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A COMPARATIVE STUDY OF UNSTABLE AND STABLE (ARTIFICIAL CHANNEL) SPAWNING STREAMS FOR INCUBATING KING SALMON AT MILL CREEK[1]

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INTRODUCTION

King salmon *(Oncorhynchus tshawytscha)* originating in the Sacramento River are a valuable resource for the sport and commercial fisheries in the State of California. The Sacramento River also contributes to the coastal salmon fisheries of Oregon, Washington, and British Columbia (Fry and Hughes, 1951). A decline in abundance of the resource has caused concern among sportsmen as well as commercial fishermen *(Commercial Fisheries Review*, 1958, Ryan, 1959). Decreases in numbers of salmon returning to the Sacramento River were explained by the California Department of Fish and Game as being caused by pollution, predation, fishing pressure (river catch and expanding ocean troll), loss of spawning area by construction of dams, direct stream damage by various man-created activities, and streamflow and temperature change from water diversion *(Outdoor California*, 1958).

The United States Bureau of Commercial Fisheries, in cooperation with the California Department of Fish and Game, has been investigating the causes of limited production of salmon in the spawning streams of the Sacramento River area. Measurement of spawn losses determined from experimental sampling indicates an average mortality to fry stage of 96 percent from natural causes. It was hypothesized that if man created the unfavorable conditions for salmon production listed above he might also alter conditions in spawning streams to produce larger yields of salmon. The prospect of increasing the numbers of adult salmon by controlling the natural factors that limit production of young salmon made improvement of spawning streams well worth investigating. Studies therefore were undertaken to determine the principal factor limiting natural production, to show how it operates, and to describe means by which production could be improved.

PROCEDURES

Sampling techniques were established to provide measurements of environmental conditions and of salmon egg survival during the incubation period. The progress of survival was followed by planting known quantities of eggs in plastic containers of .07-inch mesh in simulated redds 12 to 14 inches under the streambed (Gangmark and Broad,

[1] Submitted for publication November 1959.

1955). A systematic recording of the environment was made possible by placing two plastic standpipes (Gangmark and Bakkala, 1958) in each artificial redd.

Selection of a site in the natural stream for planting eggs was confined to those areas where natural spawning had occurred, and in addition, involved consideration of two conflicting factors. On one hand we preferred to plant the salmon eggs under swift water where the possibility of siltation and suffocation of the eggs was minimized. On the other hand, the stream velocity at the planting site must be moderate to afford protection against streambed erosion during periods of fast runoff that are normally expected in Mill Creek, a tributary of the Sacramento River. We, therefore, compromised by choosing a site for deposition of test eggs in moderately fast-flowing water but also a site that afforded some protection from high velocities. In previous experiments severe losses of the test eggs were caused by erosion or siltation of the streambed. In addition, the planted eggs became inaccessible for sampling during periods of high water. Consequently, in recent years, these Mill Creek plants have been reduced to 3,000 eggs planted in 30 plastic containers divided equally among three redds. Many times this number are planted in a control-flow stream where access is assured at all times and where equipment is safe from floods.

An unsolved weakness in the method of testing survival of eggs is our inability to observe or record the fate of the eggs that are eroded from the streambed.

Another aspect of the Mill Creek procedures deserving consideration is the influence on survival of artificially fertilizing and planting the test eggs in plastic containers. Reasonable confidence that these procedures do not adversely affect the test eggs is gained from a comparison of survival between naturally spawned and artificially planted eggs from the same environment. Although results of the natural spawning experiments are not included here, production of young salmon has been comparable to, but not as successful as production from the artificially planted eggs. Further confidence in these planting methods is gained from results already obtained which show production of salmon fry in individual containers ranging from 0 to 9? percent. Thus, survival has not been restricted to certain levels by our test procedures and it has been demonstrated that the maximum possible range of survival can be obtained.

CAUSE OF LIMITED NATURAL PRODUCTION

Experiments at Mill Creek Fisheries Station during the last six years, show that mortality of king salmon to fry stage ranges from 85.2 to 100 percent and averages 95.8 percent. It is quite obvious that the incubation stage is the most critical period in the life history of king salmon. From these studies it was determined that unstable streamflow was the principal cause of the losses. This became increasingly apparent after recent floods in California and after the incubation seasons that produced the poor 1956 and 1957 returns (*Commercial Fisheries Review*, 1958). These studies indicated a consistent mortality-freshet relationship over a period of five years.

Effect of Recent Floods in California

In December 1955 and February 1958, floods occurred in most streams of Northern California including Mill Creek. They caused losses of 100 and 98.2 percent respectively of incubating eggs which had been planted in Mill Creek. Personnel of the California Department of Fish and Game, who count adult upstream migrants and sample downstream migrants by trapping at Mill Creek, captured only two and ten downstream migrants during the winters of 1955-56 and 1957-58 respectively (personal communication with R. Hallock, W. Cunningham, J. Riggs, and W. Van Woert). As indicated in Table 1 these counts entailing 2,440 hours of trapping contrast sharply to the count of 1,942 fry intercepted in 1954. Although the Fish and Game Department's installations are some distance upstream from our operations on Mill Creek and the effectiveness of their downstream trap varies somewhat with the volume of flow, the department's counts substantiate data obtained by our sampling methods. The count of adults moving upstream shows that even 1953-54 may not have been a good incubation season, since 1,339 adults were counted at the station in 1957 from 3,743 parent king salmon counted in 1953.

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		California Fish and Game Counts		
			Downstream migrant sampling	
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	Percent		*Hours*	
1953-54	8.7	3,743	1,992	1,942
1955-56	0.0	1,704	1,274	2
1957-58	1.7	1,339	1,166	10

* No downstream migrant counts available for 1954-55, and 1956-57 incubation seasons.

Reasons for Poor Production in Other Years

Experiments indicate that stream runoff of less than disaster level can create conditions lethal for spawn. The influence of freshets on spawn in five seasons is depicted in Figure 1, which shows that in every instance survival dropped with the appearance of the first freshet of the season. The significant factor in Figure 1 is the strikingly different records noted in 1952-53 and 1956-57 when the first freshets occurred in later stages of development than in the other three seasons shown. In Figure 1 the slope of decline in survival does not necessarily correspond to the intensity of the freshet occurring before the decline. This is explained by the relationship of the time of the freshet to the phase of development of the incubating salmon egg. An extremely "tender" phase extends from the time of fertilization until

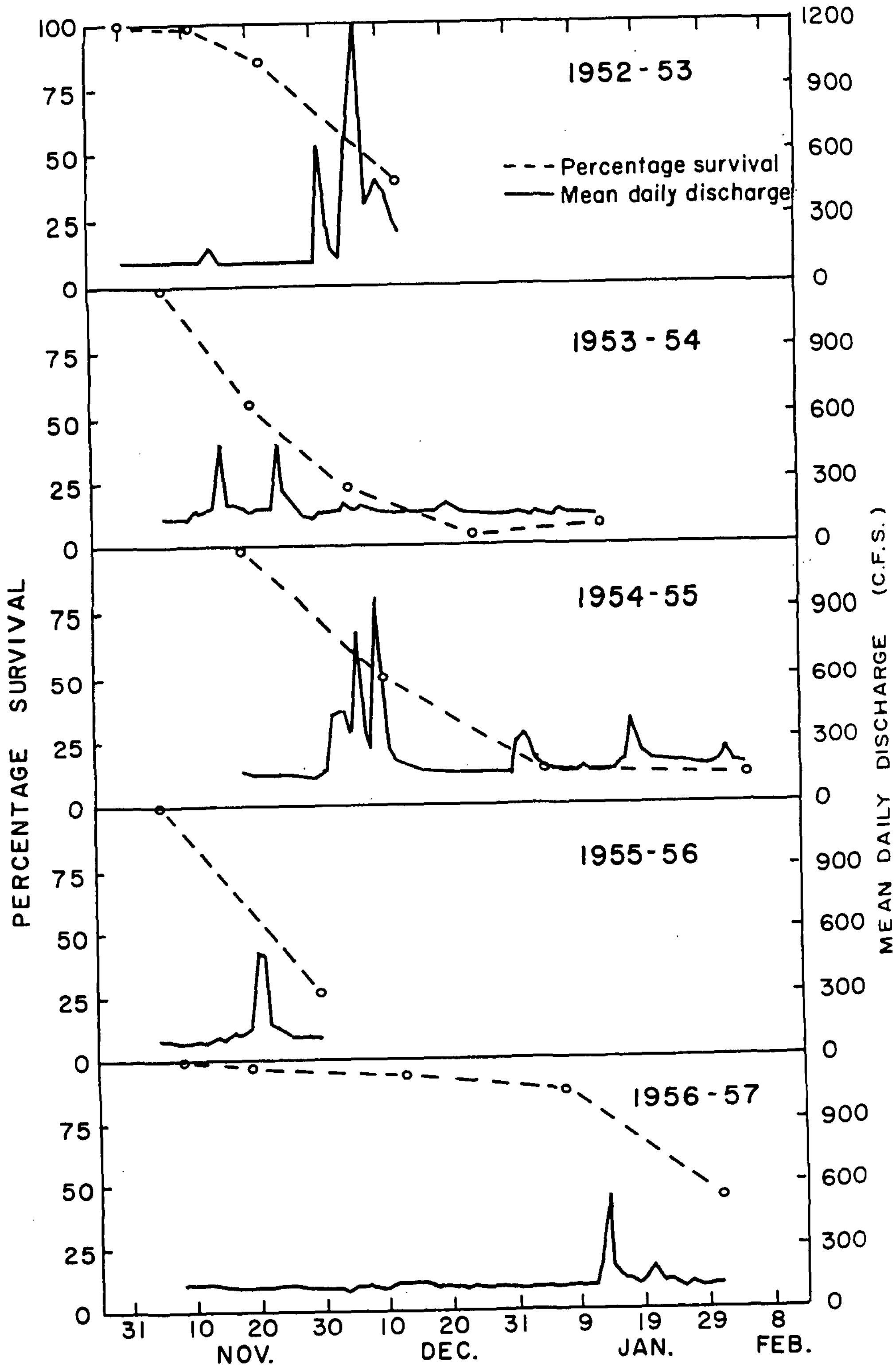
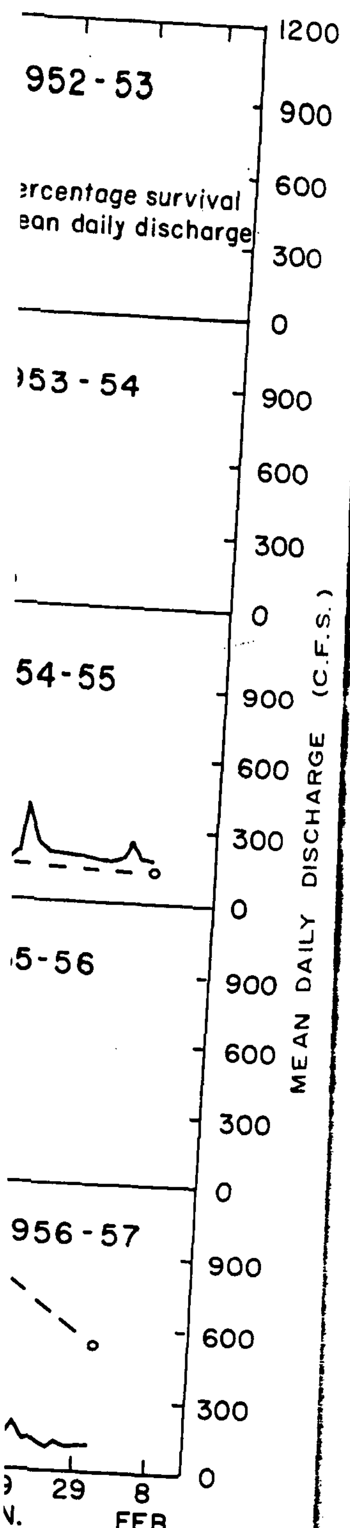


FIGURE 1. Influence of fluctuations in mean daily discharge on king salmon egg survival in Mill Creek, California, 1952-57. Flow records provided by the State of California Division of Water Resources and United States Geological Survey.



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the closing of the blastodisk around the yolk. Another period that may be marked by sudden losses occurs when the young salmon emerges from the outer chorion or shell of the egg (Wolf 1957).

During the incubating seasons of 1952-53 and 1953-54 heavy freshets occurred in Mill Creek (Gangmark and Broad, 1955 and 1956). Since king salmon of the Sacramento River area are predominantly four-year-cycle fish, the 1956 and 1957 runs originated from the 1952 and 1953 brood years. As expected, returns were poor in both 1956 and 1957 (*Commercial Fisheries Review*, 1958).

When compared with other tributaries of the upper Sacramento system and with the Sacramento River proper, Mill Creek is not unique in its severe fluctuation in discharge. Table 2 shows the average flow records of some of the important tributaries in this area listed in order of severity of fluctuation. It is noteworthy that this order approximates the order of importance of the streams as salmon producers.

TABLE 2

Flow Rates During the Salmon Spawning and Incubation Season (November 1 to March 31) of the Sacramento River and Some of its Tributaries Located Below Shasta Dam. Flow Rates from U.S. Geological Survey Papers

Stream	Years considered to 1954-55		Flow rate for extreme days during seasons considered			Ratio of maximum to minimum
	From	Total years	Average maximum	Average minimum	Average mean	
			Cubic feet per second			
Battle Creek	1940-41	15	3,603	231	550	16:1
Sacramento River (Near Red Bluff)	1939-40	16	80,350	4,153	14,194	19:1
Mill Creek	1939-40	16	3,392	111	382	31:1
Deer Creek	1939-40	16	4,389	103	465	43:1
Antelope Creek	1940-41	15	2,634	40	215	66:1
Big Chico Creek	1939-40	16	2,824	28	262	101:1
Cottonwood Creek	1940-41	15	12,310	92	1,417	134:1
Cow Creek	1949-50	6	13,043	88	1,205	148:1
Thomes Creek	1939-40	16	4,686	16	444	293:1
Paynes Creek	1949-50	6	1,810	4.4	159	411:1
Elder Creek	1949-50	6	2,314	0	165	----

Based on the relative stability of its flow, the Sacramento River rates higher than most of its tributary streams, for natural reproduction of salmon. In both the 1957 and 1958 incubation seasons, 30 plastic sacks each containing 100 eggs were buried in three experimental redds. Prior to hatching of the fry all of the sacks were eroded away from under 12 to 14 inches of Sacramento River gravel. In the vicinity of the site of planting and downstream from it we found evidence that egg samples may have been plowed out of the Sacramento River gravel by large uprooted trees.

From these data, the role that rapid stream runoff played in limiting natural reproduction of salmon in Mill Creek became evident. Other sources of possible losses at Mill Creek include pollution, high water temperature during spawning, various types of infestation such

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HOW CAUSES OF LIMITED NATURAL PRODUCTION OPERATE

With the knowledge that fast stream runoff was significant in the mortality of spawn, effort was directed toward finding exactly how severe runoff caused these losses. It was determined that mortalities were caused by both direct and indirect factors.

Direct Spawn Losses

Direct losses of spawn were due primarily to erosion of the streambed by high velocities of water. Information as to the fate of spawn washed out is not available, but it is reasonable to assume that once the eggs are washed from the protecting gravel bed out into the stream of violent water flow and shifting gravel, their chance of survival is low. Dead eggs found floating in eddies after periods of fast runoff bear this out.

Indirect Spawn Losses

Indirect losses of spawn occurred from a series of events of diverse and complex nature involving loss of spawning gravel and erosion of soil.

Loss of Spawning Gravel

In streams of the Sacramento River system, loose gravel is constantly washed out and piled high on vast bars where it is no longer available to salmon for spawning purposes. The effect is that adult female salmon must compete for limited spawning areas. This often results in crowding, and causes the later spawners to dislodge the eggs of earlier spawners.

TABLE 3

Mortality Rate of King Salmon Spawn in Relationship to the Dissolved Oxygen in the Gravel Adjacent to Eggs Planted in Mill Creek During the 1956-57 and 1957-58 Incubation Seasons

Dissolved oxygen		Average mortality	
Number of determinations	Amount of oxygen	Number 100-egg tests	Extent of mortality
	P.P.M.		*Percent*
10	< 5	16	37.8
21	5 - < 7	34	13.6
43	7 - < 9	62	12.2
40	9 - < 11	52	9.6
43	11 - < 13	50	10.8
6	> 13	6	3.9

Soil Erosion

Another series of events causing indirect loss of salmon spawn starts with soil erosion and subsequent deposit of silt and sand that clogs the redd. This blockage leads to:

1. Inadequate oxygen: when seepage of water is retarded in the gravel of a stream bed, there generally is a loss of oxygen from the water due to decomposition of humus (Pollard, 1955). Ellis, Westfall, and Ellis (1948) concluded that five p.p.m. (parts per million) is the minimum oxygen concentration for survival of freshwater salmonoids. Table 3 shows the relationship between dissolved oxygen and egg mortalities found during the 1956-57 and 1957-58 tests at Mill Creek. Large mortalities occurred at levels of less than five p.p.m. of oxygen.

TABLE 4

Mortality Rate of King Salmon in Relation to Velocity of Seepage in Gravel Adjacent to Planted Eggs

Seepage velocities		Average mortalities of spawn	
Number of readings	Velocity of seepage water	Number of 100-egg tests	Average mortality
	Feet per hour		*Percent*
21	.5	34	40.0
8	.5 - < 1.0	14	33.1
7	1.0 - < 1.5	14	24.0
3	1.5 - < 2.0	6	10.1
16	2.0 - < 2.5	24	12.9
14	2.5 - < 3.0	20	13.0
25	3.0 - < 3.5	26	10.8
29	3.5 - < 4.0	34	5.3
20	4.0 - < 4.5	20	2.9
4	4.5 - < 5.0	4	3.8
6	> 5.0	6	5.8

2. Poor delivery of oxygen to the eggs (Wickett, 1954) and poor cleansing of metabolic waste products (Wolf, 1957): from the 1956-57 and 1957-58 data taken at Mill Creek, the rate of seepage was related to the survival of eggs. The data are presented in Table 4. It can be seen that the mortality rate of eggs was dependent in large measure upon the rate of seepage of water through the gravel. The data indicate that the optimum velocity is roughly 4.0 to 4.5 feet per hour.

IMPROVEMENT IN NATURAL SPAWNING CONDITIONS

As a result of the studies at Mill Creek, effort has been directed toward reducing or eliminating the principal causes of mortality of salmon spawn by establishing a flow-control area similar to the experimental area at Nile Creek on Vancouver Island (Wickett, 1952).

Experimental Test Area at Mill Creek

The Mill Creek experimental area, previously described by Broad and Gangmark (1956), consisted of a section of an old streambed through which a channel has been bulldozed and from which silt has been flushed to provide an area suitable for tests on incubating salmon

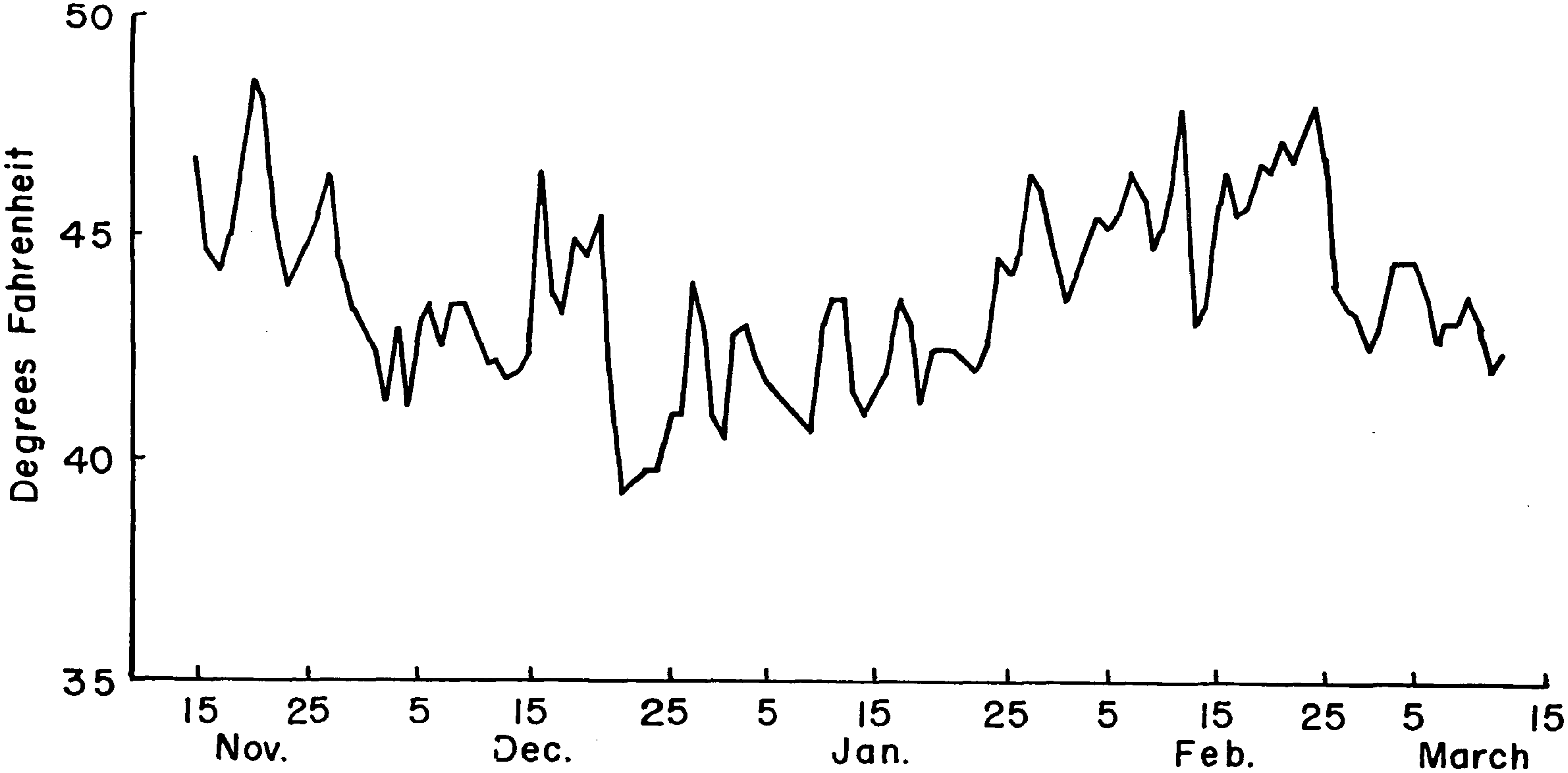

FIGURE 2. Mean daily water temperatures in Mill Creek during the 1957-58 incubation season.

eggs. Two pipes, each 30 inches in diameter and equipped with gate valves, provide for a controlled-flow of water to the area. The amount of silt in the water is reduced before it reaches the test section of the stream by filtering the water through gravel and passing it through a settling basin. A dike protects the area from severe run-off from the main stream of Mill Creek. Adjacent to this controlled-flow area, Mill Creek proper provided an uncontrolled-flow area for comparison.

Comparison of Factors

Testing survival of salmon spawn in the controlled-flow area and in Mill Creek has provided fundamental information on the effect of rapid stream runoff. Stream erosion, temperatures, dissolved oxygen, and seepage rates were compared and measured in these two areas during the 1957-58 incubation season.

Erosion

Rapid runoff eroded out one-half of the planted egg samples in Mill Creek, but no eggs were eroded out in the control area.

Temperature

Temperature was not a factor in differential survival in the 1957-58 tests since the temperature was the same in both areas (Figure 2).

Dissolved Oxygen

In Figure 3 the values obtained during the 1957-58 incubation season reveal a greater concentration of oxygen in the stream gravel in the controlled-flow area than in the open stream. The average level remained above five p.p.m. in both environments. In Mill Creek, however, the concentration of dissolved oxygen at hatching stage, was slightly below the seven p.p.m. considered to be a critical minimum, just prior to hatching, for the chum salmon *Oncorhynchus keta* (Alderdice, Wickett, and Brett, 1958). Nevertheless, in Mill Creek concentrations of

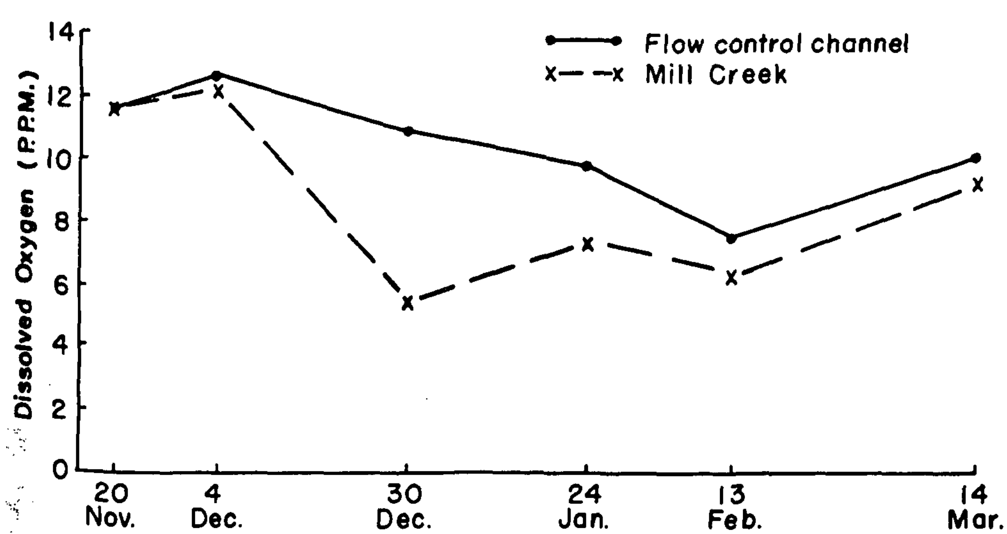

FIGURE 3. Comparison of average dissolved oxygen levels from planted redds in Mill Creek and in the flow-control channel determined at intervals throughout the 1957-58 incubation season. Oxygen samples were obtained in the immediate vicinity of the developing eggs.

oxygen were well above the range of 1.0-1.4 p.p.m. that Alderdice et al. found as the median lethal level (50 percent mortality) for chum salmon spawn just before hatching.

Seepage Rate

Comparing seepage velocities in the gravel in the control area with those in the gravel of the uncontrolled stream provided the most impressive difference between the two areas. The average velocity was 3.5 feet per hour in the controlled area during the 1957-58 season. In contrast, the seepage rate was only 0.3 foot per hour in the uncontrolled stream during a greater part of the season (Figure 4).

Survival

The superiority of stabilized streamflow to the natural stream conditions in Mill Creek was clearly demonstrated during the 1957-58 incubation season by the production of young salmon in the control-flow area. Based on sampling techniques which indicated a 1.7 percent fry survival of one-half of the originally planted samples, it was calculated that one female produced only 50 surviving young salmon in Mill Creek. The other half of the samples were eroded from under 12 to 14 inches of gravel in the main stream. In sharp contrast, it was calculated that one female produced 3,450 surviving young salmon in the controlled-flow area where conditions of optimum flow and reduced silt prevailed. Survival in the control area was thus 69 times $\left(\frac{3,450}{50}\right)$ better than in the uncontrolled stream.

DISCUSSION

Production of salmon in the Sacramento River area is limited by a variety of complex factors affecting the incubation of eggs, principal of which is the silt deposit left by heavy runoff of water that is typical of streams in this area. The means for alleviating damage resulting from heavy stream runoff appears to be control of the natural stream. In the assessment of factors that caused the superior production of salmon in the experimental controlled stream, the most impressive relationship in 1958 was the one associated with seepage rate in the gravel (Figure 4). Wickett (1954) points out that poor seepage may be the cause of failure to deliver an adequate amount of oxygen to the eggs. Wolf (1957) states that inadequate seepage fails to cleanse the eggs of metabolic waste.

Mortality to fry stage was 98.3 percent in the 1957-58 Mill Creek plants. This high mortality was obviously associated with reduced seepage in the gravel, which averaged only 0.3 foot per hour during most of the incubation season. In the controlled-flow area, with seepage rates in the gravel averaging 3.5 feet per hour, survivals were either very good or very poor. Seventy-two percent of the samples averaged 75 percent production of salmon and were associated with good seepages. In the other extreme, 22 percent of the 100-egg samples were all dead—a result of poor seepages that were not always detected by the standpipes.

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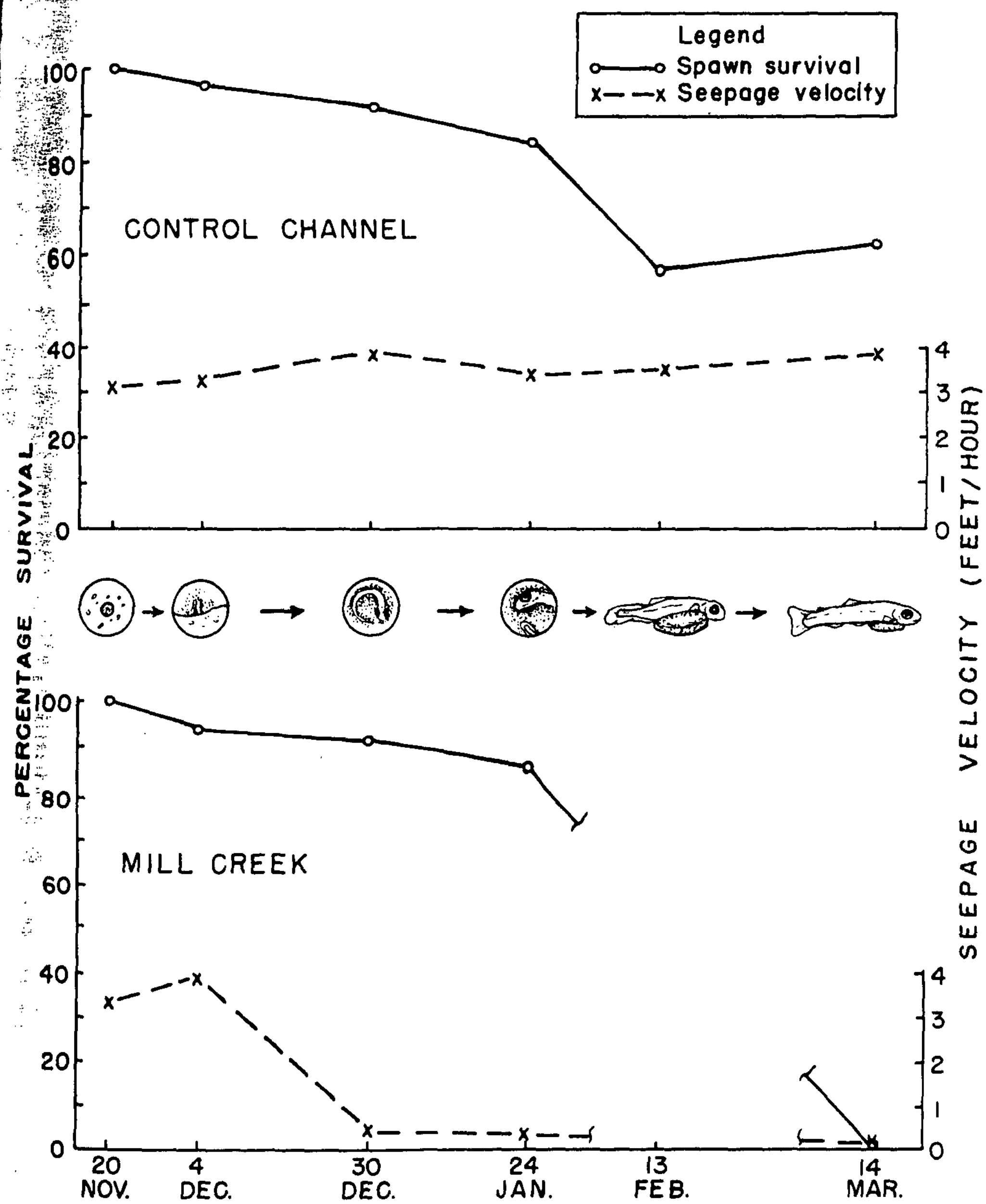

FIGURE 4. Relation of average king salmon egg survival to average seepage velocity in planted redds in Mill Creek and in the flow-control channel during the 1957-58 incubation season. Data for Mill Creek at hatched stage was unobtainable because of high water.

Specific Advantages of Improved Spawning Streams

The experiments at Mill Creek indicate the practicality of increasing the production of salmon by stabilizing stream-flow. Increased production would result from:

(1) Protection to incubating salmon eggs from erosion of the stream-bed by high velocities of flood water.
(2) Conservation of spawning gravel areas, which are critically depleted in the Sacramento River and its tributaries through flood action.
(3) Reduced smothering of eggs by silt.

Other anticipated advantages of flow-control methods include:

(1) Facilitation of predator control (Wickett 1952).
(2) Retention of nutrients (Briggs 1950).
(3) Easier measurement of production for more efficient management of the fishery.

Immediate Plans at Mill Creek

Since production of salmon to the fry stage in this experiment was 69 times greater under stable streamflows than under unstable streamflow in uncontrolled stream areas, the greater part of an old channel of Mill Creek is being rehabilitated for 9,000 feet from where it branches from Mill Creek to where it enters the Sacramento River. The 1958 returning mature king salmon are to be trapped and introduced into this area. Production will be measured by trapping migrants. Of particular interest in this expanded experiment will be the counts of fry after the adults have selected their own spawning site.

Application to Future Management of the Fishery Resource

As a result of the information we have gained at Mill Creek, we are considering the application of flow-control as a management measure for improving production of salmon in California. One suggestion is the establishment of more controlled-flow salmon producing sanctuaries such as the one presently in use at Mill Creek.

Another suggestion is the establishment of new habitats in the Sacramento River tributaries that presently do not qualify as salmon streams. Briefly the ideas under consideration for improving present salmon streams and creating new salmon streams in California embody the following:

(1) That flood waters be impounded in the headwaters of streams by numerous earthfilled or other dams with automatic self-adjusting gates that will permit stabilized flow of water;

(2) That the water-management program be based on the recommendations of all water users and controllers of water. This should assure best use of the water;

(3) That the impoundments be remotely situated so that they will not interfere with the migration of salmonoids; the water be released throughout the year; and the discharge from impoundments be from a stratum of water that provides suitable oxygen and temperature for salmonoids.

SUMMARY AND CONCLUSIONS

1. It has been determined that production of king salmon in the Sacramento River system in California is limited by a series of factors which result from the unstable stream flow found in that area.
2. Direct losses of spawn are caused by erosion of spawn from stream gravel. Fifty percent of planted egg samples observed were washed out and lost in this manner during six years of tests.
3. Indirect losses result from deposit of silt and sand in salmon redds. This deposition reduces seepage rate and leads to poor delivery of oxygen to incubating eggs, low dissolved oxygen levels from humus decomposition, and poor cleansing of metabolic waste products.

4. Indirect losses result from a critical shortage of suitable spawning gravel eroded from the streambed.
5. The effects of flooding were successfully dealt with in a controlled-flow stream at Mill Creek.
6. Settling and filtering methods, made possible by controlled streamflow, reduced siltation in the controlled-flow area.
7. As a result of reduced siltation, seepage velocities averaged 3.5 feet per hour in the controlled-flow area during the 1957-58 incubation season. In comparison, seepage velocities in Mill Creek proper were only 0.3 foot per hour during the greater part of the incubation season.
8. Advantages from controlled-flow resulted in a 69-fold improvement in production of fry.
9. Of the factors that might affect the survival of spawn, erosion and reduced seepage were critical during the incubation season investigated.
10. The demonstration of improved survival by the controlled-flow method has led to expansion of the experimental area. A 9,000-foot section of controlled-flow channel for spawning, where production of young salmon can be measured, is being developed.
11. An extensive and far-reaching consideration for improving existing conditions for production of salmonoids and for creating entire new areas for this purpose is suggested as a result of the work at Mill Creek. This improvement would entail impoundment of flood waters in the headwaters of tributaries and release during dry seasons to stabilize flow.

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