visiting, and amount of sunlight and shadow, may also affect the operation of the fishways and the movements of the fish.

In March 1950 the Washington Shore counting station was moved to the upper end of the fish ladder, at forebay level. The upper six stop-log weirs were replaced with weirs having submerged openings 8 inches below the water surface as the only route of passage for water and fish. This arrangement of weirs was considered superior as a means of regulating the ladder at fluctuating forebay levels, but unfortunately proved to discourage the passage of some species of fish, including shad. In 1950, only 574 shad were counted through this fishway, as compared with 7,242 in the Bradford ladder.

Hourly Counts at Bonneville Fishways

Hourly counts of shad were studied in detail in order to understand better the periods of maximum movements of shad in the ladder during each 24-hour period. From these data the optimum periods for shad migration through the fish ladders were obtained. Thus, the best time of day or night in which to operate the ladders most effectively was determined.

It is the normal practice at Bonneville Dam to count during two 8-hour shifts a day. The normal counting day begins at 4 a.m. and ends at 8 p.m. The counters on duty start counting on the hour and continue for 50 minutes. At the end of that time a gate is lowered in the opening through which the fish swim while being counted. The counter rests for 10 minutes and promptly at the start of the next hour opens the gate and begins counting again. The fish counted are credited to the hour the count begins. On some occasions fish were counted at night, but this is not the usual practice. When fish are not being counted the gates remain closed, so that all fish ascending the ladders are enumerated.

Since counts of shad were erratic and irregular at the beginning and end of each run, the half-month period during which the run of each year was largest for each ladder was taken to show the distribution of counts throughout the day. The total number counted during this half-month period of each year for each ladder is shown in table 3.

It was observed that counts at the Bradford ladder were usually low for the early hours, reached a peak in the afternoon, and then dropped off during the last 2 or 3 hours of counting. To illustrate this graphically, the number of shad counted each counting hour for the largest half-month was totaled (total for 8 a.m., for 9 a.m., and so on) to eliminate minor daily variations. These total hourly counts were calculated as a percentage of the total of the half-month period so that each year's records were comparable regardless of the size of run. These data for Bradford ladder are superimposed in figure 8 for all 13 years. It can be seen that in general the number of shad passing through the ladder was low in the morning, gradually rose to a peak in the afternoon, and fell off during the last 2 or 3 hours in the evening. The one exception was in 1939 (shown as a broken line) when the total counts for the half-month period were greatest at 11 a.m. No reason for this variation could be found; it may have resulted from chance since the run this year was the smallest of any year for the highest half-month period at the Bradford ladder and few fish were counted each day.

In three of the years, 1939, 1941, and 1942, the counts were higher for the first hour of counting in the morning than for the second. This probably resulted either from shad moving up during the night or from shad that were already in the ladder the night before when counting ceased at 8 p.m.

In the same way, the percentage hourly counts for the Washington ladder are plotted in figure 9. The years 1943 and 1950 were omitted because the total counts were exceptionally small (table 3). The greatest irregularity is in the curve for 1944. No reason could be found for this anomaly.

The pattern of counts in the Washington ladder is not quite as uniform as that for the Bradford ladder. This probably occurs because the counts are smaller than those of the Bradford ladder. In general, the counts were low during the morning hours, reached a peak in the afternoon, and dropped off at night. In this respect they are similar to those for the Bradford ladder.

Only during 1938 and 1948 were fish counted at night at Bonneville. In those years an extra shift was added that counted fish from 8 p.m. to 4 a.m. During 1938 the counts were made from July 1 to September 15 in both ladders but on alternate hours only. In 1948 the night counts were made for each hour, but only during the first half of July and the first half of August.

Very few shad were counted in 1938 during the night shift. At the peak of the run (July 16 to 31) at the Bradford ladder a total of 618 shad were counted during the 16-hour daytime period, while only 8 shad were counted during the 4 night hours. Counts at the Washington ladder during the night were very small also. Strangely enough, the best night counts of the season were made at both ladders in the first half of September when the day counts were low. The total number of shad counted at night at the Bradford ladder was 90 (4 hours each night) while during the day the counts for the same period totaled only 193 (counting done 16 hours each day). At the Washington Shore ladder the night count for the same period totaled 41 shad, while during the two day-shifts only 26 shad were counted. No explanation for this anomaly has been found.

Table 3. - Total day counts at Bonneville fish ladders during highest half-month period

Year	Bradford Island		Washington Shore	
	Highest half-month period	Number Counted	Highest half-month period	Number Counted
1938	July 16-31	618	July 16-31	1,476
1939	June 16-30	393	July 1-15	1,729
1940	June 16-30	4,982	June 16-30	7,402
1941	July 1-15	4,586	July 1-15	5,102
1942	July 16-31	5,985	July 1-15	1,717
1943	July 16-31	2,144	July 16-31	171
1944	July 16-31	5,803	July 16-31	4,621
1945	July 1-15	44,510	July 1-15	13,423
1946	July 1-15	6,303	July 1-15	6,770
1947	July 1-15	12,030	July 1-15	6,772
1948	July 16-31	3,057	July 16-31	1,211
1949	July 1-15	8,026	July 1-15	7,433
1950	July 16-31	6,278	July 16-31	261

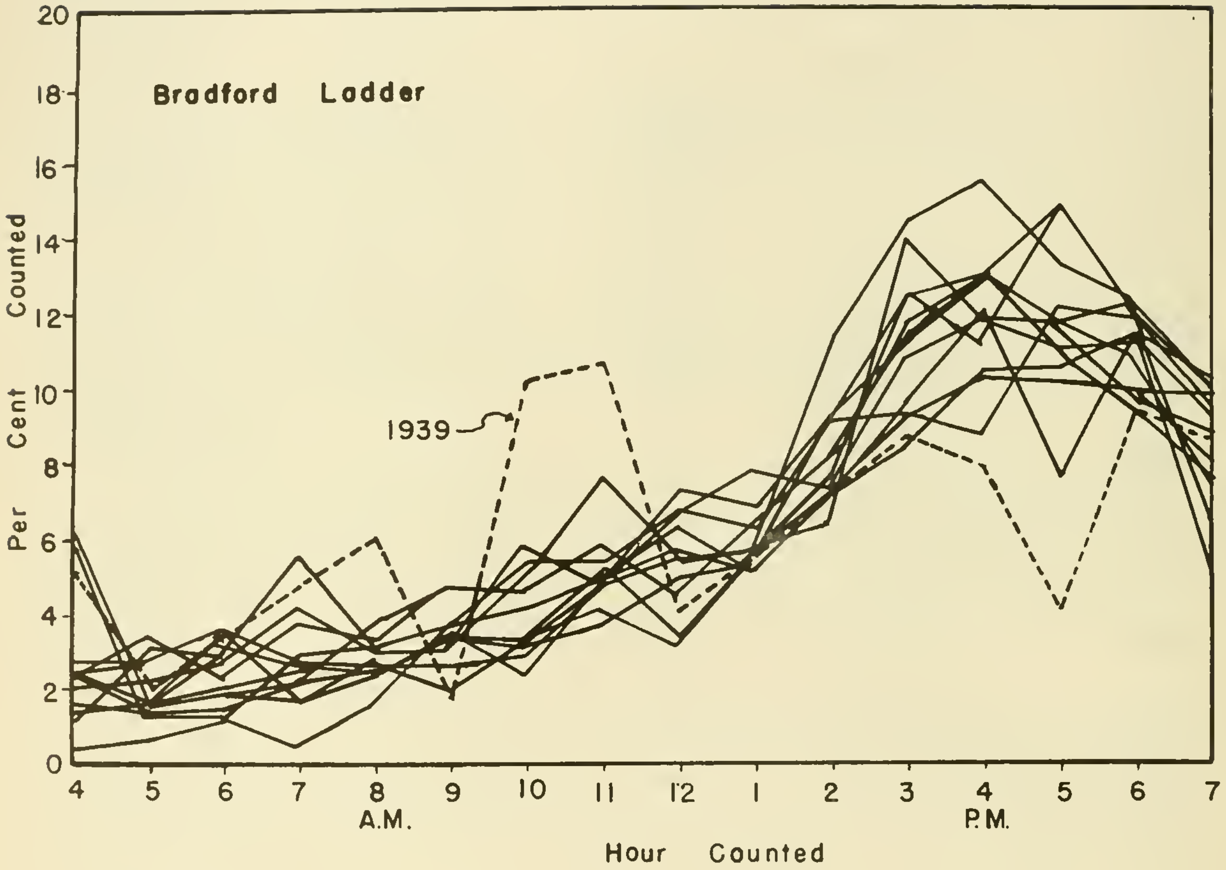

Fig. 8.--Combined hourly counts, in per cent, of shad passing through the Bradford Island Ladder for highest half-month for each year 1938-1950

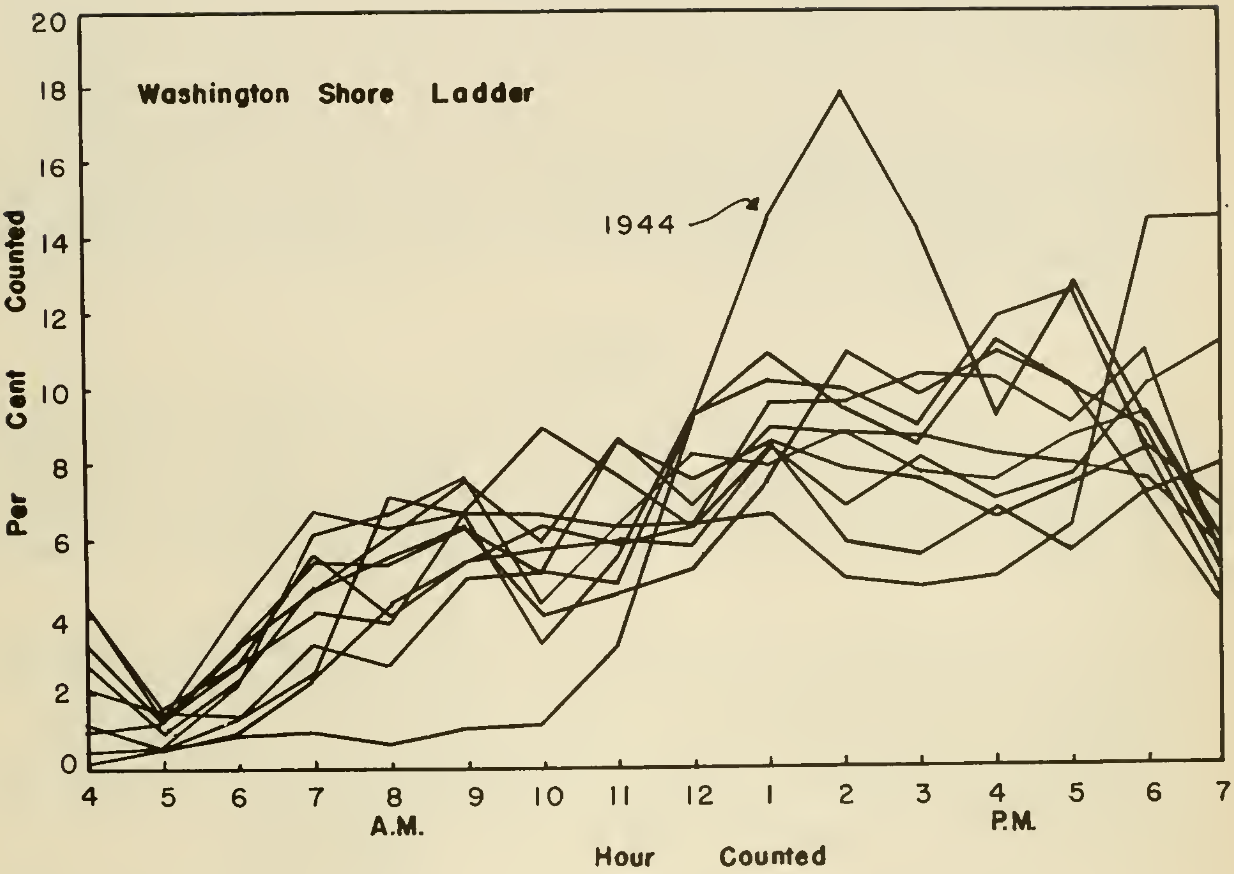

Fig. 9.--Combined hourly counts, in percent, of shad passing through the Washington Shore Ladder for highest half-month for each year

In 1948 the shad run through the fishways was about twice as large as that of 1938, and the night counts were made each hour. This gives a better idea of the movement of shad at night as compared with that during the daytime. Figure 10 shows the total counts for each hour of the day at each ladder for the period July 1-15. The day counts (4 a.m. to 7 p.m.) follow the same pattern as indicated in figures 8 and 9 except that during this particular period (the first half of July rather than the last half) the peak counts were later in the afternoon than previously shown.

The largest night counts were made during the hours immediately following the day counts, but except for the counts at 8 p.m. they were very small in comparison with the day counts. It would appear from figure 10, and from figures 8 and 9, that it would be more advantageous so far as shad are concerned to shift the day counts 1 hour later--that is, start at 5 a.m. and count until 9 p.m.

Fish Locks

The fish locks have not been used to any extent at Bonneville Dam, and few shad were assisted by these devices except in 1941. During that year an extension of the powerhouse for the addition of four more turbines interfered with the powerhouse branch of the Bradford ladder, and the powerhouse fish locks were used that season to give full opportunity for passage of fish.

The fish locks are similar in principal to navigation locks. Each lock consists of a vertical hydraulic chamber 20 feet by 30 feet in floor plan which extends from the lowest tailwater level to the highest headwater level. Near the bottom of the chamber is a gate-controlled opening to the water below the dam. A similar opening near the upper end of the chamber opens to the water above the dam. A conduit system entering the bottom of the chamber provides for filling and draining.

In operation, the entrance gate first is opened, and a moderate quantity of water admitted through the bottom of the chamber flows out through the entrance gate to attract fish into the chamber. The entrance gate is then closed and the chamber is filled with water admitted through the bottom. To assure that the fish will rise to the surface and leave the chamber at the higher level, a movable grilled floor that remains at the bottom of the lock chamber while the fish are entering is slowly raised as the chamber fills with water. This grilled floor, which slopes downward toward the exit side of the chamber, finally is raised to the water surface, thereby gently urging the fish toward the exit. After this the exit gate is closed, the lock chamber drained, the entrance gate opened, and the whole process repeated. The fish locks are constructed in pairs so that one chamber can be open for the entry of fish while the other is making a lockage.

Fig. 10.--Total hourly counts for 24 hours at Bonneville Fishways for period of July 1 to 15, 1948

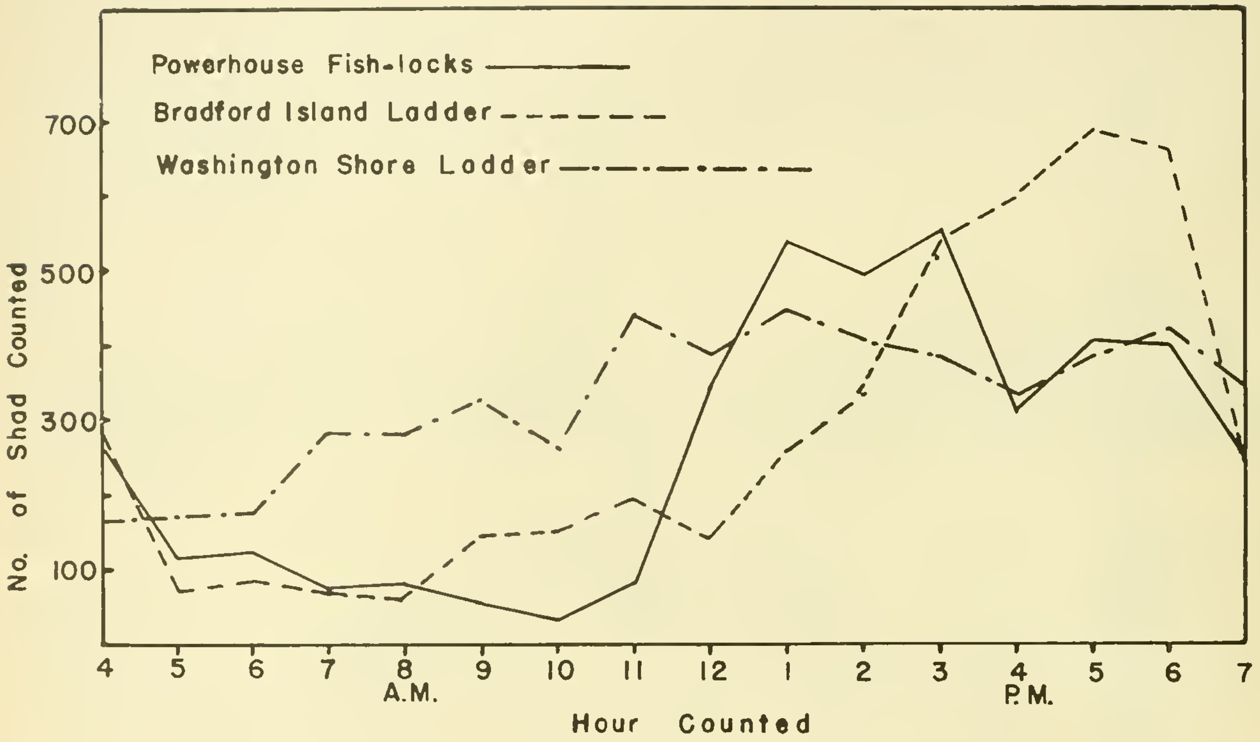

Fig. 11.--Comparison of Powerhouse Fish-locks with Bradford Island Ladder counts and Washington Shore Ladder counts for total hourly counts from July 1 to 15, 1941

In 1941 the powerhouse fish lock was operated throughout the time of the shad run. The half-month period of highest counts that year was the same for all three fish-passing facilities. The counts for each fishway during this period of highest counts are shown in figure 11. The trends of counts for the Bradford ladder and the fish locks are similar except that the peak counts in the locks occurred 2 or 3 hours earlier than in the Bradford ladder. If the locks and ladder were assisting the same group of fish, as they might well have been, the difference of a couple of hours of peak count might be the time it takes the shad to ascend to the counting station on the ladder. Those in the locks are lifted immediately from the lower water level to the higher, eliminating the time necessary to swim to the higher level. On the Washington Shore, the peak counts were earlier than in either of the other two facilities; as has already been shown in figure 9, this seems to be a characteristic of the Washington Shore ladder.

For the whole season, 4,989 shad were assisted over the dam by the fish locks as compared with 5,806 by the Bradford Island ladder and 7,862 by the Washington Shore ladder. It can be seen from this and from figure 11 that the powerhouse fish locks apparently were almost as effective as the ladders in assisting shad over the dam.

Mortalities in Fish Ladders

During some years the shad experienced considerable difficulty in ascending the ladders. This occurred, or at least was especially noticed, above the counting stations. A statement to this effect is found in the 1948 report of fish passage over Bonneville Dam, U. S. Army, Corps of Engineers, 1948, which reads:

> When the forebay is raised, due to high flood water, to elevation + 82 feet it is necessary to raise the weirs above the weir 70 counting station a total of ten feet, so as to create a gradual rise to the 82 level. When these weirs are raised by addition of stop logs, inimical hydraulic conditions are created for shad migration above the weir 70 counting station. Many shad dislike to, or cannot ascend through this area and consequently become weakened and are then forced against the picketed fish leads where the water velocity imprisons them until they die. Mortalities as high as 15% and 20% have been sustained in past years, however, in 1948 the losses were minor . . . .

In 1949 the shad run began after the water had lowered somewhat below the maximum of 82.5 feet, and this species apparently negotiated the fish ladders with ease as stated in the 1949 report (1949, U. S. Army, Corps of Engineers): " . . . with less rigorous hydraulic conditions in existence above the weir 69 counting station, the shad were able to ascend with east to the forebay."

Past records of the resident biologist at Bonneville Dam were examined for notes concerning shad passages, mortalities, or related data. Remarks concerning mortalities of shad in the fishways were found for four years. They are as follows:

1944:

Shad in large numbers passed over the dam during July. Considerable difficulty was experienced at Bradford Island in getting these fish to continue up the ladder after passing the counting station. They lay in the pool above. At first only a few fish were lost against the barrier, but the losses mounted until several hundred a day were lost. It is conservatively estimated that some 800 dead were removed from the barrier during the month. Every possible combination of weir adjustment and water flow was tried to induce the fish to work up the ladder. Finally, after some difficulty, the best adjustments were made 1/, and in a few days most of the fish had worked their way up the ladder, although a few persisted in remaining above the counting station.

1945:

The 1945 shad run was by far the largest ever to occur at Bonneville. Shad have proved to be a most difficult fish to pass over the fish ladders successfully, particularly above the counting stations. Above each counting station there is, under normal conditions, a pool of more or less quiet water of low velocity. It is here that the shad like to remain and refuse to move on up the ladder. Many different adjustments were tried in an effort to induce the fish to move upstream. It was found that the most satisfactory flow conditions were a strong, direct surface flow which forced the fish to swim strongly against it. Not having a resting place, the fish gradually moved up the ladder. In the quiet water, the fish would gather in large schools and swim aimlessly back and forth until many of the weaker ones would fall back against the barrier and die.

1/ The best adjustments referred to in the above paragraph created a strong surface flow.

1946:

The number of shad that were not able to ascend to the counting barrier is not known, but after passing through the counting gate many would not go on up the ladder. Instead they would mill about in the relatively quiet water above the counting barrier, where they would weaken and drift against the counting barrier and there die. A great deal of effort was expended to induce the shad to go on upstream. In 1946 it was found that by placing two equidistant wooden walls or leads parallel with the sides of the ladder above the Bradford Island counting station thus creating three equal sized short channels, the shad were prevented from moving back and forth above the counting station by being constrained in the central narrower channel. Somehow this treatment impelled more to go on upstream for after this was done fewer dead fish were found in the ladder.

1947:

Again in 1947, as in previous years, considerable mortality occurred to the shad in the fish ladders after these fish passed through the counting station. A record of this mortality has been kept which indicated that 15.9% of the June shad that ascended the Bradford Island ladder perished, whereas 7.1% died in the Washington Shore ladder after being counted. The fish do not like to ascend the last ten turbulent weirs into the forebay, and they migrate upstream just as the forebay level is ten feet higher than normal.

From these notes it would appear that the shad mortalities in the Bonneville fishways during past years resulted from the rigorous conditions above the counting fence when high headwater levels prevailed, and from the adverse effect of the quiet resting pools. One or both of these factors has been listed as the cause of mortalities in every instance.

During the 1950 run, only minor mortalities occurred even though the water levels were such that the two factors causing the previously mentioned mortalities prevailed. For the major part of the 1950 run the forebay was held at elevation 82 and the ladders had to be adjusted to this high level. In spite of this, mortalities were only 28 out of 7,818 shad counted.

It is also encouraging to note that since 1948 very few shad mortalities have occurred. The resident biologist's notes on shad passage for 1948 states that the "losses were minor"; in 1949 "the shad were able to ascend with ease"; and in 1950 he states that there was no appreciable mortality. In recent personal correspondence, I have learned that there was very little mortality in 1951, and since early 1952, when both counting stations have been located at forebay level, little or no mortality has been observed. It can be concluded from these records that the probable cause of the shad mortality was the effect of inimical hydraulic conditions in the fishways resulting from the installation of the counting stations in the ladders. Apparently after experimenting with various adjustments for high water levels, conditions were improved beginning with 1948, and now that the counting stations have been installed at forebay level these adverse conditions have been eliminated.

Presumably it is the opinion of fishway observers at the dam that many shad enter the ladder but do not reach the counting fence (U.S. Army, Corps of Engineers, 1950). The numbers or percentage of these is not known, of course, since the only counts of fish in the ladders are those made at the counting stations near or at the upper end of the fishways. As mentioned earlier, it is entirely possible that the shad do not have much incentive for ascending the fish ladders since there is so much available spawning area below the dam. It is also possible that construction of the dam at this point in the river usurped a formerly important spawning area, and therefore there may be no motivation for the shad to progress farther upstream.

All the fish found dead against the barrier below the pool during the 1950 season were examined. Both females and males were found. The males were all sexually mature, while the females were in all stages of sexual maturity and one was about 50-percent spawned out.

To determine whether the shad spawn in the resting pool, a plankton net was set three different times in the pool below the counting house for 16 hours during the afternoon and night. On one occasion five shad eggs were recovered. Since it is possible that these eggs may have floated down from upriver, the results are not conclusive.

Swimming Activities within the Ladders

In the fish-ladder pools in which there is a strong downstream surface flow (usually referred to as the "streaming" type of flow), shad exhibited essentially the same swimming motions as do the other species. That is, they face upstream into the current, work their way to the head of the pool, and then swim up over the weir into the next pool. In this way they proceed up the ladder and over the dam.

In the standard pools with fixed weirs in the Bonneville ladders there is a "plunging" type of flow as the water pours over each weir to the pool below. In the plunging type of flow the water is regulated so that it flows over the weir and carries deeply into the ladder pool. This results in a backroll or reverse current on the major portion of the surface of the pool. In other words, the direction of flow on most of the surface of the pools is upstream rather than downstream.

In the plunging type of flow the shad that were seen during the 1950 observations exhibited swimming actions entirely different from those found in most species. In the surface layer they swam into the current, that is, faced downstream, and slowly worked their way backwards toward the head of the pool. When they reached the head of the pool they made a quick turn and swam up over the weir into the next higher pool where the whole operation was repeated. During the whole operation they exhibited their characteristic behavior of swimming back and forth across the pool, but always faced downstream.

Later observations by the resident biologist (personal correspondence) has shown that many of the shad, in passing from one pool to the next higher pool, rise from the depths of the pool and swim over the weir in a manner similar to other fishes. Those seen on the surface of the pools faced downstream as was previously reported.

The relative merits of plunging versus streaming flow, so far as shad passage is concerned, cannot be decided at this time. From the experience in passing shad above the counting gate before they were moved to the head of the ladder, it might appear that the streaming type of flow is more suitable for shad than the plunging type; but since the fish that reach the counting gate have already climbed 40 or 50 feet above tailwater through the standard pools where plunging flow prevails, no conclusions are possible. More experimentation on the reactions of shad to various hydraulic conditions is needed to determine the best design and method of operation for this species.

A watertight chamber equipped with windows for underwater observations was placed in the pool below the Bradford counting station during the shad run of 1950. It was hoped to determine whether shad utilized the submerged openings in the weirs, but the water was too high and turbid to permit observations.

Other Fishways Ascended by Shad

Review of the literature has brought to our attention an Atlantic fishway, no longer in operation, that helped many shad over a dam. The report of the Pennsylvania State Commissioners of Fisheries for the years 1892-94 (Pennsylvania 1895) has the following statement:

> The work of restoration in Delaware was marvelous in its success. The fishways in the Lackawaxen dam, put in jointly by Pennsylvania and New York Commissions, gave one hundred miles more of the river to shad, yielded that much more area for spawning purposes and enabled the people of the far upper valley to once more enjoy a food fish of which they had long been deprived.

The report by Fish Protector Snyder to the New York Commission of Fisheries in 1890 (New York Commission of Fisheries 1891) states:

> Since the building of the Lackawaxen Dam, 45 or 50 years ago, not a shad was seen above the dam until the spring of 1890, after the fishways were put in, which have proven a great success.

The Lackawaxen Dam, on the Delaware River near Lackawaxen, Pa., was part of the Delaware Hudson Canal system which ceased operation about 1900. At about that time ice jams carried away the dam, and it no longer presented a barrier to fish migration. Apparently the fish ladder surmounting the dam on the Pennsylvania side of the river passed large numbers of shad for a period of about 10 years. Unfortunately, no records have been found to indicate the type of fishway, reasons for its apparent success, or the magnitude of the run passing.

Recently it became known that shad successfully use a fishway at Lawrence, Mass., on the Merrimac River (Collins 1950). This fishway uses about 10 cubic feet of water a second, and the drop between pools is 0.6 foot. Because of pollution and lack of adequate spawning ground the number of shad using the fishway is limited.

Summary and Conclusions

The Bonneville fishways, while operated primarily for the passage of salmon, have successfully passed large numbers of shad over the dam.

Time of passage was influenced both by flow and by temperature, but flow appeared to have the greater effect. Low water flows (and to some extent high water temperatures) tended to result in earlier runs than those occurring when high water flows (and lower water temperatures) prevailed. These conditions affecting the runs at Bonneville apparently affect shad in general in the Columbia River since there was a significant correlation between time of run at Bonneville and time of commercial catch of shad in the river below.

A study of the time of daily migration through the fish ladders illustrated that peak migrations occur during the day--usually in the afternoons. From our analysis of the data it would appear that counts 1 hour later than those regularly made at Bonneville would be more useful for recording passage of shad.

The fish locks, though not regularly operated, appear to be as effective as the ladders in passing shad.

Some mortality occurred in the fish ladders and appeared to be caused by a reluctance on the part of the shad to leave the quiet resting pools above the counting station at high forebay levels. This can be alleviated by proper adjustment of weirs and water flow in the upper pools, and has been eliminated entirely by moving the counting stations to forebay levels.

In view of the success of the Bonneville fishways, it is probable that inaccessibility of the entrance or lack of attractive currents was responsible for the lack of success in passing shad in many of the early fishways. These two factors have been listed by Mugnier and Swartz 1/ as the probable reason for failure of the two previous fishways constructed at Holyoke Dam, Massachusetts. As mentioned in their report, present plans for the new fish-passage facilities at Holyoke Dam include an experimental phase to determine methods of inducing shad to enter fish-passing devices.

The success in passing shad over dams at Bonneville, Lackawaxen, and Lawrence demonstrates that shad can be induced to use fishways as readily as do salmon. The difficulties inherent in the problem are probably no greater than similar ones already overcome for the salmonoid fishes.

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