INTERNATIONAL PACIFIC SALMON FISHERIES COMMISSION

BULLETIN XI

SOCKEYE AND PINK SALMON PRODUCTION IN RELATION TO PROPOSED DAMS IN THE FRASER RIVER SYSTEM

F. J. ANDREW and G. H. GEEN

NEW WESTMINSTER, B. C., CANADA, 1960

INTERNATIONAL PACIFIC SALMON
FISHERIES COMMISSION

APPOINTED UNDER A CONVENTION
BETWEEN CANADA AND THE UNITED STATES FOR THE
PROTECTION, PRESERVATION AND EXTENSION OF
THE SOCKEYE SALMON FISHERIES IN
THE FRASER RIVER SYSTEM

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Mr. A. C. Cooper, Chief Engineer, International Pacific Salmon Fisheries Commission.

Dr. P. A. Larkin, Director, Institute of Fisheries, University of British Columbia.

Mr. C. H. Clay, Chief Engineer, Pacific Area, Department of Fisheries of Canada.

Mr. Milo C. Bell, Professor, College of Fisheries, University of Washington.

Original calculations made by Mr. Cooper have been used extensively to indicate probable temperature and discharge changes that would result from proposed water-use projects, particularly Moran Dam.

ABSTRACT

Extensive dam construction recently proposed for the Fraser River system would, on the basis of present knowledge, seriously deplete the sockeye and pink salmon populations. To contribute towards a better understanding of the complicated nature of problems that would be involved in preserving sockeye and pink salmon if dams were constructed in the Fraser River system, and to contribute towards the possible solution of these problems, this report presents a review of available information concerning methods of passing adult and juvenile salmon over dams, the possible effects of environmental changes on production of sockeye and pink salmon, and methods of artificially propagating these species. Efficient passage of adult salmon over dams would be a critical problem in the Fraser River system in view of the large numbers of fish involved and the known intolerance of many races to migratory delay. Because methods have not been developed for safely passing large numbers of seaward migrants over the proposed Fraser River dams, a significant proportion of these fish would be killed in passage over spillways and through turbines. Other obvious effects of dam construction, such as creation of reservoirs, inundation of spawning areas, and alteration of lake rearing areas would also seriously reduce productivity. The effects of subtle environmental changes, such as altered temperatures and discharges, are more difficult to evaluate but, in view of the sensitive relationship between the fish and their environment, such changes could have serious adverse effects on productivity. Maintenance of the delicately balanced environmental conditions to which Fraser River sockeye and pink salmon have become adapted appears to be a prerequisite for maximum production. Alteration of the natural environment, an inevitable consequence of dam construction, could result in seriously reduced production of Fraser River sockeye and pink salmon. On the basis of present knowledge, hatcheries, artificial spawning grounds, and other artificial production methods in the downriver area would not compensate for loss of natural upriver production of sockeye and pink salmon. Extensive basic and applied research in salmon biology and fish-power problems is now being undertaken but there is no justification for expecting early solutions to all of the particularly complex Fraser River fish-power problems.

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INTRODUCTION

The Fraser River salmon resource has been an important economic factor for many years. Historical records of the Hudson's Bay Company show that both the fur traders and native Indians depended on the annual salmon runs for much of their food supply. The first commercial exploitation apparently occurred before 1835 with shipments of salted salmon to Asia and the Hawaiian Islands. The value of the resource increased rapidly during the period 1870 to 1900 following development of a process for preserving salmon in cans. As shown in FIGURE 1, the Fraser River sockeye resource was extensively utilized from 1900 to 1913. The marked reduction in catch following 1913, the year of maximum production, resulted from an obstruction to migration of adult sockeye salmon at Hell's Gate in the Fraser Canyon (Thompson, 1945). Fishways were constructed at this site in 1945 and there is now every reason to believe, from the current increase in the annual catch and escapement, that with the application of scientific management procedures the former high levels of abundance will again be reached and possibly exceeded. The pink salmon resource was not fully utilized prior to the

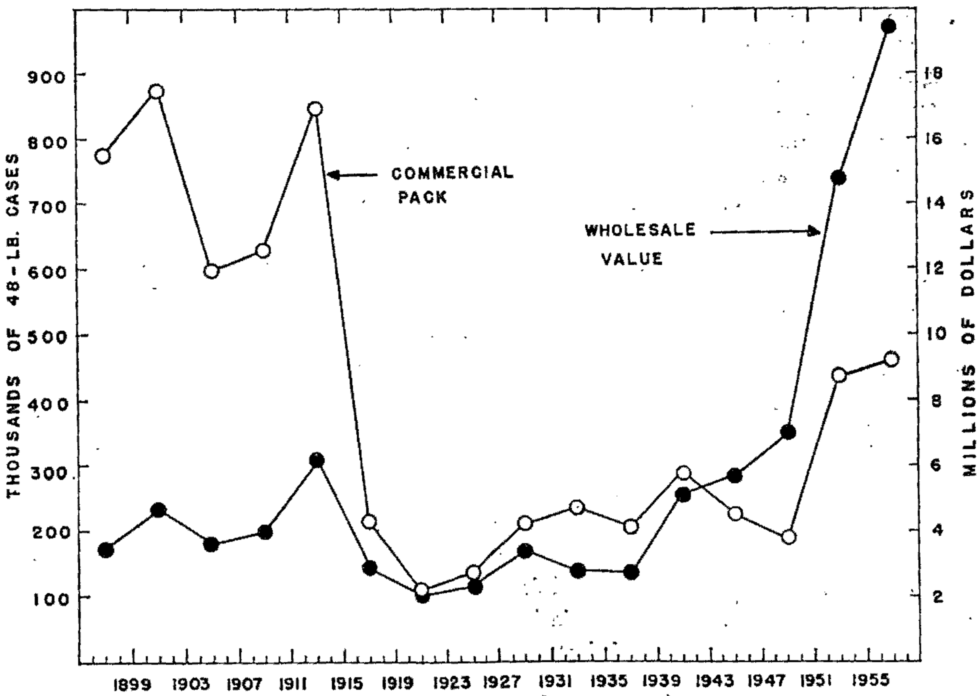


FIGURE 1—Fraser River sockeye salmon packs averaged for each four-year cycle from 1896 to 1959 inclusive. The Johnstone Strait catch is included only for 1958, when unusually large numbers of Fraser River sockeye were taken in this fishery. Average packs and values calculated from data in Pacific Fisherman (1914-1960).

Hell's Gate obstruction. Accurate estimates of potential production are therefore not available. However, there is no question that productivity prior to the Hell's Gate obstruction was substantially above current production. It is significant that pink salmon now spawn in the upriver areas that were virtually barren from 1913 to 1945 and substantial increases in the size of Fraser River pink salmon stocks are expected. Meanwhile, the commercial value of the Fraser River system as a salmon producer has been increasing each year. It annually yields a renewable, high-protein food resource of great economic value. It can be seen from FIGURE 1 that in recent years the Fraser River sockeye salmon resource has shown a progressive increase in economic value, not only because of the increased number of fish being produced but also because of the increased value of the canned product. In addition to their commercial value, the salmon and trout populations of the Fraser River system have an ever-increasing value as a recreational asset.

Dam construction presents a serious threat to the continued expansion—and possibly the very existence—of the commercial and recreational value of the Fraser River fisheries resource. After adding to the wealth of the region for more than 125 years, the fisheries resource could be depleted by construction of hydroelectric and other water-use projects on the migration routes and rearing areas of the Fraser River system. Although the fish-dam problem has existed for centuries in many countries, no practical solutions have yet been found that afford complete protection for anadromous fish in rivers obstructed and altered by large dams. At least 700 years ago, concern was expressed for the free passage of fish in rivers. The earliest known reference to the problem of fish passage is contained in the Magna Carta, signed in 1215. It was demanded at that time that man-made obstructions to fish migration should not be constructed across certain of the salmon-producing rivers and streams of England. The earliest attempts at conserving salmon at dams concerned the problem of ensuring upstream passage for migrating adult salmon en route to their spawning grounds. In recent years it has become apparent, however, that any consideration of the problem of salmon production in relation to dams must include a critical assessment of many factors in addition to the obvious need for safe upstream passage for adult salmon. Through current research efforts, problems that were not evident even a few years ago are continually being revealed.

Since its inception in 1938, the International Pacific Salmon Fisheries Commission has studied factors influencing productivity of sockeye salmon *(Oncorhynchus nerka)*. A further expansion of these biological investigations followed an amendment of the Sockeye Salmon Fisheries Convention in 1957 that placed responsibility with the Commission for the management and conservation of Fraser River stocks of pink salmon *(O. gorbuscha)*. These extensive studies have revealed a close relationship between sockeye and pink salmon productivity and environmental factors.

The sockeye runs to the Fraser River are not homogeneous but are composed of a number of sub-populations, usually called races (Royal, 1953). Each race enters the Fraser River at its own particular time and spawns consistently in its home stream at a specific time. When the sockeye enter Juan de Fuca and Georgia Straits they cease feeding and during the remainder of the spawning migration, involving in some cases a distance of 850 miles, they subsist on energy reserves. The whole sequence of sockeye migration and spawning appears to be adjusted to this energy reserve and to the seasonal occurrence of suitable water temperatures for migration and spawning. Development and survival of eggs and alevins is related to percolation of water through the gravel in which the eggs are laid and to changes in water temperature from autumn to spring. Times of hatching and subsequent emergence of fry from the gravel are related to temperature. Entrance of free-swimming fry into their rearing lake generally occurs at a time of favorable environmental conditions. Young sockeye live for one or sometimes two years in a lake, feeding primarily on zooplankton. In the spring of their second year of life, while undergoing certain physiological changes, yearling sockeye respond to a combination of biological and environmental factors, as yet poorly defined, and leave the lakes, migrating down tributary streams into the Fraser River and thence to the sea. They grow rapidly in the ocean and accumulate stores of energy for the return journey to their respective spawning areas. Most of the fish move towards the Fraser River after spending two years feeding in the ocean. Some stimulus or combination of stimuli, at least in part associated with a response to odor, induces the fish to swim upriver to their "home" lake or stream. Thus the life history of sockeye salmon is completely adjusted to, or integrated with, the environment. As long as the delicate relationship between the fish and the environment remains stable, rates of reproduction and survival are relatively high but marked changes in the environment can bring disaster.

The observed relationship between racial stocks of sockeye and their specific environment forms the basis for management of Fraser River sockeye populations. Royal (1953) proposed the concept that each race or spawning population is a separate management problem and that "The character of the migration of a race is related to the character of the environmental cycle in the reproductive area, the timing being controlled indirectly by the solar cycle, hence the maintenance of maximum productivity in a fishery depends upon the maintenance of normalcy in the character of the escapement." He further proposed that for any given race the early arrivals on the spawning ground and those fish that arrive late do not usually reproduce as effectively as the central part of the run because they are not properly timed with the environmental cycle. Nevertheless, the very early and the very late fish are vital to perpetuation of the run in certain years when conditions on the spawning grounds are unusual. Present management policy for Fraser River sockeye therefore consists of regulating the commercial fishery so that the escapement of each race to the spawning grounds originates primarily from the main, central portion of each run.

The observed sensitivity of Fraser River sockeye to environmental conditions is an important factor in an assessment of the effects of dam construction on sockeye production. Environmental extremes occurring under natural conditions have an important effect in controlling productivity of sockeye. The extensive changes that would likely result from dam construction must therefore be thoroughly evaluated. The relationship between pink salmon and their environment is not well known but, as for sockeye, maintenance of existing natural environments may be highly important for maximum production.

As shown in FIGURE 2, the present large sockeye populations and those that have the greatest potential for growth spawn in areas far removed from the ocean. While the lower river area supports significant populations of pinks at present, historical records indicate that the Thompson River was formerly a major spawning area for this species. Sockeye and pink salmon runs that were depleted by effects of the obstruction at Hell's Gate are being rehabilitated by regulating the commercial fishery and, where possible, by transplantations from suitable donor stocks. It has been estimated, on the basis of available historical data, that approximately 90 per cent of pre-1913 sockeye production originated upstream from Hope, with 30 per cent of the sockeye spawning and rearing in the Thompson River system and 60 per cent in the upper reaches of the Fraser River system (Anon., 1955). Examination of sketchy historical records has led to the conclusion that the Thompson River system was probably one of the more important pink salmon producing areas of the watershed. Its potential is by no means being utilized at present. It was estimated that, in 1955, 12 per cent of Fraser River pink salmon spawned above Hope *(ibid.)*. In 1957 and 1959, the proportions spawning in this upriver area were 14 and 10 per cent, respectively (Internat. Pacific Salmon Fish. Comm., 1960). This observed distribution of the major sockeye and pink salmon producing areas is of great importance in considerations of the effects of hydroelectric developments.

Many of the dams recently considered for hydroelectric and flood control purposes in the Fraser River system would be located downstream from major spawning and rearing areas of Fraser River sockeye and would also affect a large proportion of pink salmon spawning areas. Four dams have been proposed on the Fraser River between Hope and Lytton, eleven (including alternate sites) between Lytton and Prince George and five on the Thompson River between Lytton and Kamloops. Numerous other major dams and storage and diversion projects proposed for tributary streams would also affect important spawning and rearing areas. It has been proposed that part of the flood waters of the Columbia River be diverted to and stored in Shuswap Lake which, at present, is the most important sockeye rearing lake in the Fraser River watershed. Diversions of foreign discharges from the Skeena and Peace River watersheds to the Fraser systems have also been proposed. The possibility of diverting waters of the Chilko-Taseko system through the Coast Range to tidewater is being actively studied. Other recent proposals include the use of important sockeye rearing lakes, such as Shuswap, Adams, Kamloops, Quesnel, Stuart and Francois Lakes, for storage. FIGURE 3 and TABLE 1 show the location and tentative dam heights of potential power and storage sites on the Fraser River, as recently outlined by the Fraser River Board (1958).

The duties of the International Pacific Salmon Fisheries Commission, as defined in a Convention ratified by the Governments of Canada and the United

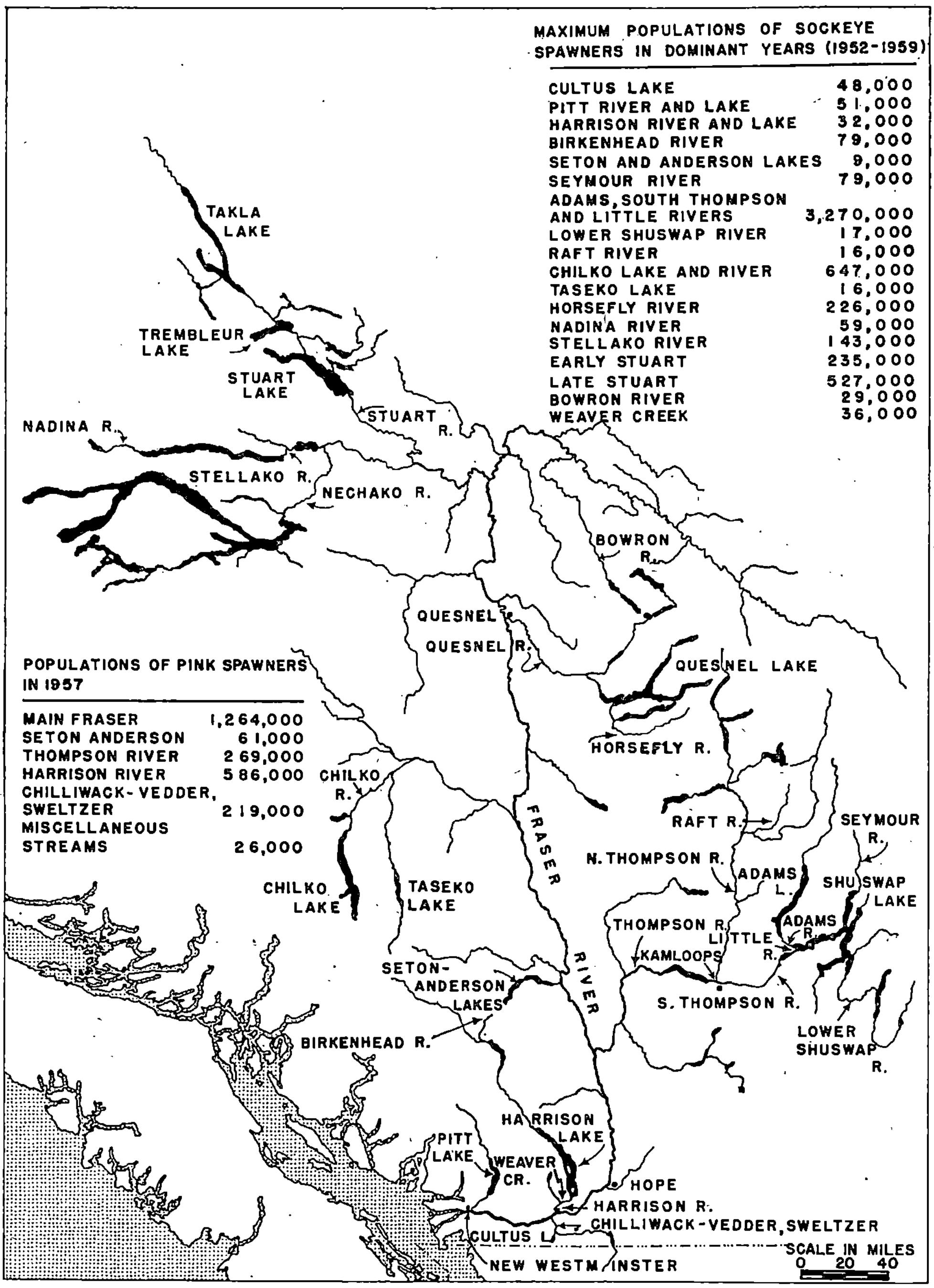


FIGURE 2—Areas of the Fraser River watershed utilized by major sockeye and pink salmon spawning populations.

TABLE 1—Potential power and storage sites in the Fraser River watershed, as determined by the Fraser River Board, but not including power sites having a potential of less than 10,000 horsepower. Sites downstream from sockeye or pink salmon spawning areas are noted.

Reference Number	STREAM	SITE NAME	GROSS HEAD	ON MIGRATION ROUTE OF	
			Feet	Sockeye Salmon	Pink Salmon
111	Fraser River	Grand Canyon	99		
185		Olsson Creek	91	x	
100		Fort George Canyon	61	x	
96		Cottonwood Canyon	239	x	
83		Soda Creek	175	x	
198		Chimney Creek Bridge	105	x	
197		Little Dog Canyon	115	x	
196		Upper China Gulch	115	x	
75A		Upper Moran Canyon	192	x	
75		Moran Canyon	732	x	
211		Bridge River Junction	179	x	
189		Cisco	102	x	x
188		Boston Bar	94	x	x
187		Spuzzum	89	x	x
49		Yale	60	x	x
182		Raush Valley*	161		
185A		Eaglet Lake	247	x	
212		Stein	110	x	x
116	Moose River	Moose			
177	McGregor River	Upper McGregor	182		
104		Lower McGregor	402		
117	Nechako River	Isle Pierre	40	x	
98	West Road River	Black Canyon			
91	Cariboo River	Swamp Falls			
90		Limestone Canyon			
89		Cariboo Falls	168		
210		Sandy Lake*	64		
186	Quesnel River	Red Canyon	251	x	
87		Third Canyon	90	x	
86		Little Canyon	80	x	
85		Big Canyon	119	x	
88		Quesnel Lake*	20	x	
176	Mitchell River	Mitchell Lake			
81	Chilko River	Chilko Lake		x	
81A	Taseko River	Taseko Lake		x	

TABLE 1—(Continued)

Reference Number	STREAM	SITE NAME	GROSS HEAD	ON MIGRATION ROUTE OF	
			Feet	Sockeye Salmon	Pink Salmon
153	Clearwater River	Hobson Lake	570		
142A		Clearwater-Azure	287		
142		Hemp Creek	472		
194		Clearwater X	120		
141		Clearwater	126		
154		Hobson-Quesnel			
152	Angushorne Creek	Angushorne Creek			
145	Murtle River	Helmcken Falls	775		
151		Murtle Lake-Blue River			
133	Barriere River	Kamloops		x	
193	Thompson River	McAbee	93	x	x
192		Basque	98	x	x
191		Martel	98	x	x
190		Seddell	90	x	x
122		Gladwin	95	x	x
		Shuswap Lake*	60	x	
		Kamloops Lake*		x	
50	Nahatlatch River	Nahatlatch Lakes			
22	Lillooet River	Fire Creek	539	x	
20	Harrison River	Harrison Lake		x	
15	Chehalis River	Chehalis Lake	787		
11	Chilliwack River	Chilliwack Lake	640		
11A		Chipmunk	1135		x
119	Stuart River	Stuart Lake*	28	x	
92	Isaac River	Isaac Lake	44		
155	Adams River	Adams Lake*	34	x	
168	Shuswap River	Mabel Lake*	82	x	

Site data obtained from Fraser River Board Preliminary Report, 1958.
Sites for which gross heads have not been tabulated were considered unsuitable for development at the present time or were not adequately investigated for other reasons.

* Proposed for storage development only.

x Indicates presence of significant numbers of sockeye or pink salmon.

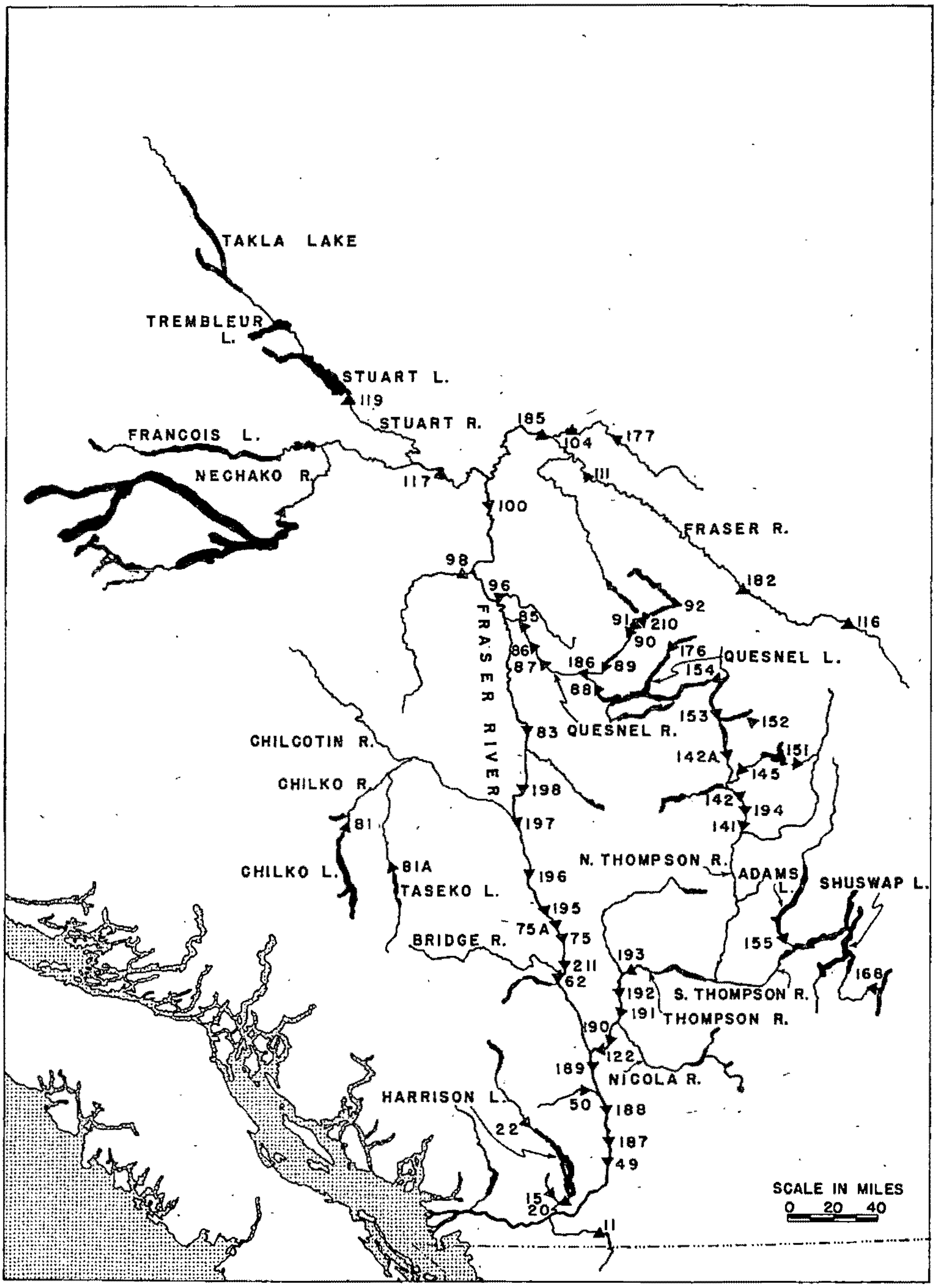


FIGURE 3—Locations of potential dams and diversions on the Fraser River watershed, as listed in the Fraser River Board Preliminary Report, 1958. Only those power sites having a potential of 10,000 horsepower or more are included. Numbers indicate "Reference Numbers" of sites, as given in TABLE 1.

States, provide for the protection, preservation and extension of the sockeye and pink salmon fisheries of the Fraser River system. These terms of reference therefore require that adequate consideration be given to all aspects of the problem of conserving sockeye and pink salmon at proposed multiple-water-use projects on the Fraser River. To promote better understanding of the over-all problem, this report presents a review of available information concerning environmental factors necessary for maximum production of Fraser River sockeye and pink salmon, together with an examination of the extent to which the environment could be changed by hydroelectric and flood control dams. Another important purpose of this report is to demonstrate the complexity of the fish-dam problem. Past and present research on fish-dam problems is discussed and current knowledge of existing and proposed methods of protecting fish at dams is presented. Sections of the report are arranged in the chronological order of the fresh-water phases of the life history of the two species, beginning with the spawning migration of the adults and proceeding to the seaward migration of the juveniles. Finally, problems involved in maintaining Fraser River sockeye and pink salmon runs by artificial methods of propagation or increasing natural production in unaffected areas are discussed. Much of the pertinent literature has been summarized. Reference has also been made to pertinent unpublished data collected by the International Pacific Salmon Fisheries Commission.

Discussions and conclusions in this report refer specifically to problems involved in protection of Fraser River sockeye and pink salmon. While there are certain basic similarities in the behavior and tolerances of all species and races of Pacific salmon, studies have suggested that the relationship between upriver races of Fraser River sockeye and their environment is particularly sensitive. Since other species and races in other river systems may react differently to environmental changes, application of certain of the findings in this report to these other species and races could be inappropriate.

The report is intended to be a reference work summarizing available information, thereby contributing towards a better understanding of the complicated nature of problems that would be involved in preserving sockeye and pink salmon populations if dams were constructed in the Fraser River system. While it is important to emphasize the complexity of the Fraser River fish-power problem, it is also important to consolidate the pertinent findings of the Salmon Commission and those of other agencies so that research efforts can be directed in the most effective manner towards the possible solution of component parts of the over-all problem.

MIGRATION OF ADULT SALMON

One requirement for obtaining maximum production of salmon is that the adults arrive on their spawning grounds at the optimum time and in suitable condition for effective spawning. However, dams constructed on the migration routes or upstream from spawning areas of Fraser River salmon would introduce numerous hazards to the safe, undelayed, upstream migration of these fish. Changes in the river environment downstream from dams could reduce the survival and reproductive ability of adult salmon and have profound effects on their migratory behavior. Such factors as discharge and temperature, for example, may be critical for successful migration. The attraction and collection of adult salmon below spillways, outlet works, and powerhouses presents many problems, as does the transportation of these fish over dams. Various types of fishways, fish locks and hauling systems have been proposed for providing passage over low- and high-head dams but none of these schemes appears to be capable of providing completely safe passage for millions of sockeye and pink salmon. Passage of these fish through large, low-velocity reservoirs also presents several biological problems. The problem of providing passage adequate in all respects for migrating adult salmon requires consideration of local downstream migrations as well as the normal upstream migrations. At Chilko Lake, for example, approximately 25 per cent of the fish, comprising the early portion of the run, mature for a period in Chilko Lake and then move back downstream into Chilko River for spawning. A low dam at the outlet of Chilko Lake might adversely affect the spawning of these fish. The problems that could arise as a result of dam construction in the Fraser River watershed are discussed in this section with relation to current knowledge of the spawning migrations of sockeye and pink salmon.

Adult Migration and Changed River Environments

DISCHARGE

The upstream migration of some species of salmon into spawning streams is related to river discharge. Pritchard (1936) found a positive correlation between the numbers of pink salmon migrating up McClinton Creek and both the daily rainfall and daily water height, with the exception that extreme freshets retarded the migration. Neave (1943) reported that the numbers of coho *(Oncorhynchus kisutch)* and chinook *(O. tshawytscha)* migrating upstream greatly increased during a period of rising water but that no relationship was evident between numbers of fish and diurnal changes in discharge. Davidson *et al.* (1943) also noted that flow and change of flow were important in initiating upstream movement. Hayes (1953), working with Atlantic salmon *(Salmo salar)*, showed that artificially created freshets could initiate upstream migration.

Gilhousen (1960) has demonstrated a relationship between Fraser River discharge at Hope and timing of upstream migration of the late Adams run of sockeye salmon. The total volume of flow for some period prior to upstream migration may be related to the duration of river migration through the effect of this flow on oceanographic conditions in the estuarial area. In years of high run-off, the main migration into the Fraser River occurs primarily from September 15 to 30. However, during years of low spring and summer run-off, the period of delay off the mouth of the river is extended and migration occurs over a longer period of time and at a later average date. In such years, the fish in the last part of the run often do not arrive at the spawning grounds or arrive too late for efficient spawning.

One of the basic requirements for economic power production on the Fraser River would be the storage of peak flows for use during periods of low flow. Under these conditions, the magnitude of spring run-off would be considerably reduced. Sufficient storage volume would be provided at the proposed Moran Canyon high dam on the Fraser River to retain the water of the spring flood for power generation during the low-flow months from October through March. The project proposal indicates that in some years there would be no spill at this dam and even in an average water year the reservoir level would not reach maximum height until sometime in July. Since the correlation described by Gilhousen suggests that reduced spring-summer discharges are related to delay in the entrance of Adams River sockeye into the Fraser River, such regulation of the river flows either for power generation or flood control could have serious consequences by delaying the time of arrival of adult salmon on their spawning grounds.

Reduced or variable flows below hydroelectric developments are known to affect the upstream migration of adult salmon. At the Puntledge River development on Vancouver Island, a flow of 1000 c.f.s. is diverted from the river to a powerhouse located approximately four miles downstream. Residual flow in the river below the diversion dam is from 100 to 200 c.f.s. This difference in discharge at the point where the turbines discharge the diverted flow back into the river results in the attraction and accumulation of adult salmon in the powerhouse tailrace (Can. Dept. Fish., 1958). Migration up the river from the powerhouse has, in several instances, been initiated by means of a sharp increase in discharge over the diversion dam. In the White River in Washington State, catches of coho in the fish-collection facilities below Stevens Dam are related to discharge. Spilling of water at Stevens Dam often results in a marked increase in the intensity of upstream migration. The variation in discharge below Baker River Dam, another development in Washington State, also affects the upstream migration of sockeye and coho in the system. Sudden reductions in discharge are accompanied by a downstream retreat of fish, possibly as far as the Skagit River. The fish do not reappear until some time after a high, stable discharge is re-established. Further, even with the plant operating at full load, spill over the dam results in a marked increase in catch in the collection facilities. The operators of the dam, recognizing this fact, have often spilled water to increase the efficiency of the fish-collection facilities. It is apparent that low or variable flow may retard upstream migration of adult salmon.

Drastically changed river flows may also create obstructions not present under normal levels of discharge. Pink salmon destined for spawning areas in the Tsolum River on Vancouver Island suffered severe losses during a year of low river discharge because their passage was obstructed, water temperatures were high and oxygen saturation was low (Anon., 1951a). It has been estimated that proposed hydroelectric development at Moran might reduce flows in the Fraser River to 15,000 c.f.s. during the initial stage of development. Tests at Bridge River rapids on the Fraser River several miles downstream from Moran have shown that sockeye and probably other species of salmon are blocked at this point in the river when the discharge is less than 19,200 c.f.s. The problem of providing free access to spawning grounds might also arise in the Chilcotin and Chilko Rivers under a proposed plan to divert water from Chilko and Taseko Lakes (FIGURE 4). One proposal would involve diversion of water from Taseko Lake to Chilko Lake, construction of a low-head dam at the outlet of Chilko Lake and diversion of water from Chilko Lake to hydro-electric plants which would be located between this lake and Bute Inlet It has been estimated that such a diversion would reduce the flow of the Chilcotin River to 15.2 per cent of its present volume (Internat. Pacific Salmon Fish. Comm., 1949). The suggestions for diversion of water from Chilko Lake would leave only a small intermittent flow in the present river channel. Even assuming a controlled flow downstream to safeguard salmon and trout populations, the stream with a greatly reduced discharge could not carry away sediments, move slide material, or stay encroachment of vegetation in the old channel with anything like its former effectiveness. Many points on the Chilko and Chilcotin Rivers now passable because of the large volume of flow might become impassable as depth and width decreased and roughness of the channel exercised a proportionately greater effect. Other schemes that have been proposed in recent years for utiliz-

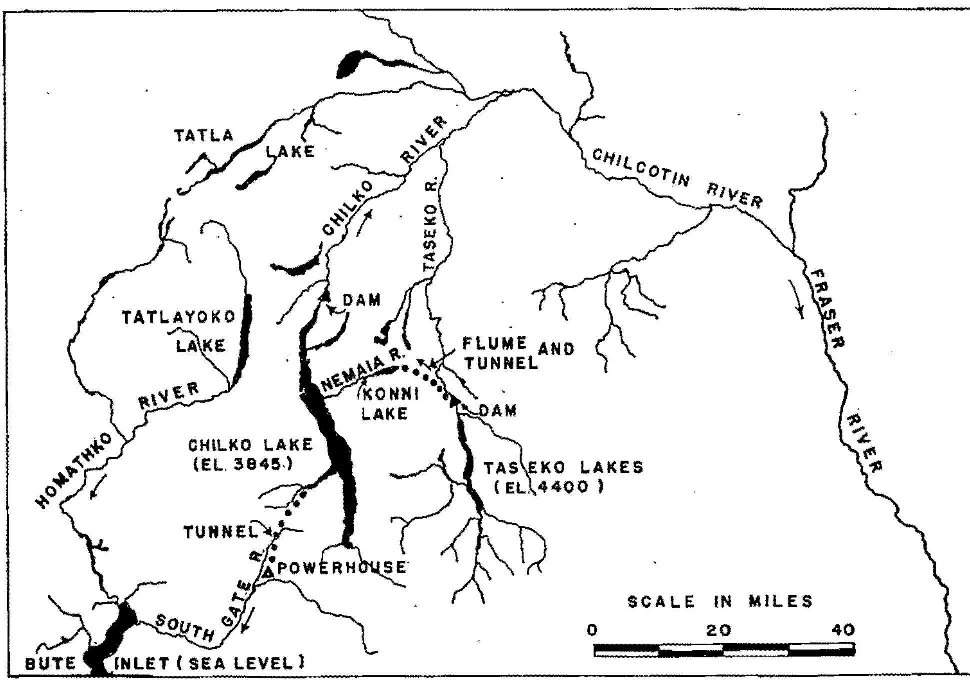


FIGURE 4—An early proposal for power development utilizing water from Chilko and Taseko Lakes.

ing water from Chilko and Taseko Lakes for power generation would eliminate many of the above-mentioned fisheries problems.

In some cases, re-regulating dams can be constructed downstream from hydroelectric plants to control the discharge, thereby avoiding extreme variations in flow, which may have serious adverse effects on fish during all phases of their fresh-water existence. To avoid changes in the natural discharge cycle, re-regulating dams must provide sufficient storage volume to enable stabilization of flow in the river downstream so that it approximates the flow into the reservoir of the hydroelectric dam. This is practical only in the case of hydroelectric installations that do not have much storage. For instance, Pelton Dam on the Deschutes River in Oregon is a typical peaking plant with a re-regulating dam (Eicher, 1958a). The hydroelectric reservoir fluctuates 7 ft., which is only sufficient to provide daily control of the Deschutes River discharge. Thus, very little storage is required in the re-regulating reservoir to compensate for variations in discharge at the hydroelectric plant. However, full compensation would be impractical or impossible in the proposed integrated development of the Fraser River system because water would be stored during the spring and summer months for power generation during the winter low-flow period. Annual flow cycles instead of daily or weekly variations would therefore have to be considered. The cost and physical problems of providing such large storage volumes appear to preclude the possibility of re-regulating dams being used on the Fraser River to compensate for annual discharge changes. Re-regulating dams might be feasible, however, for preventing extreme daily discharge variations.

WATER TEMPERATURE IN RELATION TO DISCHARGE

When the discharge of a stream is reduced, climatological conditions exercise a proportionately greater effect on the temperature of the residual flow. Studies have shown that when the diversion of the Nechako River (FIGURE 5) for power production at tidewater is fully utilized, a critical temperature problem will be created in the residual flow below Kenney Dam in some years (Anon., 1951b; Internat. Pacific Salmon Fish. Comm., 1953). Since the velocity and depth of the residual Nechako River have been reduced, the river can reach temperatures sufficiently high during parts of July and August to produce serious loss of upstream-migrating adult sockeye. This temperature rise might act as a physical block to sockeye destined for spawning grounds in the Nechako watershed. As described in following pages of this report, high water temperatures are detrimental to upstream-migrating salmon because they increase the rate of energy consumption and the incidence of disease and parasitism, and may also be directly lethal. Available information indicates that a mean daily water temperature of 68°F should be considered the upper limit permissible in the Nechako River during the migration period. The Nechako diversion did not exist in 1951 but calculations made by the fisheries agencies indicated that if the diversion had been operative on July 24, 1951, the river would have had a mean temperature immediately above the Stuart confluence of 72.8°F (Anon., 1952). Independently made calculations indicated that the temperature would have

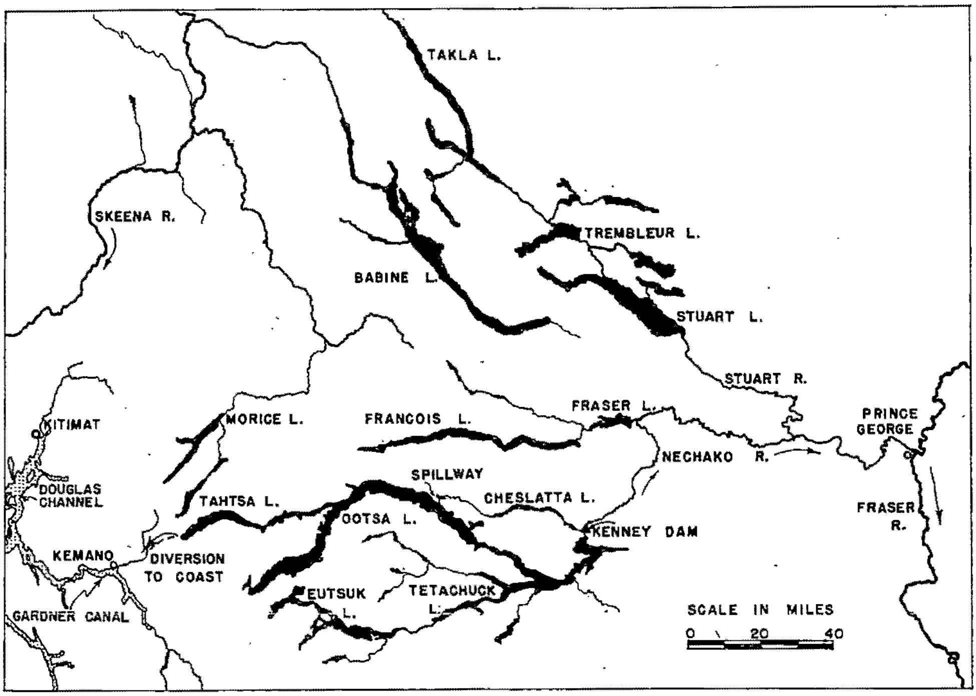


FIGURE 5—Diversion of Nechako River for power development.

reached 74.0 to 75.2°F (Internat. Pacific Salmon Fish. Comm., 1953). Under adverse conditions, such as existed in 1951, a severe reduction in sockeye productivity can be expected.

An increase in water temperature of the residual flow below the Puntledge River diversion dam during periods of adult salmon migration has been reported (Can. Dept. Fish., 1958). During a study of the upstream migration in 1955, a maximum temperature of 72°F was recorded. Between July 12 and September 6, there were 23 days when the water temperature was 68°F or higher. This was regarded as a critical level. In 1956, conditions during the early part of the upstream migration were more favorable as a result of higher discharge down the river channel. Later, however, as a result of reduced stream discharge, water temperatures were frequently in the lethal range. Some of the adult salmon mortality in this system has been attributed to the high temperatures of the residual flow. Increased water temperatures may be anticipated in many instances when river discharge is markedly reduced during the summer months.

EFFECT OF RESERVOIRS IN CHANGING RIVER TEMPERATURES

Major development of large rivers usually involves construction of mainstem dams of sufficient size to create substantial reservoirs. These impounded waters constitute an entirely artificial type of environment for aquatic organisms and have profound effects on temperature, water quality and discharge.

Natural lakes in the temperate climates usually follow a typical annual cycle in temperature structure. In deep lakes, bottom temperatures remain close to 39°F; surface temperatures vary seasonally from 32°F (ice cover) to 80°F or higher in some cases; formation of a thermocline often occurs in midsummer and if the lake is relatively productive this stratification may lead to oxygen depletion in lower levels; complete circulation of the water mass may occur during isothermal conditions in the spring and fall.

Several factors contribute to distortion of this natural state in reservoirs:

1. Reservoir basins are shaped differently from natural lakes. Reservoirs have been described by Ellis (1940) as "half lakes", the deepest spot usually being at the extreme downstream end, rather than in the middle. Reservoirs created by main-stem dams commonly show constrictions along their length corresponding to canyons of the former stream. Because a narrowing in a river canyon is the usual choice of site for a dam, the cross section at a dam is relatively narrow. These features may result in peculiarities in water circulation and temperature regime in reservoirs. Each construction of the basin may act as a bottleneck in circulation so that the reservoir may function as several separate basins connected by these narrow necks.

2. The location and schedule of operation of the outlet works of reservoirs is often highly artificial as compared to natural lakes. Where water is drawn from an intermediate or great depth, surface temperatures in reservoirs tend to remain high for long periods in the autumn months and the river below the dam is generally colder in summer and warmer in winter than formerly. Surface spill may profundly affect temperature structure in reservoirs if it is intermittent or highly variable during summer months (Harris and Silvey, 1940). Also, intermittent spilling of warm, surface water from reservoirs can cause rapid changes in the temperature of the river downstream.

3. Main-stem dams commonly have inflows that carry large loads of silt. The silt load contributes to the water mass of which it is a part, producing a density higher than clear water of the same temperature. Inflowing streams that are cooler than surface waters of lakes commonly "dive" to depths where they mix with or displace water of the same density. Inflowing heavily silted waters, having a density inconsistent with their temperature, dive to regions where temperatures are much cooler than their own. A remarkable number of effects on physical and chemical structure can ensue from the "density currents" thus created. In a series of papers, Wiebe (1939, 1940) has described the effect of these density currents on the vertical distribution of temperature and oxygen in Norris Reservoir in Tennessee. Ellis (1940) described similar conditions in Elephant Butte Reservoir, New Mexico. Temperature inversions, with warm silt-laden waters sandwiched between cooler, clear water occur sporadically in both reservoirs. Large water masses differing from the surrounding strata eddy at great depths and contribute to a highly complex structure. Ellis concluded that physical and chemical conditions were so irregular because of the combined action of density currents, the shape of the basin, and the regime of

regulation that regions of specific temperature and oxygen content were "hardly predictable". Inflowing loads of silt also cause high turbidity in reservoirs as well as smothering bottom organisms. In some instances the silt load may have a substantial oxygen demand and thus contribute to oxygen depletion at intermediate depths.

4. Fluctuation in water level is characteristic of most storage reservoirs. Its effects usually include shore erosion and additional complication of temperature structure.

Ellis (1942), in summarizing the relationships between the biological environment and the observed physical features of fresh-water impoundments, pointed out that since the position of the outlet is different in reservoirs than in lakes the temperature patterns of lakes and reservoirs are often distinctly different. Stable reservoirs generally have typical thermal patterns but draw-downs can abruptly alter the temperature regime. Draw-downs of reservoirs can also cause removal of stagnant water or accelerate the advancement of oxygen-deficient water. Fish production is limited in reservoirs by the lack of littoral areas and stable breeding and feeding areas. Biological productivity in reservoirs is often high initially but generally declines after a few years. Rawson (1958) reviewed these changes in productivity in reservoirs and cited the Spray reservoir, Lake Mead, Fort Peck and Canton reservoirs as examples where productivity was high initially and then declined. This is usually attributed to the initial fertilization of the basin by flooding and by washing plant and other organic matter into the lake. Streams upstream and downstream from reservoirs are also affected in many ways. Upstream from the dam, reduced velocity and increased depth may affect fish life. However, the main effect is felt in the area below the dam. The midsummer temperature is generally lower, the extent of change depending on the depth of draw-off. Draw-off of stagnant water, as a result of reservoir draw-down, could produce unfavorable conditions by introducing high-temperature, oxygen-deficient, or noxious water into the river downstream. Conditions lethal to fish could exist some distance downstream from the dam. Under certain circumstances, on the other hand, the reduced midsummer temperature and reduced silt load in water discharged from reservoirs might be beneficial to fish life.

The fact that water temperatures are affected by retention of water in reservoirs and are controlled by meteorologic and hydrologic conditions is evident. While the exact temperature regime of water in reservoirs is difficult to predict, certain conclusions concerning the effect of proposed reservoirs on river temperature can be drawn. Turbine intakes at the proposed Moran Dam, for example, would be located 230 ft. below maximum forebay elevation and about 30 ft. below minimum anticipated forebay elevation. Spill outlets would be located 60 and 260 ft. below the turbine intakes. Regardless of forebay elevation, the turbine and spill flow would be withdrawn from fixed elevations. This dam, proposed for construction on the main stem of the Fraser River 25 miles upstream from Lillooet, would have a head of about 720 ft., which would create a reservoir about 180 miles long (Potter, 1957).

Temperature distributions in this reservoir would be extremely variable and would be expected to vary considerably from year to year. This is well illustrated by data, particularly in August, for Lake Roosevelt, the impoundment behind Grand Coulee Dam (FIGURE 6). There is a range of temperature from 51° to 59.5°F at the 300-ft. depth, and from 66.2° to 70.5°F at the surface. Highest temperatures at the 300-ft. depth occurred in years of high discharge, which presumably resulted in greater than average replacement of water in the reservoir and consequently introduced warmer water to the bottom of the reservoir. It is significant to note that in the months illustrated, none of the water reached the temperature of maximum density (39.2°F) and there was little evidence of a stable thermocline. The depth-temperature relationship in this reservoir follows

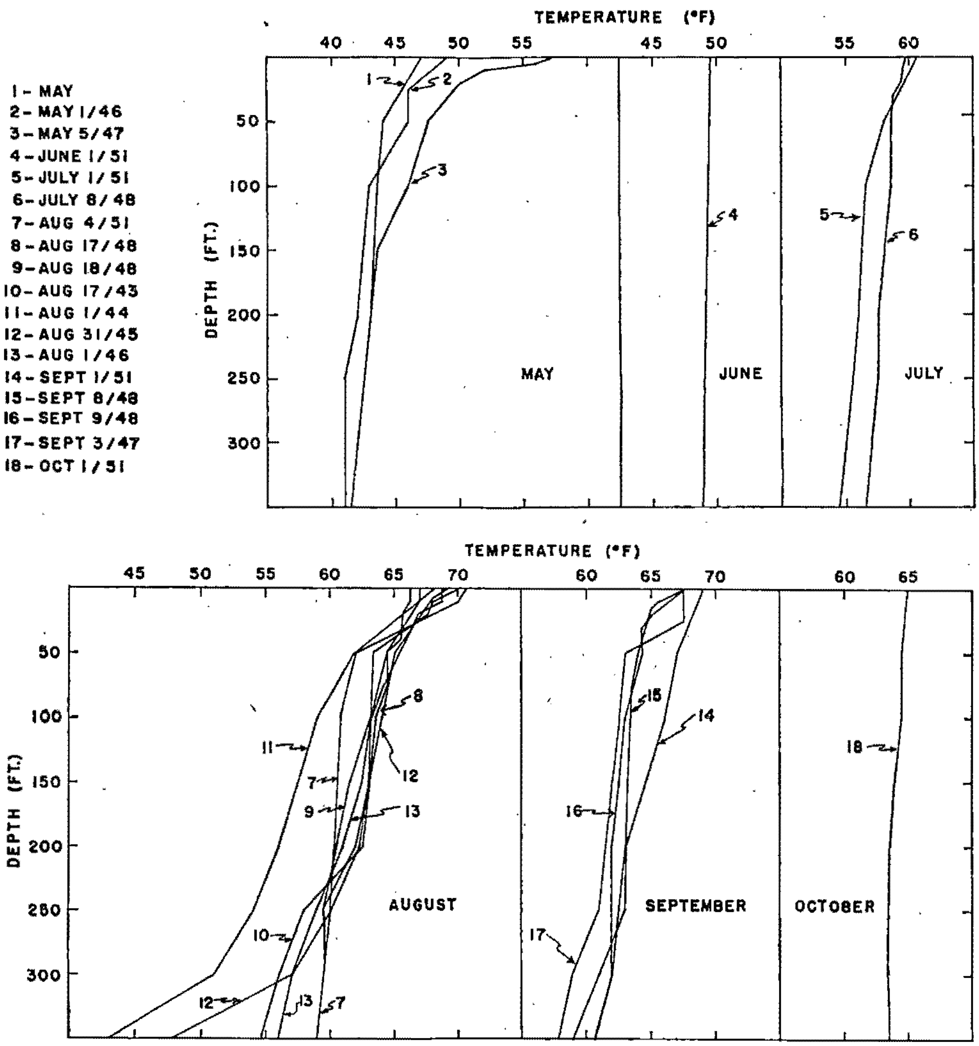


FIGURE 6—Water temperatures in Roosevelt Lake, the reservoir formed by Grand Coulee Dam. (From Anon., 1954 and Gangmark and Fulton, 1949.)

a much different pattern from that of deep lakes, of which Shuswap Lake is typical (FIGURE 7). Since the rate of volume change in the proposed Moran reservoir would be between that for Roosevelt Lake and that for Shuswap, it is indicated that the depth-temperature relationship at Moran Dam would be between these two limits. Data from Lake Shannon, the reservoir behind Baker Dam in Washington State, illustrates such an intermediate type of depth-temperature relationship (FIGURE 8). Temperature conditions in this reservoir, however, probably approach the lake type more closely than would be expected in the Moran reservoir.

Preliminary estimates of the probable depth-temperature relationships at Moran Dam have been prepared for an average year on the basis of river inflow temperature, travel time, and rate of replacement of reservoir volume, using the surface temperature of Shuswap Lake as a guide to reservoir surface temperature. These estimates indicate that the temperature of water discharged from the reservoir through spill and turbine outlets during the period of adult migrations would range from 43°F on July 1 to 56°F on September 30. These temperatures are 11°F colder and 9°F warmer respectively than average temperatures on those dates in the undeveloped river. The estimates of combined temperatures for all outflow from the dam compared with normal river temperatures for an average year and for a minimum water year are shown in FIGURE 9.

Water temperature is one of the most important features of the fishes' environment. The extensive temperature changes that would be created by reservoir construction on the Fraser River could affect upstream-migrating salmon in many ways.

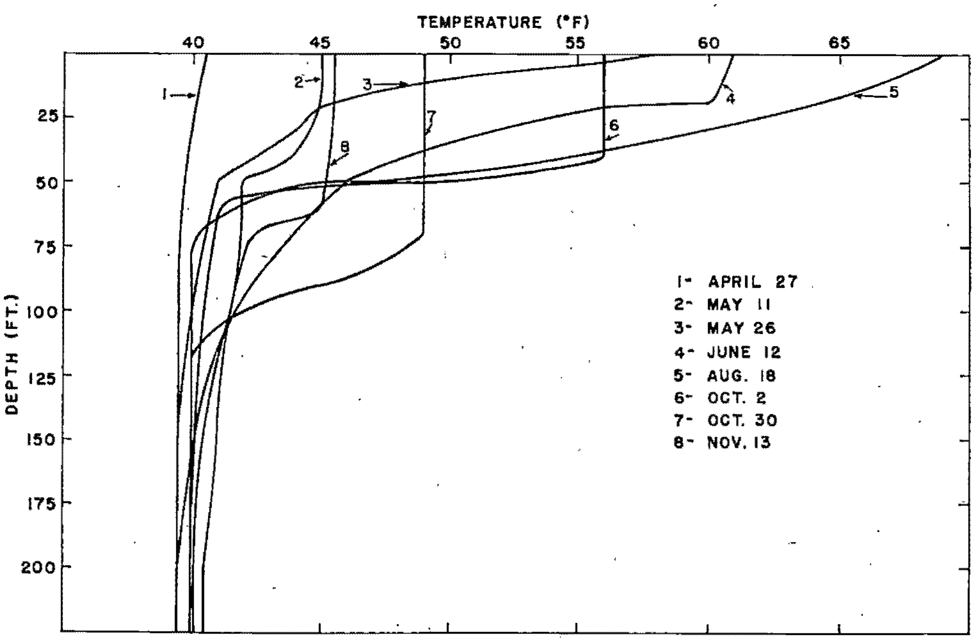


FIGURE 7—Water temperatures at Lee Creek Point in Shuswap Lake, 1948.

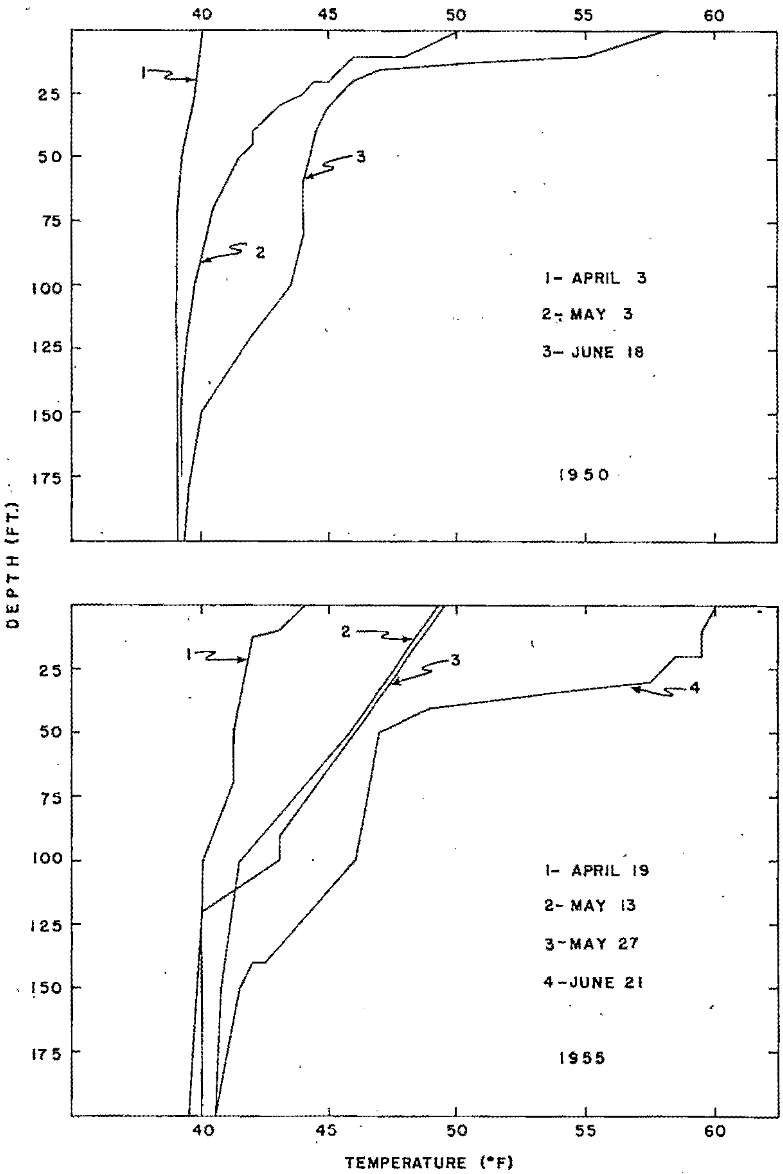


FIGURE 8—Water temperatures in Lake Shannon, the reservoir formed by Baker Dam.

EFFECTS OF TEMPERATURE ON FISH

Several workers have investigated the effects of temperature on metabolism and performance of fish. Lethal temperatures for some fish have also been determined but the majority of work done to date has been on the char (*Salvelinus*). Some of the basic temperature relationships have been determined and the following generalizations can be drawn:

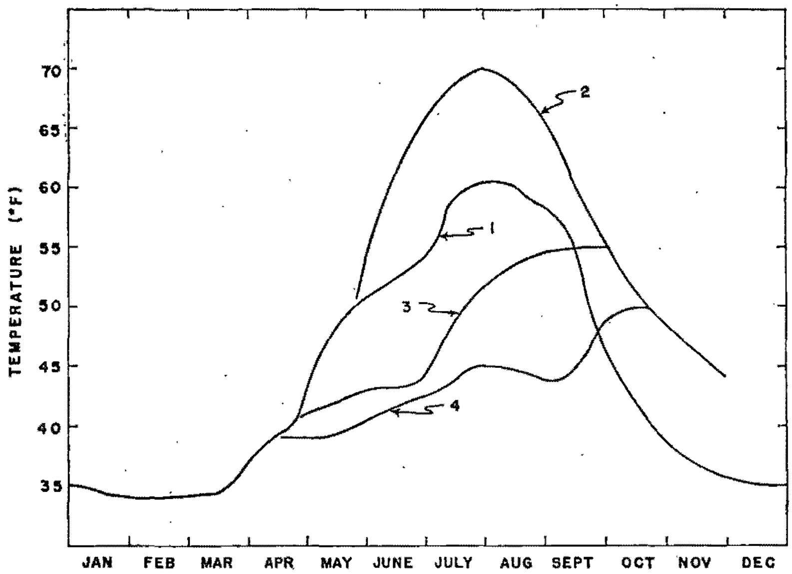


FIGURE 9—Estimated effect of the proposed dam at Moran Canyon on river temperatures.
1. Average temperature of the existing river.
2. Estimated average reservoir surface temperature.
3. Probable river temperature below the proposed dam in an average water year.
4. Probable river temperature below the proposed dam in a minimum water year, such as 1941.

1. The metabolic rate of fish, like that of other "cold-blooded" animals, is related to environmental temperatures.
2. The ability of fish to perform, generally expressed by sustained swimming speed, is also a function of water temperatures.
3. Certain temperatures are lethal to fish.
4. The responses of fish to temperature are, in part, a function of the thermal history of the fish.

Hoar (1956) described temperature as a factor controlling metabolism and activity. Gibson and Fry (1954) measured the standard (resting) and active metabolism of lake trout (*Salvelinus namaycush*) at various temperatures and noted that the standard metabolic rate increased with rising temperature up to the lethal temperature. However, the curves for active metabolism reached a maximum between 15°C (59°F) and 17°C (63°F) and then declined steadily. These findings applied both to one-year and two-year-old stock. Graham (1949) and Elson (1942) made comparable observations on brook trout (*Salvelinus fontinalus*). The active metabolic rate of this species increased with temperature up to 19°C (66.2°F). Sustained swimming speed was maximal between 16°C (61.1°F) and 20°C (68°F). Fry (1958) stated that, at present, cruising speed provides the best direct measure of activity. In goldfish (*Carassius auratus*), this is maximal at 24°C (75°F) and declines to 35°C (95°F). Brett *et al.* (1958) described the relation of temperature to sustained swimming speed of young sockeye and coho salmon. Peak activity, as illustrated in FIGURE 10, occurs at 15°C (59°F).

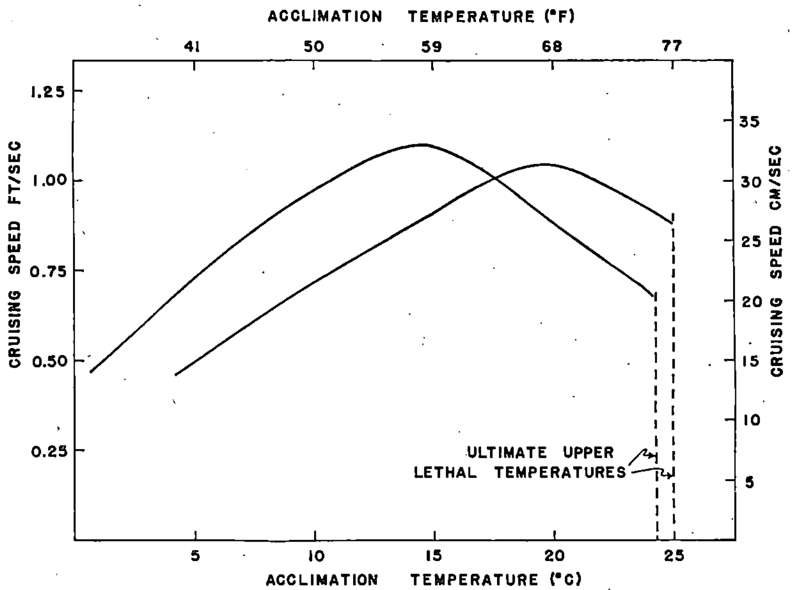


FIGURE 10—Maximum sustained cruising speed of sockeye and coho underyearlings in relation to temperature. (From Brett *et al.*, 1958.)

In general, work conducted to date indicates a steady increase in standard metabolism with rising temperature and a peak in the curve of active metabolism and temperature. The point of maximal difference between the standard and active curves of metabolism is the point at which the greatest scope for activity occurs and where the optimum energy release occurs. The temperatures of maximum sustained swimming speed and peak of active metabolic rate are generally in close agreement. However, all these relationships can be shifted one way or another depending on the temperature of acclimation. Fry and Hart (1948) presented evidence on this subject for goldfish.

Salmon and trout are not infrequently killed when they encounter unusual extremes of temperature. Huntsman (1942) reported a mortality of Atlantic salmon resulting from high temperature. Fresh-run fish died at 29.5°C (85°F) and those that had been in the river for some time succumbed at 30.5°C (86°F). Huntsman attributed this difference to acclimation. Sockeye salmon were found dead in 1942 in the Nechako and Fraser Rivers at Prince George when water temperatures ranged from 68° to 72.5°F (Internat. Pacific Salmon Fish. Comm., 1953). Fish and Hanavan (1948) reported that sockeye and chinook salmon and steelhead trout of the Columbia River near Bonneville and Rock Island Dams were observed in 1941 congregating in small, hitherto unused cold creeks when the temperature of the Columbia was 71° to 75°F. Many fish may have died during this period. Craddock (1958) attributed an observed high, pre-spawning mortality among Columbia River sockeye to high water temperatures on the migration route. High mortality of unspawned sockeye of the Late Stuart run of the Fraser River system has also been attributed to high temperatures on the spawning grounds.

Brett (1956) presented a comprehensive review of knowledge concerning the thermal requirements of fishes. He pointed out that lethal temperatures can be determined for fish to within ±0.2°C but that acclimation temperatures greatly affect the lethal level. The Salmonidae have the lowest thermal tolerance of fish tested to date, including many of the common fish of Canada. Black (1953) presented data on upper lethal temperatures of some British Columbia fresh-water fishes and his conclusions were in agreement with those of Brett. Death due to high temperature seems to result initially from a breakdown of nervous tissue, affecting respiration. Death from low temperatures occurs as a result of interference with the nervous system, osmotic balance and possibly other essential functions.

It is entirely possible that lethal temperatures may result when dams reduce river flow or when river flow consists of surface water spilled from a reservoir. Since metabolic rate is controlled by water temperature, high stream temperatures cause rapid and inefficient utilization of energy reserves of upstream-migrating salmon and thus may reduce the ability of the fish to reproduce successfully.

The extensive temperature changes that would be created by hydroelectric development on the Fraser River would also affect the behavior of upstream-migrating salmon. Calderwood (1903) found that Atlantic salmon ascended the Tay River from the estuary during times when there was either a rise in water temperature and level or a rise in temperature unaccompanied by a rise in level. Mottley (1938) concluded that temperature was the main factor influencing the migration of rainbow trout (*Salmo gairdnerii*) into the inlet of Paul Lake, B.C. Whereas Davidson *et al.* (1943) reported no relationship between temperature and numbers of upstream-migrant pink salmon, Briggs (1953) noted that steelhead did not migrate upriver with an increased discharge of cold water but remained downstream until the temperature rose several degrees. Delay of sockeye salmon has been reported off the glacial Upper Pitt River in the Lower Mainland of B.C. until the water temperature is raised by fall rains. Elson (1942) considered that temperature was an important stimulus controlling the movement of trout from a lake into a stream.

Studies of fish populations in the Tennessee River have shown that reservoirs constructed on that river and its tributaries have changed the pattern of fish migration as well as the species composition. Shields (1944), Eschmeyer (1944), and Eschmeyer and Manges (1945) all report extensive migrations of fish precipitated by temperature changes resulting from reservoir construction. These migrations were related to the discharge of cold water from deeply submerged outlets at dams. These temperature changes in rivers below dams caused migrations of large populations and resulted in local concentrations of fish. Since some species of fish have different temperature preferences than others, the temperature changes caused by storage of water and submerged-orifice discharge at dams have been observed to result in changes in species composition (Dendy, 1946; Swingle, 1954; Thompson, 1955). Coarse or trash fish frequently become more numerous.

Pfitzer (1954) reported that construction of dams in the Tennessee Valley has caused major changes in the ecology of the waters downstream. The river temperature has been lowered, the extreme temperature limits have been reduced, and an erratic seasonal dissolved oxygen pattern has resulted. Changes have been noted in both the plant and animal populations. Resident fish populations have changed from large warm-water species to small cold-water species. Many minnow species have disappeared. Rainbow trout fingerlings seem to have been provided with an improved environment but brook trout have not survived in the new environmental conditions. Eschmeyer and Smith (1943) reported that water discharged from Norris Dam is taken, except on rare occasions, from below the thermocline and that the resultant decrease in river temperature has adversely affected the production of warm-water species. Several species do not deposit their eggs in the new cold-water environment.

Temperature changes in the Fraser River might delay the migration of fish from the estuary. Further delay of migrating fish in the river might result from reduced metabolism and activity. Such delays would mean that adult salmon migrating upriver would be late in arriving on the spawning grounds. Late arrival on the spawning grounds would generally mean poor timing with the environmental cycle and consequent inefficient spawning and poor egg and fry survival. Available evidence suggests that it would be necessary to maintain a normal river environment to ensure safe undelayed passage and successful spawning of sockeye salmon.

Water temperatures below dams would, of course, depend on the amount of any spill from the surface and the amount and depth of draw-off of water passing through the turbines or outlet works. At high dams, there would be a differential between the temperature of tailwater and forebay, the extent of the difference depending on the depth of draw-off. Any fish moving up fishways or being transported around the dam would be subjected to a sharp temperature change that might be detrimental.

The temperature preferences of migrating salmon must be considered in designing passage facilities. Large differences in temperature of tailwater and fishway water could occur at high-head dams. Sullivan and Fisher (1953) have reported preferred temperatures for brook trout and Fisher and Elson (1950) have reported temperature preference of Atlantic salmon and brook trout but no experiments have yet been conducted on adult sockeye and pink salmon. It has been noted that the preferred temperature varies for different species, and depends on the age and thermal history of the fish. Seasonal changes in preferred temperature have also been noted, possibly related to some inherent rhythmic cycle (Sullivan and Fisher, *ibid.*).

A problem of temperature preference or a temperature barrier was indicated during passage of adult salmon at Pelton Dam on the Deschutes River in Oregon in 1958. Water is discharged from the reservoir through deeply submerged outlets whereas the water in the fishway is drawn from the reservoir surface (Eicher, 1958a; Pretious and Kersey, 1957). The fishway extends for three miles below the dam, in which distance the water temperature may increase considerably during periods of warm weather, thus accentuating the temperature differential between the river and the fishway entrance. It was observed that the fish appeared hesitant to enter the fishway under these conditions. They therefore had to be trapped and then transported over the dam by tank truck. While it was possible to handle the small number of migrants at Pelton Dam in this manner, the problem would have been much more difficult if not impossible to resolve if many millions of salmon had been involved.

Changed temperatures might have a serious effect on pink salmon spawning in the main stem of the Fraser River below proposed dams. As shown in FIGURE 9, it is likely that temperatures in the Fraser River would be higher than normal after September 15 if the proposed Moran Dam were built. The extent of the temperature change would vary from year to year but calculations indicate that in an average year the water below Moran Dam would be at least 5°F warmer than normal during the period of pink salmon spawning in the main stem of the Fraser River. The egg incubation period would be reduced as a result of higher temperature. The resultant earlier fry emergence could cause inappropriate timing with conditions most favorable for maximum survival.

This summary of the possible effects of temperature changes on upstream-migrating adult salmon indicates that serious consequences could result if dams were constructed on the Fraser River. The magnitude of change and the total effects of such change would vary for different proposed projects. Under certain conditions, temperature changes may benefit certain species of salmon and trout. For example, the construction of Shasta Dam on the Sacramento River prevented the migration of chinook salmon to their native spawning grounds but temperatures in the river below the dam were reduced and these fish were therefore able to use the lower area of the stream to a much greater extent than was formerly possible (Moffett, 1949). Such compensatory results are unusual.

Sockeye, and probably pink salmon, are inherently adapted to present temperature cycles. The existing populations have become adapted to the natural environment over a period of many generations. The range of natural variation is, in many cases, relatively small. For instance, the annual variation in average water temperature during the incubation period of sockeye eggs in the Stellako River has been approximately 1°F above or below the mean incubation temperature for a seven-year period. There has probably been selection in favor of fish with responses appropriate to this narrow range of variation. Any proposed change from natural conditions must therefore be carefully considered. Considerable evidence indicates that adult salmon are affected by changes in temperature. However, further research will be required to permit confident prediction of either the extent of temperature change to be expected from various water utilization projects or the total effect of such changes on productivity of salmonid fishes. It is abundantly clear, therefore, that this problem requires much more study before the effects of proposed dams can be thoroughly evaluated.

CHANGES IN WATER QUALITY

Man has altered the water quality of natural rivers by reservoir storages, releases, diversions, sewage and industrial waste discharge, return of spent irrigation waters, and by other multiple-water-use developments. In general, reservoirs have their principal effect on water quality by reducing turbidity and changing downstream water temperature but they may also produce increases or decreases in the dissolved constituents (Sylvester, 1958). Columbia River water quality studies in 1910 and 1911, before major dam construction, and from 1952 to 1956, after large-scale development of the river, indicated a general rise in dissolved constituents between the two periods. The increase in all tributaries was not the same because of the differences in waste discharge, water impoundment, irrigated acreage, and soil composition. Groundwater flows from irrigated areas caused the greatest increase in dissolved constituents. Sylvester considered that in no instance had a water constituent increased to the point that the water was nearing the upper limit of acceptability for propagation of fish life.

Odor is an important factor influencing the orientation of adult salmon migrating upstream (Hasler, 1956; Wisby and Hasler, 1954). These authors concluded that the odor or odors concerned with migration may be volatile aromatic compounds. Hasler and Larsen (1955) commented that orientation may not be the result of the response to one odor but to the subtle combination of several odors in the parent stream. It is not yet possible to state what effect impoundments of river water, return of spent irrigation water, leaching of various compounds from the reservoir basin, and similar consequences of impoundments have on odor orientation and homing of salmon. Possibly such changes could alter the cues which the salmon use as a guide to their "home" stream. However, until such time as further work is done concerning factors that guide salmon to their natal stream, no evaluation of the effects of water impoundments in changing the home-stream cues can be made.

Ward (1927) maintained that adult sockeye on their spawning migration consistently chose cold-water streams but Foerster (1929a) showed that sockeye salmon destined for Sweltzer Creek, a tributary to the Vedder River, sometimes chose the colder stream and in other cases the warmer stream. Oxygen content and pH seemed to have no directive influence on sockeye migration. Foerster concluded: "It seems only reasonable to believe that some physio-chemical attribute or attributes of the waters traversed, either singly or in association, direct the route of migration but the determination of the directing constituents seems yet far distant." Powers (1939) presented a thorough summary of available information concerning chemical factors affecting the migratory movements of Pacific salmon. He noted that fish possess chemical receptors sensitive to carbon dioxide tension and that laboratory experiments have shown that fishes, including salmon, respond to gradients of physical and chemical characteristics. In a later report (Powers and Clark, 1943), further evidence was presented that led to the suggestion that "a response to a carbon dioxide gradient is a dominant factor in the spawning migratory movements of fishes especially the salmon." While the significance of carbon dioxide gradient has not been demonstrated in field experiments with Pacific salmon, sensitivity of fish to various physio-chemical gradients is apparent. If this sensitivity provides a directive influence in the migration of Fraser River sockeye and pink salmon, the possible hazards involved in changing the quality of water by hydroelectric and other water-use projects are obvious.

Construction of storage dams would inevitably result in a reduction of flow for part of each year. Reduction of velocity in a river such as the Fraser would increase the settling of silt and consequently decrease the turbidity of the water. Data collected from Roosevelt Lake indicate a considerable clarification of the Columbia River during passage through this reservoir. Turbidities in the reservoir were 7 p.p.m. in September 1952 compared with 19 p.p.m. in the incoming Columbia River (Robeck *et al.,* 1954). Similar changes could be expected if dams were constructed on the Fraser. The effects of a decrease in turbidity are unknown. Possibly home-stream cues are in some way associated with suspended material carried by the water. The associated increase in light penetration might influence the daily pattern of migration. It seems likely, however, that decreased turbidity would have more profound effects during other phases of the life cycle, such as during downstream migration when the fish might become more susceptible to predation.

Regulation of the flow of the Fraser River would result in a decreased dilution of pollutants and toxicants during part of each year. Pollution resulting from disposal of industrial wastes and domestic sewage is becoming more evident, especially in the lower river area. Increased river temperatures and reduced flow, in combination with increased industrial expansion, might result in an increased concentration of pollutants and a reduction in the amount of oxygen available to the fish. A survey conducted in 1951 and 1952 revealed that:

"1. The North Arm of the Fraser River is moderately polluted. The principal indices are the *coli-aerogenes* tests and the B.O.D. It is probable that domestic sewage is the chief contributor to the condition.

"2. The dissolved oxygen level in the North Arm is below normal but not sufficiently so as yet to menace the fisheries. A twenty per cent depletion was found at Marpole in the winter months but the water temperature was low and the 20% deficiency still left a fair surplus of oxygen for aquatic life which has a low metabolic demand at that time of year." There was no significant indication of organic pollution at other points in the river, except for slight oxygen depletions near Prince George, Quesnel, and Kamloops, but the report pointed out that with large industrial developments in prospect for British Columbia severe pollution could develop in the North Arm of the Fraser River (B.C. Res. Council, 1952). Any decreased flow would result in reduced dilution of toxic materials. If proper precautions are not taken, industrial expansion and population increase could result in a pollution level not only in the lower Fraser River but also in the upriver areas that would be lethal for both young and adult salmon. This condition would be aggravated by the temperature increase and flow reduction that would be caused by proposed hydroelectric developments.

Fish and Wagner (1950) reported that pollution of the Willamette River in Oregon in 1949 was of sufficient magnitude to overload the lower reaches during periods of low flows and high temperatures. During July, August and September, the dissolved oxygen level was less than 5 p.p.m. The authors stated: "The lowest reach of the river is degraded to the point where oxygen deficiency precludes any movement of migratory fishes through the affected area." This blockade of the river, caused by oxygen deficiency, destroyed a significant run of fall chinooks in the Willamette River.

Several workers have studied oxygen requirements of salmonids but the results must still be considered inconclusive. Ellis (1937) found that desirable fish populations (trout, bass, etc.) were not found in waters containing less than 5 p.p.m. of oxygen. Lincoln and Foster (1943) observed that 5 p.p.m. dissolved oxygen was the lowest level that may reasonably be expected to maintain a varied fish fauna. Shepard (1955), working with brook trout, noted that the incipient lethal level of oxygen concentration was 1.85 p.p.m. at 9° to 10°C (48° to 50°F). The lowest level to which these trout could be acclimated was 1.05 p.p.m. Gibson and Fry (1954) reported that the uptake of oxygen by active lake trout became dependent on the amount of oxygen dissolved in the water when the oxygen content fell to two thirds or less of the saturation level.

The earliest experiments to determine minimum oxygen requirements of salmon were conducted by observing the levels at which fish showed definite signs of distress. Chapman (1940a) conducted experiments with both adult and young sockeye and chinook salmon and found that at a dissolved oxygen content of 3.5 p.p.m. salmon showed definite signs of distress; a reduction below 3.0 p.p.m. caused death of some fish; a reduction below 2.5 p.p.m. brought about the asphyxiation of most of the fish in a short time. Considerable individual variation was found, some fish not dying until the oxygen concentration had dropped to 1.2 p.p.m. Chapman also observed that suckers (Catostomidae) and carp *(Cyprinus carpio)*, were more tolerant to low oxygen levels than were salmon.

In a review of literature concerning dissolved oxygen requirements of fish, Tarzwell (1958) summarized the findings of many investigators and noted that the amount of oxygen required by fishes is determined in part by activity. The following are some of the observations from Tarzwell's paper: From two to four times as much oxygen is required by a fish when it is active as when it is resting. Under actual stream conditions a fish must maintain its position against the current, find, pursue and catch its food, avoid its enemies, and reproduce. All these activities require oxygen in such amounts that dissolved oxygen levels at which the fish can *just* survive are unsatisfactory. Age, size and season are also of importance. In general, fry and younger fish have a higher metabolic rate and require more oxygen than adults. Because of their physiological condition and increased activity, fish require more oxygen at the spawning season. An actively feeding, growing fish requires considerably more oxygen than one that feeds very little. Since growth is rapid in the fry to fingerling stage, it is expected that for many species, dissolved oxygen requirements will be higher at this period. Incubating eggs require higher dissolved oxygen levels than do adult fish. Since the velocity of flow through bottom materials surrounding the incubating eggs is low, the water must contain a high level of dissolved oxygen to provide the needed requirements.

Tarzwell further maintained that short-term studies carried out in aquaria at low temperatures with unfed, resistant species of fish indicate only that certain fishes can survive very low concentrations of dissolved oxygen for limited periods. It should be recognized that these levels are not adequate for normal existence. In setting water-quality criteria for the protection of aquatic life, it must be recognized that mere survival is not sufficient and that the minimum dissolved oxygen level must be suitable for the continuous maintenance of a satisfactory fish fauna. Minimum oxygen levels at which some species can, through adaptation, resist death by asphyxiation for a time are not adequate for completion of the normal life cycle. In order that oxygen levels may be continuously adequate for maintenance of salmonid populations, Tarzwell (1958) recommended a minimum dissolved oxygen level of 5 p.p.m. during periods of stream residence of adults and 6 p.p.m. during periods of egg incubation and fry development. During discussion of Tarzwell's paper, it was indicated that high egg survival is obtained only at oxygen levels higher than 9 or 10 p.p.m. and that minimum criteria for streams should be raised to at least 7 p.p.m. during the spawning and egg incubation period.

The interrelationships of temperature, oxygen, carbon dioxide and other factors in determining the activity of salmonids have not been adequately studied. Because respiration is an oxygen and carbon dioxide exchange, carbon dioxide levels are important in determining the minimum permissible dissolved oxygen levels at each temperature. Basu (1959) made a systematic study of the respiration of five species of fish stimulated to activity in the presence of various concentrations of oxygen and carbon dioxide and found that the scope for activity was decreased as the carbon dioxide concentrations were increased. The mineral content of the water may also be an important factor in determining minimum permissible oxygen concentrations in that low mineral levels increase the osmo-regulatory stress. Phillips (1959) pointed out that trout transferred from high calcium waters into low calcium waters show a marked increase in their metabolic rate. In low calcium waters the metabolism of the fish, and therefore the oxygen consumption, increases to oppose changes in blood concentration. These factors, as well as others, require further study before minimum permissible oxygen levels can be adequately expressed.

Brett (1958) has pointed out that a sublethal stress, affecting the ability of young sockeye to extract oxygen, occurred during sulphate mill effluent toxicity studies. He pointed out the possible necessity for revising the limits of oxygen necessary for respiration. Oxygen requirements have, in the past, been determined by experiments with fish not previously stressed. Such standards may not be adequate.

Collection of Adults at Dams

Facilities for passing fish over dams constructed on the migration routes of Fraser River sockeye would have to be capable of providing immediate passage for very large numbers of fish. However, many factors contribute to delayed and restricted passage of adult salmon at dams. Some of the problems resulting from temperature change, alteration of water quality, decreased dilution of pollutants and toxic wastes, and variable discharges downstream from dams have already been pointed out. In addition, upstream-migrating salmon may be fatigued, delayed and even injured in finding and ascending passage facilities at dams. The relatively small size and discharge of fish-collection facilities compared with spillway and turbine discharges delays upstream passage of salmon. Further, the turbulence and changing, multi-directional flow from spillways and turbines may disorient the fish. Observations of salmon migrations have shown that, unless the fish are blocked, they generally do not choose small side channels along their migration route. Even when passage through the major flow is blocked, salmon appear reluctant to enter a small alternate flow. Passage at dams can therefore be seriously impeded.

Serious consequences can result when salmon are prevented from migrating upstream, even for short periods of time. For instance, Ricker and Robertson (1935) observed that adult sockeye, after encountering an obstacle in their parent stream, returned downstream to a larger river and some ascended a considerable distance up this river. In an experimentally marked group of 100 such salmon, all eventually returned to the parent stream but some did not appear until after a delay of three weeks. Such delays would likely eliminate the productive capacity of most races of Fraser River sockeye. Thompson (1945) showed that a delay of 12 days at Hell's Gate, before construction of the fishways, was sufficient to prevent sockeye from reaching their spawning grounds and suggested that lesser delays reduced the reproductive capacity of the fish. Subsequent data indicate that a delay of two to four days may be critical for some upriver races of sockeye.

The fishways at Hell's Gate are ideally placed in that the entrances are located at the farthest upstream point to which the fish can swim. The fish are then led directly to the entrances by following the only path available to them, the narrow marginal areas between the river bank and the high mid-stream velocities. At Hell's Gate, the fish have no choice because mid-stream velocities of close to 20 f.p.s. force them to follow the banks. The success of such fishways in collecting and passing fish would suggest that the same system should be used at dams. However, as discussed in a subsequent section, it has been found practically impossible to confine fish at dams to narrow marginal areas. Fish can generally traverse the entire width of dams in attempts to swim upstream in the variable flows from the turbines and spillway gates.

The amount of flow available for attracting salmon to fish-passage facilities at dams can be only a small proportion of total stream flow. As a result, fish often make many attempts to pass upstream through spillway or turbine discharges.

Delay experienced by chinook salmon in finding fish-passage facilities at Bonneville Dam was measured in 1948 by tagging groups of fish above and below the dam and recovering tagged fish from the two groups in the commercial fishery 60 miles upstream (Schoning and Johnson, 1956). It was found that the migration was delayed about 2.6 to 3.0 days by the dam. Since fish are known to require about two hours to ascend 35 vertical feet of the fishways at Bonneville Dam, which has a nominal head of 60 ft., it is suggested that the average delay below the dam in finding entrances to the fishways is at least two days.

Delaying adult sockeye at dams during their upstream migration would seriously affect their productivity. The timing of the upstream migration of Fraser River sockeye appears to be more critical than for other salmon populations. These fish do not delay in the river as do the chinook populations of the Columbia River, for example. It is also very important to note that hydroelectric development of the Fraser River system would eventually result in the construction of many dams on salmon migration routes. It is therefore completely unrealistic to consider the possible effects of only one dam. Available information, which is presented in some detail in succeeding pages, indicates that unless the delay at dams could be eliminated, hydrolectric development of the Fraser River system would destroy most of the upriver sockeye populations.

In assessing the problem of collecting upstream-migrant sockeye and pink salmon for transportation over proposed hydroelectric installations on the Fraser River, it is necessary to consider the great number of fish that would have to be handled on a daily and hourly basis, the effects of delaying the upstream migration of these fish, their limited energy reserves, the effect of fatigue on their swimming ability, and the possibility of artificially attracting or directing the fish to entrances of passage facilities.

NUMBERS TO BE HANDLED

One of the first considerations in assessing the physical and biological problem of collecting and transporting adult salmon at dams involves a determination of the numbers of fish to be handled on a daily and hourly basis. Good estimates of the numbers of sockeye and pink salmon spawning in different areas in the Fraser River watershed are obtained each year. Most of the upriver races, which are the ones that would be affected to the greatest extent by dam construction, are increasing in numbers as a result of rehabilitation measures. From 1913 to 1945 most of these upriver races were seriously affected by an obstruction in the Fraser River at Hell's Gate that reduced some of the populations to a very low level of abundance and completely destroyed others. Construction of fishways at Hell's Gate in 1945, protection of depleted populations in the commercial fishery and other conservation measures have resulted in substantial increases in the spawning populations. However, the historical levels of abundance have by no means been reached at the present time. Available historical data must therefore be used as well as knowledge of present population sizes in estimating the numbers of adult salmon that would have to be handled if dams were constructed on the sockeye and pink salmon migration routes of the Fraser River watershed.

It has been estimated that a minimum of 750,000 sockeye may be expected to migrate up the Fraser River in a single day during peak escapements of large runs such as that to Adams River (Anon., 1955). This estimate was based on the 1913 daily commercial catch. In 1913, the United States commercial fishery caught about 1,000,000 sockeye per day during the peak of the run in late July and early August while Canadian fishermen caught in excess of 500,000 sockeye daily from the same run. Thus, the maximum daily run may have consisted of considerably more than 1,500,000 sockeye. Since it is a management necessity to regulate the fishery by periodic closed seasons in such a manner as to provide the bulk of the spawning escapement of each race from the peak of each run, the maximum daily escapement could consist of at least 1,500,000 sockeye if the effect of the fishery in reducing the size of the maximum daily escapement is neglected. Even if it is reasonably assumed that the peak of the run suffered a 50 per cent fishing mortality before fishing was closed, the maximum daily escapement could exceed 750,000 fish.

An even greater number of fish is believed to have entered the Fraser River in a single day in 1954 during the peak of escapement of the sockeye run destined for the Adams River area. The spawning migration of this run started at a point one mile above Steveston at the mouth of the Fraser River at about 3:00 p.m. on September 16, 1954 and within three days it was almost completed. It was estimated that practically the entire escapement of 2,048,000 sockeye entered the river in 60 hours, with about 1,250,000 passing upstream on the peak day. Therefore, with this type of regulation of the commercial fishery, which is considered essential for providing an adequate escapement, the peak daily escapement of each race can be expected to reach 60 per cent of the total escapement.

While much has been written in recent years concerning the Adams River sockeye run, the importance of other sockeye runs in the upriver areas should not be neglected. The Quesnel sockeye run was almost destroyed by the effects of the Hell's Gate obstruction and a dam at the outlet of Quesnel Lake, but early escapement records suggest that the Quesnel run was even larger than the Adams River run. Evidence indicates that production in both 1909 and 1913 exceeded 10,000,000 sockeye, of which about 20 per cent escaped to the spawning area in Horsefly River. The Hell's Gate obstruction so reduced the original large run that by 1941 only an estimated 1000 spawners remained. With the construction of the Hell's Gate fishways in 1945, and the advent of special regulations in 1949, the spawning escapement increased to 107,500 fish in 1953 and 229,000 in 1957. Historical records also suggest that the lakes of the Stuart River system formerly produced sockeye runs that were exceeded in numbers only by the Quesnel and South Thompson River systems. The spectacular recovery of the early and late runs to the Stuart system following construction of the Hell's Gate fishways indicates the great potential of this area as a sockeye producer. In 1941, one cycle before completion of the Hell's Gate fishways, the escapement of the early run was 6300 and the escapement of the late run was 5500, totalling 11,800 spawning sockeye for the entire district. In 1953, two cycles after completion of the fishways, the escapement totalled 509,000. In the next cycle year, when both runs were again heavily fished, the escapement totalled 762,000 fish. The present production of sockeye in the upriver lake systems is considerably less than the potential production. Any dams constructed on the migrations routes of these upriver races would have to provide fish-passage facilities for very large numbers of fish. The previously estimated daily run of 750,000 fish must be considered conservative when it is realized that in 1954 over 2,000,000 Adams River sockeye entered the Fraser River in a 60-hour period.

The Adams River run, which enters the Fraser River later than other major sockeye runs, delays off the mouth of the Fraser River for at least two weeks before moving upstream. Early migrating races, such as Chilko, Quesnel and Stuart runs, generally enter the Fraser River over a period of about 30 days and the peak daily escapement is about 20 per cent of the total escapement (Anon., 1955). Thus, from a fully rehabilitated Quesnel run, consisting of 2,000,000 spawners, it would be reasonable to expect a peak daily escapement of 400,000. It must also be realized that several races of sockeye migrate upriver simultaneously, although peak escapements generally do not coincide. The Chilko, Quesnel, Late Stuart and Stellako races migrate at about the same time, along with sockeye from the last part of the Gates, Nadina, Bowron, Raft and Seymour runs. In view of the ever-increasing efficiency of the commercial fishery it is likely that management requirements will necessitate complete closures at the peak of each run. Consequently, large daily escapements to these areas can be expected and may readily exceed 750,000 fish.

The late Adams River sockeye, unlike many other races, have apparently become adapted to a slower rate of migration and to periodic short delays caused by low water at the time of their migration. As a result, it is considered unlikely that fish facilities at proposed dams on the Thompson River would have to pass more than 375,000 sockeye per day. Fish facilities constructed to pass the other major sockeye runs, such as to the Quesnel area, would have to be capable of handling at least 750,000 fish per day.

Facilities would also have to be provided at Fraser River dams for passing pink salmon. Numerous small streams tributary to the Fraser River from Hope to Lytton support minor populations totalling approximately 10,000 pink salmon at the present time. In 1957, the Seton-Anderson system supported a spawning population of about 60,000 pinks. A few spawning pink salmon have also been found in Churn Creek, a tributary of the Fraser River about 15 miles south of the Chilcotin-Fraser junction. The main spawning of pink salmon above Hope occurs in the Thompson River from Spences Bridge to Kamloops Lake. Some spawning also occurs in the Nicola River and other tributaries of the Thompson River below Kamloops Lake. The Seton-Anderson and Fraser Canyon populations appear to be limited in size by the availability of spawning areas but the Thompson River is expected to support substantially increased spawning runs in the next few years. In 1957, the Thompson River system supported a total population of 266,000 fish, of which only 1560 spawned in the Nicola River. An indication of the historical levels of abundance of pink salmon spawning in the Thompson River and its tributaries can be obtained from a report of the Provincial Commissioner of Fisheries: "Thompson River—Previous to the blockade in 1913 many millions of pink salmon passed up the Thompson every other year and spawned on its gravel reaches or entered its tributaries. The bed of the Nicola, the principal tributary of the Thompson, from its source to its mouth, was literally paved with pink salmon every other year." (Babcock, 1918). This and other historical references, combined with recent studies to determine the extent of available spawning area, suggest that the former spawning populations may have been 10 times as large as the 1957 population. Thus, the Thompson River pink salmon spawning population might reach 2,000,000.

Pink salmon runs do not normally coincide in timing with the sockeye runs because the latter, with the exception of the large Adams River run, are considerably earlier. Thus, the Quesnel, Stuart, Chilko and other upriver sockeye runs migrate upstream before arrival of the pink salmon runs. Since the Adams River sockeye run is dominant on the 1950-54-58 cycle and the pink salmon runs occur in the Fraser only on odd-numbered years, the pink salmon runs coincide only with the off-year Adams River runs. Adams River spawning populations in the years preceding the dominant runs can be expected to consist of over 200,000 jack sockeye and a few adults. In 1953 there were 218,000 jacks and 4000 adults and in 1957 the population consisted of 258,000 jacks and 2000 adults. Spawning populations in years following the dominant runs (1951-55-59) can be expected to consist of less than 200,000 adult sockeye and very few jacks. These fish migrate up the Fraser and Thompson Rivers at about the same time as pink salmon destined for the Seton-Anderson system and for the Thompson River.

Visual counts of pink salmon migrating up the Thompson River in 1957 revealed that the proportion of the run migrating on the peak day was much lower than for sockeye. A counting station was located on the Thompson River about 10 miles upstream from Lytton. Of 118,000 pinks counted, only 7.8 per cent migrated upstream on the peak day (Ward, 1959). It has been observed on numerous occasions that the upstream migration of pink salmon is not as sharply peaked as that of sockeye.

On this basis, if the maximum spawning poulations migrating up the Thompson River consisted of 2,000,000 pink salmon and 258,000 jack sockeye, with 7.8 per cent of the pink salmon and 20 per cent of the sockeye appearing on the peak day, the maximum daily migration would be about 208,000 fish. It appears, therefore, that fish-handling facilities at proposed dams on the Thompson River would have to be capable of handling at least 200,000 fish per day in years of pink salmon spawning and 375,000 during dominant-year runs of Adams River sockeye.

The diurnal variation in daily migration is an important consideration in calculating the number of fish that would have to be passed at proposed Fraser River dams. MacKinnon and Brett (1953) reported a definite pattern in the hourly intensity of a salmon run through a fishway at a natural obstruction on the Stamp River, Vancouver Island. The authors reported a direct relationship between intensity of the run and light intensity, particularly during the morning hours. The run began at about 5:00 a.m., increased rapidly until 10:00 a.m., rose gradually to mid-afternoon, then fell rapidly to zero at about 10:00 p.m. Continuous observations at a fishway over Seton Dam in 1956 during passage of the Gates Creek sockeye run showed that 19 per cent of the total run passed through the fishway on the peak day, with an average of 10 per cent and a maximum of 22 per cent of each day's migration passing through the fishway during the peak hour from 5:00 to 6:00 a.m. (Andrew and Geen, 1958). The peak hourly migration of sockeye at Bonneville Dam on the Columbia River occurs from 6:00 to 7:00 a.m., with an average of 14 per cent of the fish passing upstream during this peak hour (Anon., 1955). At Seton Dam, it was determined that the maximum migration in a 15-minute period was 10.7 per cent of the daily migration. On this basis, for a peak daily escapement of 750,000 sockeye, a maximum of 22 per cent or 165,000 would be expected to move upstream in one hour and a maximum of 10.7 per cent or 80,000 in a single 15-minute period.

Providing undelayed passage over a dam for such large numbers of salmon presents unprecedented problems. The fishways at Bonneville Dam have passed a maximum of 580,000 salmon in a whole year (Corps of Engineers, 1958). The maximum number of salmon of all species counted through the fishways at Bonneville Dam in one day amounted to only 49,582 whereas any fish facilities constructed on the main migration routes of Fraser River sockeye and pink salmon would have to be capable of passing at least 750,000 sockeye per day as well as lesser numbers of other species.

DELAY DURING SPAWNING MIGRATION

Fishways and fish-collection systems have been observed to delay the upstream migration of salmon. Even at the efficient Hell's Gate fishways visual observations suggested that a delay of about four days occurred in 1954 during passage of the Adams River sockeye. It was estimated that over a million fish arrived at Hell's Gate in a single day. The four-day delay experienced by the fish indicated that these fishways, at least at the lower limit of their operating range, are not adequate for rapidly collecting and passing such large numbers of fish. The early migrating sockeye races, which pass through Hell's Gate when water levels are higher, would probably be seriously affected by this delay but, as previously mentioned, Adams River sockeye appear able to withstand minor delays along the migration route without serious adverse effect.

Brett (1957) has pointed out that when the environment is altered the behavior of migrating adults may be changed in such a way as to result in the fish arriving on their spawning grounds at a later-than-normal time. This delay may occur in reservoirs as a result of behavior changes. Increased temperatures, thermal stratification, or changes in chemical composition of the water may act as deterrents. Reduction in water velocity may remove a directive factor. When dams flood out spawning grounds, any directive odor from them may be effectively lost or altered. These possible changes in behavior, resulting from environmental changes, require a great deal of study to assess their effect in delaying the upstream migration of salmon.

In a brief review of possible effects of hydroelectric development on Fraser River salmon, Clemens (1958) stated: "It would appear that delay may be one of the most important factors in the problem of salmon and dams. The following questions need to be answered:

"What delays in time and character may occur at each dam?

"Will the energy expenditure in ascending the fishways be significantly greater than that in swimming up the natural river?

"Will an excess expenditure of energy in negotiating the fishway be compensated for in swimming through the impoundment above with its very slow current, assuming that there is no tardiness therein on the part of the fish?

"In reference to the problems of passing salmon at dams, it is evident that any attempts at guidance of whatever nature must take into account the innate behavior patterns of the fish and its sensory mechanisms. A thorough knowledge of the responses of the fish to stimuli through its sense organs especially those of sight and smell would seem to be essential to the development of efficient guiding devices."

The problem of the adverse effect of delay during upstream migration has only recently been emphasized. Studies to determine the seriousness of the Hell's Gate obstruction revealed that "After a long delay fish are less able to traverse the distance still remaining to the spawning grounds, and that when delay is too great fish do not pass Hell's Gate. Others fail on the way up the river." (Thompson, 1945). A delay of 12 days at Hell's Gate prior to construction of the fishways was found to prevent all sockeye salmon from reaching their spawning grounds and lesser delays reduced the reproductive capacity of the fish. The fishways constructed at Hell's Gate in 1945 enabled the fish to pass upstream to their spawning grounds and also eliminated most of the delay at this point. The substantial increase in production of races spawning upstream from Hell's Gate, following completion of the fishways, has demonstrated the necessity for immediate upstream passage. From a comparison of escapements above Hell's Gate, Royal (1953) concluded that productivity doubled following the construction of the Hell's Gate fishways. Presumably, this substantial increase in the rate of productivity of sockeye spawning in the upper reaches of the Fraser River watershed was due to the elimination of delay and mortalities at Hell's Gate.

Fishways were also constructed in the Fraser Canyon near Yale to aid the upstream passage of the early run of sockeye to the Stuart River. In 1955, before the Yale fishways were constructed, unseasonably late high water delayed the Early Stuart run at this obstruction. Although the block lasted only six days, only 2170 sockeye reached the spawning grounds out of an estimated 30,000 to 35,000 arriving at the block area. Commercial fishing for this race of sockeye was not allowed in its cycle year, 1959, in order to rebuild the spawning population to its former size. Despite complete protection in the commercial fishery, the total escapement in 1959 consisted of only 2660 sockeye. This illustration of the adverse effect of delaying adult sockeye during their spawning migration substantiates the warnings that frequently have been given concerning dam construction on the Fraser River.

The effect of delay on productivity of Pacific salmon has been emphasized by studies of fish passage at a rock slide on the Babine River (Godfrey *et al.,* 1954). Tagging of fish below the point of difficult passage and recovery of the tagged fish at a counting fence 40 miles upstream showed that some of the fish delayed below the obstruction were able to migrate to their spawning grounds but relatively few were able to spawn successfully. Because fish were delayed and weakened below the obstruction they were not able to migrate at a normal rate after passing the obstruction. The effective spawning in 1952, when some sockeye were delayed for extended periods, was estimated as 30 to 42 per cent of the numbers of female sockeye that reached the spawning grounds or 7 to 10 per cent of the total escapement. From 30 to 40 per cent of the female sockeye examined on the spawning ground died unspawned and others died after passing the obstruction but before reaching the spawning ground.

The effect of migrational delay on the productivity of pink salmon has not been extensively investigated. Godfrey *et al.* (*ibid.*) showed that pink salmon were blocked by the Babine rock slide to a much greater extent than sockeye, illustrating a difference in swimming ability of sockeye and pinks that has frequently been observed. Pinks were completely obstructed by the slide at Hell's Gate on the Fraser River, whereas significant numbers of sockeye migrating at about the same time were able to reach their spawning grounds. The recent return of pinks to spawning areas above Hell's Gate, however, demonstrates that these fish are able to migrate through the vertical-slot fishways at Hell's Gate. The effects of delay during migration have not been determined for this species although it may be presumed that delayed arrival on the spawning grounds would affect their reproductive ability for the same reasons that sockeye are adversely affected by delay.

McGrath (1958), describing dams as barriers or deterrents to the migration of fish, discussed various ways in which the spawning migration of Atlantic salmon in Ireland has been "impeded, prevented or nullified" by dams. He noted, in particular, the necessity for improving the entrances to fish passes to reduce the delay and energy expenditure of migrating salmon at dams.

Two important factors appear to be involved in contributing to reduced productivity of salmon delayed during their spawning migration:

1. The fish arrive on the spawning grounds later than normal so that conditions for spawning and egg and fry survival are less favorable.
2. During the delay period the fish utilize energy reserves that would otherwise be available for migration, gonad development and spawning activities.

ENERGY RESERVES OF ADULT SOCKEYE

Recent studies suggest that depletion of energy reserves of migrating adult sockeye may reduce their productivity even under natural condiitons. The pre-ously mentioned natural delay of Early Stuart sockeye at Yale illustrates the seriousness of migratory delay. Since migrating adult salmon cease feeding before entering fresh water, all the energy required for final maturation, swimming and spawning must be drawn from body energy reserves.

A study of utilization of energy stores by sockeye destined for streams in the Stuart River watershed of the Fraser River system has shown that the reserves of fats and proteins are steadily diminished from the time the fish enter the estuary until completion of spawning activities (Idler and Clemens, 1959). In 1956, Stuart Lake fish and Chilko Lake fish started their fresh-water migration with an average of approximately 350 grams of oil. From the time of entrance into the Fraser River until completion of spawning, the average Stuart Lake male used 91 per cent of its body fat reserves and the female 96 per cent; the Chilko male used 77.6 per cent and the female 91.4 per cent. During the same time, the Stuart male used 31 per cent of its protein reserves and the female 53 per cent while the Chilko male used 42 per cent and the female 61 per cent. By sampling the fish at various stages during the spawning migration it was determined that the rate of energy utilization was much greater during the time when the fish were moving through high-velocity sections of the Fraser River than during and after spawning. A delay of only a few days at a dam or other obstruction in the Fraser River would probably be lethal for the early races of Stuart Lake sockeye. Chilko Lake sockeye appear to be more tolerant of delay. These fish arrive on the spawning grounds in an immature condition at least 10 days before spawning commences. However, these fish might not reproduce effectively if they were forced to withstand a 10-day delay at dams or other obstructions on the migration route.

This significant difference between the rates of energy utilization and the timing of migration and spawning of Stuart Lake and Chilko Lake sockeye illustrates the importance of considering racial differences in any analysis of the effects of multiple-water-use developments on salmon productivity. Although studies have not yet been made of the energy reserves of sockeye destined for the Quesnel area, it seems likely that these fish, like the Stuart fish, would be seriously affected even by short-term delays in fresh-water migration. All of the early spawning races—Bowron, Early Stuart, Early Nadina, Horsefly, Raft, Seymour and Gates — seem to begin spawning shortly after arrival on their spawning grounds. It is likely that any delay along the migration route would have a serious effect on productivity of these fish. Races that spawn later in the season—Cultus, Harrison, Lower Adams, Chilko, Stellako, Birkenhead, Weaver, Portage, Little River and South Thompson—appear to migrate at a slower rate and may be more tolerant of minor delays along the fresh-water migration route.

This apparent increased tolerance of the late runs may be due in part to temperature. Water temperatures are considerably lower during the migration of the late runs than the early runs. Storage of water for power, flood control or other use that raised water temperatures during the period of migration of the late runs would be expected to aggravate harmful effects of delay on these fish.

Dunstan (1956) showed a distinct reduction in fat content among sockeye salmon at each of the Columbia River dams. The reduction in fat content at Bonneville Dam was 19.3 per cent. The results presented by Dunstan were different from those of Greene (1926) who studied energy utilization of Columbia River salmon before the dams were built and found a gradual fat reduction depending on mileage and elevation. The difficulty that salmon experience in finding and ascending fish facilities at Columbia River dams may increase the rate of energy expenditure or may merely result in a "stepped" rather than gradual energy utilization. Paulik and DeLacy (1958) conducted experiments in an annular tank and in a flume to measure the swimming ability of adult sockeye salmon taken during migration at Bonneville, McNary, Rock Island and Tumwater Dams and on the White River spawning grounds. A general decrease in swimming ability was noted as the fish progressed upstream. Performance ability on the spawning grounds was drastically reduced. Their data suggest that delay and exertion may be more harmful to the salmon at one location in the river than at another. The authors also observed that salmon that had been vigorously exercised did not survive as long as unexercised fish.

Sockeye may become more tolerant to certain adverse conditions as they approach their spawning areas but depletion of their energy reserves and maturation of their gonads apparently reduces the ability of the fish to perform. Fishways that are adequate for passing fish at Hell's Gate, only 130 miles from the ocean, might not be adequate 300 miles farther upstream.

FATIGUE OF ADULT SALMON

The physiology of muscular fatigue in fish has been studied for some years. Fats and proteins stored by the fish prior to leaving the ocean are oxidized and expended for muscular activity during fresh-water migration and spawning. The physiological processes involved require that the blood be supplied with adequate oxygen and that the metabolic waste products be removed from the blood stream. Fish may expend moderate amounts of energy for long periods of time, as in sustained swimming, but if this sustained rate of energy expenditure is exceeded, an accumulation of metabolic by-products results. Reduced activity is then necessary for equilibration of body chemistry.

Paulik *et al.* (1957) found that fatigue recovery in adult coho was 31 per cent complete after a one-hour rest, 43 per cent after two hours and 67 per cent after three hours. All fish recovered completely after an overnight rest of 18 to 24 hours. The rate at which the fish were fatigued appeared to affect the length of the recuperation period. Salmon that swam for a longer time before becoming fatigued also required a longer rest period to recover their original swimming ability. These workers concluded: "Fish released in a fatigued condition are unable to continue their journey upstream and may be swept some distance downstream before finding a suitable resting area." The following excerpt from their report is of prime importance in considerations of various salmon collection and transportation devices and methods: "The dependence of recovery time on the degree and type of fatigue is strong evidence of the necessity for adequate resting facilities in a fish-passing device in which water velocities exceed 3½ f.p.s. (e.g., a Denil fishway) for any considerable distance. Lacking information on the relationship of the work and rest pattern to total work accomplished in a given time, it is recommended that facilities should be provided that would allow the salmon to set their own pace. The experimental results indicate that to prevent extensive exhaustion, salmon should not be forced to maintain a strenuous effort for more than a few minutes."

Black (1957, 1958b) has shown that severe muscular activity causes abnormally high concentrations of lactic acid in the blood of sockeye and other salmonids. Fish so affected must rest for several hours before they are able to perform at a normal rate. In some cases, fish have died following vigorous exercise although little such mortality has been reported for adult salmon maturing in fresh water. Black (1958a) has outlined several theories on the cause of death induced by hyperactivity. He suggested that the high concentration of lactic acid, working in a manner not yet understood, might cause death. Exhaustion of fundamental energy stores has also been suggested as bringing about the death of fatigued fish.

ARTIFICIAL GUIDING METHODS

If artificial guiding methods could be utilized to direct adult salmon to fishway entrances and trapping facilities, some of the problems of fish passage at dams would be alleviated. However, not only are there physical problems involved in the application of artificial stimuli in the turbulent and high-velocity tailwater areas at dams, but also the possible biological effectiveness of such stimuli is questionable. For instance, Janssen (1938) described the use of streams of air bubbles to keep schools of fish from sounding while being brailed out of a net and to keep sharks away from tuna impounded in a purse seine. Laboratory experiments have also been described in which certain species of fish could not be forced through a veil of air bubbles rising from the bottom of a tank. However, the possible effectiveness of veils of rising air bubbles in directing the upstream migration of adult salmon has not been investigated experimentally and, further, the likelihood of maintaining air bubble barriers in turbulent high-velocity rivers seems very remote.

The value of artificial light as a method of guiding salmon to passage facilities at dams has not been investigated. Fields (1954) reported that artificial illumination deterred the entrance of adult sockeye into a small fishway. However, since observations on the Fraser River indicate that sockeye and pink salmon migrate primarily during daylight hours, artificial illumination would be of little or no value as a guiding stimulus.

Experiments have been conducted to find some odor that might be used to guide adult salmon. An aqueous solution of mammalian skin extract has been observed to cause alarm among coho and chinook salmon and to temporarily deter the migration of these fish through a fishway (Brett and MacKinnon, 1954). Solutions of 53 other substances had no observable effect on the fish. The authors considered that Pacific salmon possess an acute olfactory sense that enables them to detect predators. Thus, odors from human skin, bear paw, dog paw and sea-lion flesh had a deterrent effect on migration. However, the fish apparently acclimated to the odor after only 15 minutes, whereupon the repellent effect was destroyed. No odors have been found that can be used to attract salmon.

It has also been suggested that underwater vibrations might be used to attract or repel salmon. However, Burner and Moore (1953), using various frequencies and intensities of underwater vibrations in experiments with trout, showed that fright reactions were produced only when the vibration was first applied. Since the fish soon became accustomed to the sound, it had no guiding effect. These observations have been confirmed by other experimenters working with juvenile salmon.

Electrical stimuli have occasionally been used to control the upstream migration of adult salmon but for various reasons electric screens are seldom used at the present time. Holmes (1948) reported that the earliest application of an electric screen for stopping adult salmon was a test installation in the tailrace of the Gold Ray power plant on the Rogue River in Oregon in 1928. Local sportsmen insisted that this screen be permanently removed because dead fish had been seen in the river below the power plant. Other electric screens have also been abandoned.

Burrows (1957) described an electrical weir that has been operated in the Entiat River in Washington since 1953 for diverting adult chinook and sockeye salmon into hatchery holding ponds. The author stated: "Adult salmon, once conditioned to the electrical stimulus, may be diverted from their normal migration path into an alternate route by the electrical field. With adequate water velocities and voltage gradients the electrical weir is a positive barrier to the upstream migration of adult fish." Burrows maintained that chinook salmon were guided to a fishway with the electrical weir more quickly than with a picketed weir. Sockeye, however, do not follow along the electrical barrier to enter the fishway. Whole schools disappear from the river after encountering the electric screen and, according to Burrows, "appear in the holding ponds overnight." Not only is there no assurance that *all* of the fish reappear, but those that do may suffer extensive delay. Although Burrow's results are thus inconclusive for sockeye, they offer an avenue for further study and possible application in certain situations.

Lethlean (1953) described experiments in which electric screens were investigated in attempts to obtain cheaper methods than mechanical barriers for keeping fish out of turbine intakes and outlets. He stated: "Salmon experienced obvious discomfort when about 5 to 6 feet from the outer electrodes, and at that distance turned and glided smoothly into the shallow water. Two 8-lb. salmon, venturing further than the others into the zone, found the field so intense that they gave up the attempt to make further progress when in line with the outer electrodes. At that point they turned quickly downstream for a distance of 20 to 30 feet where they relaxed in placid water until resuming their journey through another channel.

"About one-third of the fish swimming into the zone re-entered it later, sometimes within the space of 15 minutes or so—others remained in the shallow water for periods of ¼ of an hour to 4 hours before proceeding upstream on a course clear of the screen."

An electrical barrier was also used during construction of Brownlee Dam on the Snake River to prevent upstream migrants from entering the diversion tunnel and to direct them to trapping facilities. Except during periods of electrical or mechanical failure, the electric screen appeared to be effective in preventing fish from entering the diversion tunnel. However, severely injured fish were found and much skepticism has been expressed concerning the over-all effectiveness of the electric screen. Relatively few fish spawned in spite of an apparently larger-than-average escapement past the commercial fishery. The poor spawning may, in part, have been caused by the electric screen.

Experiments conducted at Cultus Lake with various types of electric screens to investigate the possibility that electrical stimuli could be used to guide Fraser River sockeye and pink salmon to fishway entrances at dams indicated that little or no success could be expected (Andrew *et al.,* 1956b). It was found that various electrical stimuli could be used to stop the upstream migration of these fish provided the electrical field was sufficiently intense to paralyze the swimming muscles and the water velocity was high enough to carry immobilized fish out of the electrified zone. However, it was observed that fish were not guided by the electric screens tested; they merely swam into the electrified area until they were immobilized. They recovered after being swept downstream and then re-entered the electrified area. It was concluded:

"The information gained from this study did not indicate that electric screens would be effective in guiding adult salmon at dams but that they might be effective in certain applications where it was required only to stop the upstream migration. Provided the water velocity exceeds 2.0 feet per second, adult salmon can be stopped with electric screens but there is no evidence to show that fish follow along an electric screen to a fishway or other by-pass. Furthermore, fish exposed to electrical stimulation become less active and this might affect their ability to reach the spawning grounds or to spawn successfully. Before electric screens can be considered satisfactory for practical use, the biological effects of electrical stimulation must be thoroughly examined."

A unique use was made of an electric screen at Adams River in 1958. As a result of a dispute concerning the price to be paid for late-run sockeye, commercial fishing for Adams River sockeye ceased earlier than usual. Consequently, the escapement far exceeded the requirements for maximum production. To prevent late-arriving fish from digging up eggs that had been deposited at the proper spawning time, an electric screen was constructed across the mouth of Adams River. This fence prevented about 1,000,000 sockeye from entering the river, forcing them to spawn on the beaches of Shuswap Lake and in Little River. Observations at this installation substantiated those that had been made of the reaction of adult sockeye to experimental electric screens at Cultus Lake. Fish repeatedly attempted to penetrate the electrical barrier but were repelled downstream rather than being led along the electrodes.

It seems apparent that artificial stimuli hold little promise for eliminating the delay of adult salmon at dams. Certain artificial stimuli may prove effective in aiding the collection of adult salmon but the provision of suitable hydraulic conditions seems to be the only available method at present for efficiently directing or attracting adult salmon to fishway entrances at dams.

POWERHOUSE COLLECTION SYSTEMS

In view of the adverse effects of delaying and fatiguing salmon below dams, it is important that fish be attracted to fish-passage facilities without undue delay and exertion. One of the perplexing problems is that of assuring that fish are not subjected to extensive delay by attempting to migrate upstream through turbine draft tubes. It is not unusual for large hydro plants, such as those on the Columbia River, to have powerhouses in excess of one quarter of a mile long. The powerhouse at Bonneville Dam contains 10 turbines and is 1027 ft. long. The powerhouse at McNary Dam, containing 14 turbines, is 1300 ft. long. Fish migrating upstream in the late summer and early fall months, when there is little or no spill over the dams, are attracted to the powerhouse flow. In an effort to minimize delay and fatigue of fish attempting to swim into the high velocities from the draft tubes, ports are provided at the water surface to enable fish to enter a relatively non-turbulent, enclosed channel running the full length of the powerhouse and leading to a fishway or other fish-transporting device. This method of collecting fish, called the "powerhouse collection system", was first used at Bonneville Dam (FIGURE 11). Originally, four overflow weirs were provided as fish entrance ports at each turbine. The weirs were 8 ft. wide and the crest elevation was maintained about 6 in. below tailwater elevation, with the water in the fish collection channel maintained 1 ft. above tailwater elevation. Subsequent experiments, however, have shown that salmon and steelhead appear to prefer submerged ports rather than overflow weirs. This observation has also been verified in weir fishways that have submerged ports (Corps of Engineers, 1956b). The size, discharge and number of ports were arbitrarily chosen for use at Bonneville Dam and the Bonneville design has been used, with minor modifications, at numerous other installations. Experiments at Bonneville Dam (Corps of Engineers, 1956a) have shown that ports or orifices of virtually the same size and discharge as the original weirs are more effective in attracting steelhead and salmon than are the overflow weirs, provided the ports are located about 3 ft. below tailwater elevation. Ports at greater depths were much less effective in the relatively turbid water at Bonneville Dam. Numerous observations have suggested that, in turbid water, upstream-migrant salmon travel about 2 to 4 ft. below the water surface. In clear water, however, salmon are known to travel at greater depths. The submerged ports at Bonneville Dam are 1.5 ft. high by about 7 ft. long and discharge the same flow as the original overflow weirs, 60 c.f.s. The same flow is used for the fish entrance ports and weirs of the powerhouse collection system at McNary Dam.

Experiments at McNary Dam have indicated that most of the fish enter the powerhouse collection system through ports located at the extreme ends of the powerhouse. Orifice entrances using 90 c.f.s. attraction flow appeared to be more effective that orifice entrances discharging 60 c.f.s. Experiments have also been conducted to investigate the feasibility of increasing the discharge of the fish entrance ports by increasing the head, from the fish collection channel

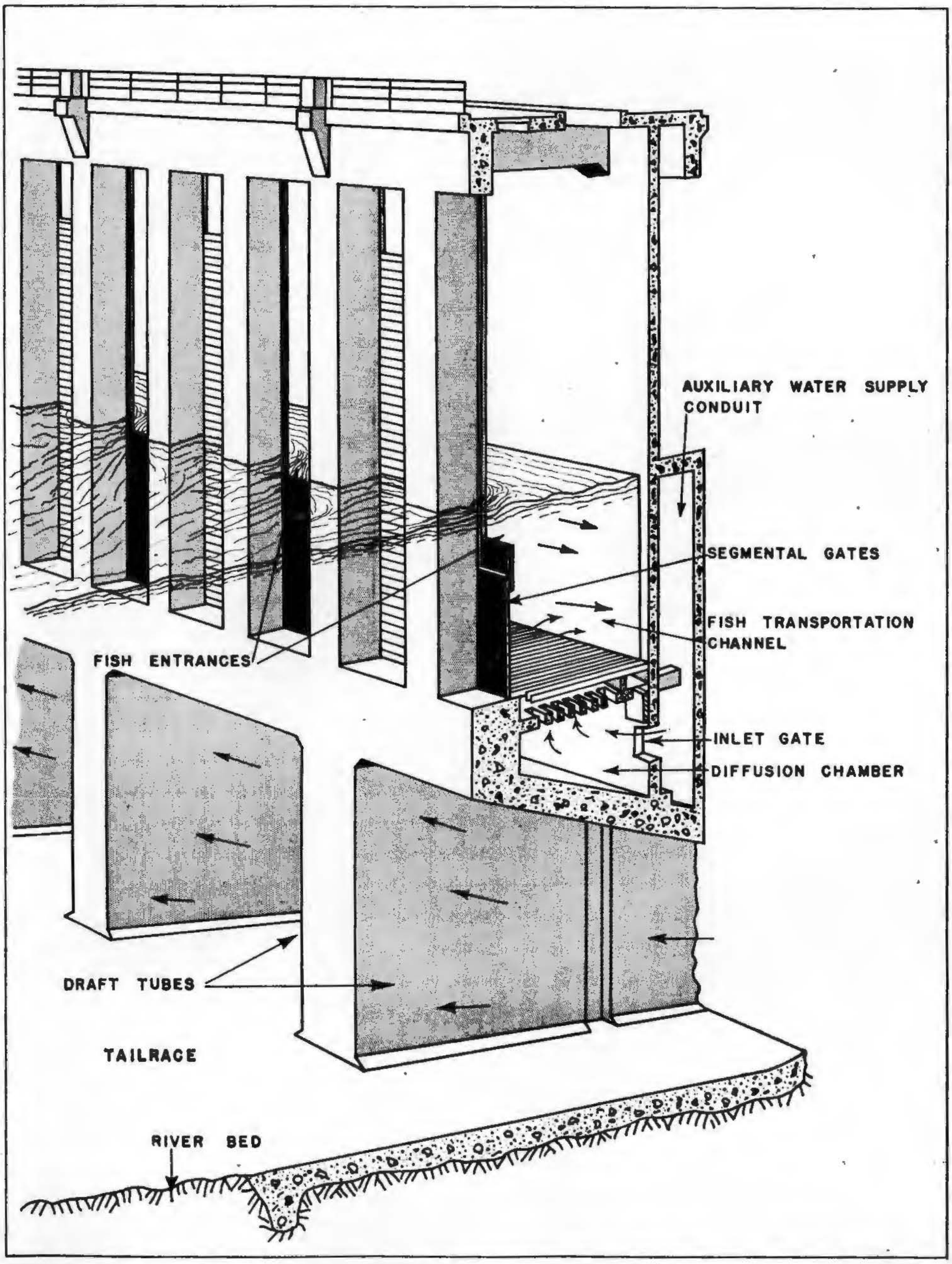


FIGURE 11—Powerhouse fish-collection system at Bonneville Dam. (From Corps of Engineers, 1950.)

to tailwater, to 18 in. instead of 12 in. Fish have been observed swimming through submerged orifices under a head of 18 in. with no apparent difficulty (Corps of Engineers, 1957).

In the original design of the powerhouse collection system at Bonneville Dam, it was considered that the velocity in the fish collection channel should be about 2 f.p.s. to induce fish to swim the length of this channel to reach the fishway. Accordingly, water is introduced along the length of this channel by means of diffusion chambers along the bottom, to compensate for the loss of water through the fish entrance ports. An attempt is made to maintain a constant transportation velocity of 2 f.p.s. but the large discharge required during the high-water months overtaxes the capacity of the water supply system and the actual velocity is somewhat less than 2 f.p.s. Recent experiments at Bonneville Dam have suggested that a transportation velocity of 1 f.p.s. is as effective as, and possibly more effective than, a velocity of 2 f.p.s. (Corps of Engineers, 1956a).

Little information is available concerning the behavior of upstream-migrant salmon and trout in artificial, enclosed channels such as those used in powerhouse collection systems. Small-scale experiments have indicated that fish move faster through a darkened fishway than through a lighted one. These experiments were conducted in a six-pool weir fishway without submerged orifices. Adult steelhead negotiated this fishway significantly faster in near-total darkness than under artificial light conditions approximating a bright cloudy day (Long, 1959).

SPILLWAY COLLECTION SYSTEMS

Collection of upstream-migrant salmon and trout from the areas below spillways of large dams is, in some cases, even more difficult than from below powerhouses. No method similar to the powerhouse collection system has been devised for collecting fish from the full length of the spillway sections of dams built on large rivers such as the Columbia. Fishway entrances are placed only at the ends of the spillway sections. Consequently, fish may make many futile attempts to penetrate the turbulent, high-velocity discharge from the open spillway gates before finding the fishway entrances. Many chinook salmon carcasses have been recovered within a short distance below Bonneville Dam. Preliminary studies by the Oregon Fish Commission, the results of which have not yet been published, suggested that during an 11-day period of observations in 1955 the number of dead fish below the dam constituted about one fifth of the count of upstream-migrant chinooks at Bonneville Dam. High mortalities were observed when the discharge exceeded 250,000 c.f.s. Although the cause of this mortality has not been determined, it seems possible that some fish, attempting to migrate upstream at Bonneville Dam, may have been caught in the back-roll and violent turbulence in the bucket or energy-dissipating area at the base of the spillway. Schoning and Johnson (1956) showed that some fish also pass downstream over the spillway after having passed through the fishways at this dam.

When water is being discharged from only a few spillway gates, a serious problem arises in that some of the fish are led to a "dead end" because they are able to migrate past the entrance to the fishway (FIGURE 12). It is desirable at all fishway installations, whether at dams or natural river obstructions, to

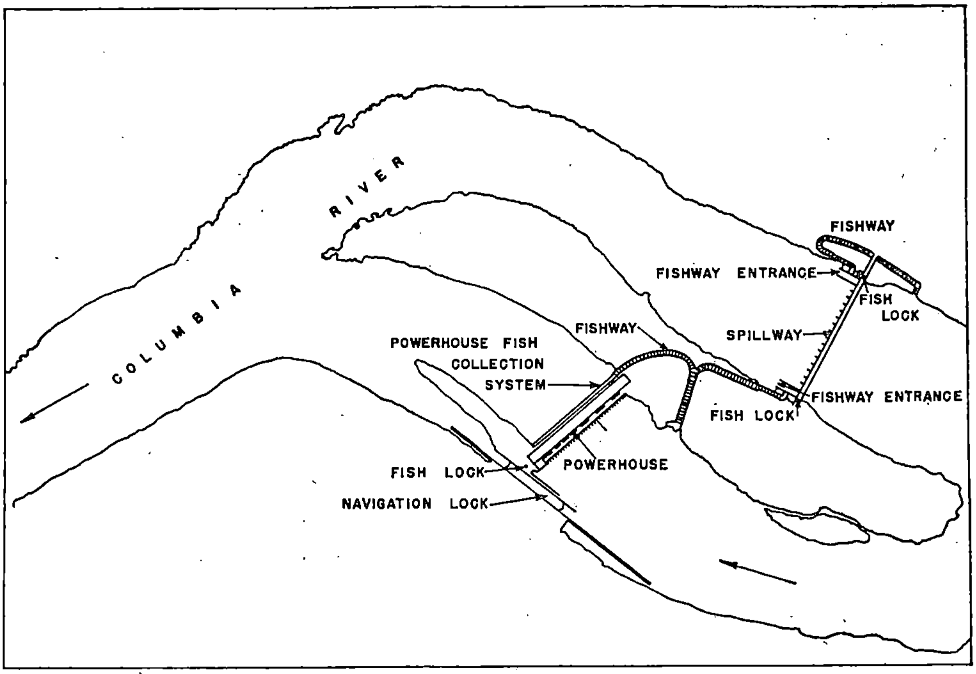


FIGURE 12—Locations of fishway entrances at Bonneville Dam in relation to spillway and turbine discharges. (From Corps of Engineers, 1950.)

place the fishway entrance at the farthest upstream point that the fish can reach and to provide a high-velocity barrier immediately upstream from the fishway. This ideal arrangement is obviously difficult to achieve at a spillway because the number of gates spilling is dependent on the amount of surplus water available.

Picketed leads, consisting of steel racks with 1½-in. openings, are sometimes used to block off some of the gate bays near the fishway entrances so that gates near the center of the spillway section can be fully opened and the gates with picketed leads can be partially opened to maintain an attractive flow near the fishway entrances. The rack bars are set at an angle of about 30° to the direction of water flow from the partially opened spillway gates so as to direct the flow away from the fishway entrance, thus providing some attraction towards the fishway. When picketed leads are used, the position of the hydraulic jump below the spillway is less variable and a desirable flow pattern for attraction of fish to the fishway entrances is more easily achieved. These racks must be easy to remove and install so as to be readily adjustable for different spill conditions.

One of the first applications of the picketed lead principle at a power dam was at Baker Dam near Concrete, Washington. In this case, however, the barrier was constructed to prevent adult sockeye and coho salmon from entering the tailrace, where they were being delayed and injured. Steel racks constructed around the tailrace of this plant were entirely unsuccessful because fish persisted in their attempts to penetrate the barrier and many were seriously injured. Many of the fish appeared reluctant to migrate past the opening that was blocked off with the steel rack bars and enter the fish trap, which was locted some 50 ft. farther up the river at the upstream end of the powerhouse.

Experience with picketed leads at McNary Dam has not been entirely satisfactory. Lampreys and other small fish often swim upstream through the 1-in. openings between the bars. After becoming fatigued in attempting to swim upstream in the high-velocity discharge below the spillway gate, they are killed by plastering on the face of the rack bars. The physical problem of maintaining the racks in place is not a simple one. The debris and high-velocity flow passing through the spillway gates may cause considerable damage.

In addition to location of the fishway entrances, the width and depth of the entrances and the velocity through them are considered important for maximum efficiency. In the 20-ft.-wide fishways at Hell's Gate, the entrances are only 5 ft. wide but in the turbulent, high-velocity reach of river immediately downstream from the fishways, the fish are naturally confined to narrow marginal areas. The entrances are ideally located because the high velocity prevents fish from proceeding farther upstream. However, because of the much more difficult problem of attracting fish at dams, fishway entrances at dams are generally made as wide as or wider than the fishways. A velocity of 4 f.p.s. is generally accepted as minimal for fishway entrances. At McNary Dam, each fishway entrance consists of four 15-ft.-wide bays with automatically controlled telescoping gates that maintain a constant water depth of 6 ft. in each bay. Three of the four gates are generally used at any one time. A minimum discharge of 1000 c.f.s. is provided at each entrance. The automatic equipment controlling the elevation of the gates is sensitive to tailwater fluctuations of 0.1 ft. The total flow down each of the McNary fishways is about 165 c.f.s. and the remaining flow of 835 c.f.s. required for providing a minimum discharge of 1000 c.f.s. at each fishway entrance is introduced near the downstream end of each fishway by means of diffusion chambers located in the floor. During high-water periods, the lower pools of weir-type fishways become drowned out and it is considered necessary to add auxiliary water to provide positive velocities in the drowned-out sections for attracting fish upstream. Enough water is added to provide a minimum average velocity of 2 f.p.s. over each of the submerged weirs (Von Gunten *et al.*, 1956).

OTHER COLLECTION SYSTEMS

Methods of collecting fish for transport over dams by fish lock, truck, or other conveyance system are essentially variations of the powerhouse and spillway collection systems previously described. In addition, however, they must provide a method whereby fish can be led to and confined in a trapping compartment. When it was decided that facilities would not be constructed to pass adult salmon and trout over Grand Coulee Dam, a unique trapping and hauling system was constructed at Rock Island Dam to salvage salmon populations destined for spawning and rearing areas above Grand Coulee (Chapman, 1940b). These fish were transported to hatchery ponds and to other streams. A similar installation for collecting, trapping and transporting fish over a dam was constructed on the White River downstream from Mud Mountain (Stevens) Dam. This installation, completed in 1940, has been used as a pattern for the design of similar installations on other streams. The facilities at Cleveland Dam on the Capilano River (FIGURE 13) were described by Hourston *et al.* (1955) as follows:

"The facilities now constructed include a rack, fishway, holding pool, brailing pool, hopper pool, hopper and tank truck. Coho salmon and steelhead trout migrating up the Capilano River are stopped by a rack several hundred yards below the dam and diverted into a fishway. The choice of location was based on several considerations including the limited areas available for sites, the effects of turbulence at the tailrace of the dam, and the limited working space available on the river banks. The rack is built of steel bars having a clear opening of 1¼ inches. It is 10 ft. high and designed to operate at all but peak flows (which latter, in any case probably deter upstream movement of fish). The rack was angled downstream away from the fishway entrance so that fish would move in an upstream and lateral direction along the face of the rack towards the fishway entrance.

"The weir-type fishway comprises 19 pools, each 10 feet long and 5 feet wide and separated by drops of 1 foot each, leading fish to a holding pool. The fishway requires about 15 c.f.s. for operation. The width and length of pools was determined by the number of fish expected at peak migration periods. A weir-type fishway was chosen because its water requirements were lower than other types and the headwater at the holding pool was at a controlled level. The first baffle at the fishway entrance was made adjustable by a telescoping arrangement so that attraction water supplied through a floor diffuser from behind maintained an attraction velocity at any operating water level. Fish are prevented from dropping back down the fishway by a finger trap positioned close to the surface at the fishway exit.

"The holding pool is 20 feet by 20 feet by 4 feet deep and is designed to hold a maximum of 400 fish (using the relationship: three gallons of water per pound of fish). To prevent the migrants from fighting the inflow to the pool, water enters through a floor diffuser at a maximum velocity of only one foot per second.

"A V-type funnel joins the holding pool to the brailing pool. When fish are to be loaded for trucking, the gate at the head of the funnel is opened and the inflow is switched to the brailing pool to attract the fish. The gate at the head of the funnel is closed when a load of fish has entered the brailing pool. The brail or false floor (hinged at the hopper side) is hoisted and fish are forced into the 5-foot square hopper which is then lifted over the tank truck (filled with water) by means of an electric hoist. The bottom of the hopper is circular and is sealed to the circular hatch on the top of the tank. A plunger type valve opens permitting water and fish to pass from the hopper into the tank as water is bled from the tank. Fish are transported to a dumping site a short distance above the head of the reservoir and released through a hinged flap gate.

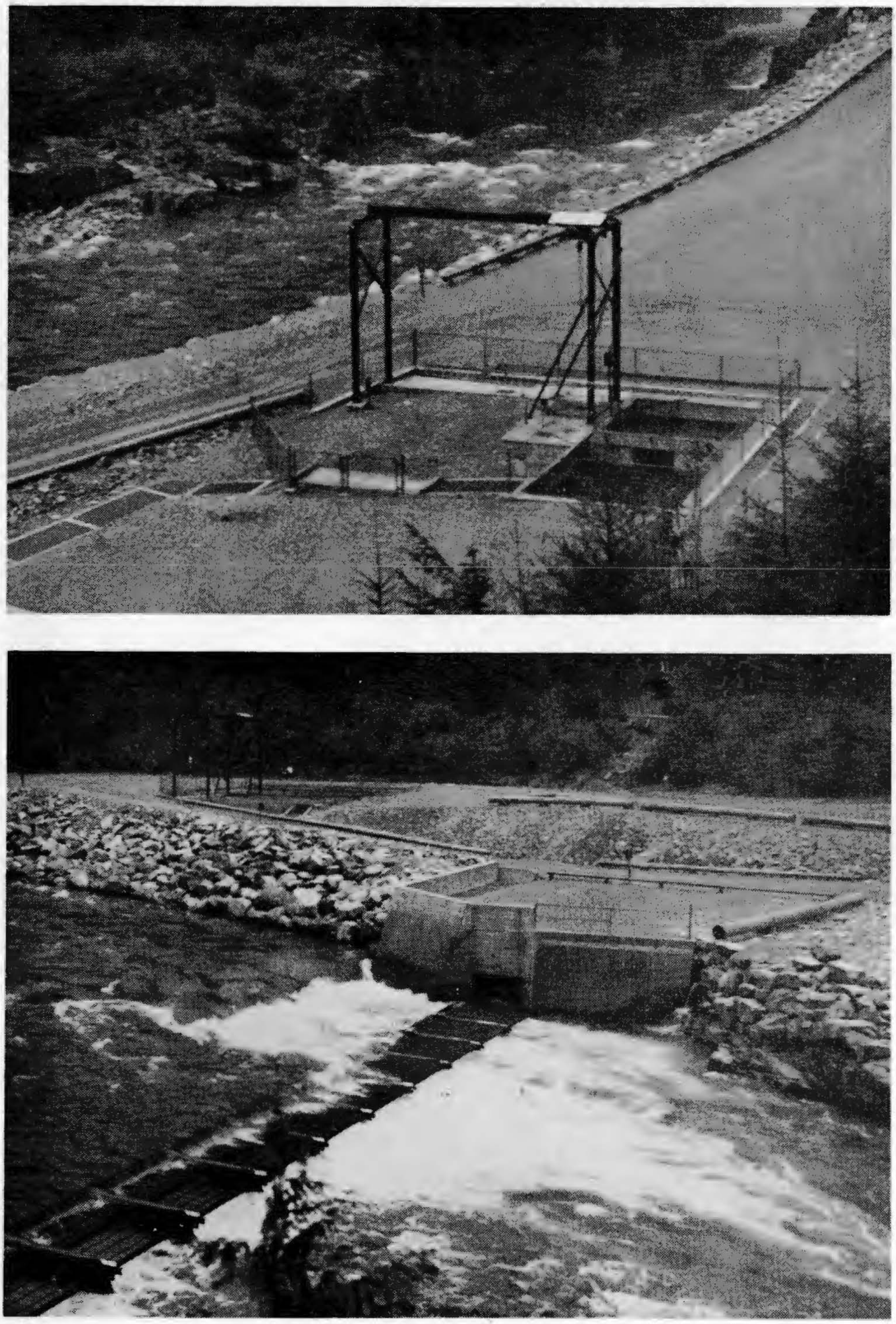


FIGURE 13—Facilities for collecting and trapping adult salmon and steelhead at Cleveland Dam on the Capilano River.

"The tank truck with a 600 gallon capacity, was designed to carry approximately 80 fish averaging 8 to 10 pounds each. It has two circulating pumps each of 120 gallons per minute capacity.

"The trucking operation was first used in 1954 and during the first six months of operation 3000 coho salmon and several steelhead trout were transported and released above the dam."

Passage of salmon over dams by means of fish locks also requires efficient collecting and trapping methods. Although many coarse or trash fish have passed through the fish locks at Bonneville Dam during various trials that have been made, relatively few salmon and steelhead have been passed. The reasons for the apparent inefficiency of fish locks for passing large numbers of salmon are not known but it appears that fish may detect the cyclic flow changes involved in lock operation. They may also sense and be repelled by the spatial restrictions of the collection and trapping facilities.

The fish locks at McNary Dam may be more effective than those at Bonneville Dam as a result of improvements made in the method of collecting fish. The gravity lock on the Washington shore at McNary Dam utilizes the fishway entrance for attraction of fish. After entering the fishway, the fish swim over the lower weirs to a junction pool that is above maximum tailwater elevation. They can then swim over a 20-ft.-wide telescopic weir to enter a holding basin immediately downstream from the fish lock. The crest of this adjustable weir is equipped with a finger trap consisting of closely spaced vertical steel rods curved upstream to prevent fish from returning downstream over the weir. The discharge over this weir is not interrupted during lock operation, a uniform flow being maintained by automatic regulation of the discharge through diffusion chambers located in the holding basin and lock chamber (Von Gunten *et al.,* 1956).

Various proposals have been made for improving the collection and trapping methods for mechanical transport systems and fish locks. Essentially, these proposed schemes consist of methods that might be used to *force* the fish to enter the confinement of traps or lock chambers. Presumably, fish would enter a long, rectangular fish entrance channel and a "forcing screen" would then be placed in the channel downstream from the fish, thus trapping them. The screen would be slowly moved upstream to force schools of fish to enter a small trapping compartment. Such screens might be mechanical barriers consisting of rack bars or wire screen. However, fish might be injured by such screens. Artificial stimuli, such as electricity or veils or air bubbles, have also been considered for confining fish in collection facilities of this kind but they would be of doubtful effectiveness and their use for this purpose has therefore not been investigated experimentally.

Systems for collecting and trapping fish for passage through fish locks or for mechanical transport have not been used for passing large numbers of salmon. Because of the artificial nature of the necessary collection and trapping facilities, such mechanical systems could not be expected to reduce or eliminate delay of salmon below dams. The confinement and interrupted, cyclic operation of such systems are serious disadvantages that tend to impede collection of fish. Where only small numbers of fish must be transported, the cycles can be quite long, but on the Fraser River the cycling would have to be so rapid to handle the large numbers of fish that the flow patterns would frequently be changed, which might lead to a serious delay in upstream migration.

The problems of collecting upstream-migrant salmon at dams are particularly complex when the spillway is not immediately adjacent to the powerhouse. The fish should be collected at both locations but to do so would complicate the collection and transportation facilities and add considerably to their cost. Further, variable discharges from the spillway and turbines result in variable distribution of fish between the collecting facilities at the two locations. In some cases, collecting facilities have been provided at only one location—either the spillway or the powerhouse, whichever is farthest upstream. The problems that this creates have been described for the Seton Creek hydroelectric plant (Andrew and Geen, 1958) and the Puntledge River hydroelectric development (Can. Dept. Fish., 1958). Periodic powerhouse shutdowns and occasional surges of spill have been tried at these plants to prevent excessive delay and injury of fish in the powerhouse tailraces, which are located downstream from the spillways in both cases. A better solution is obtained when the fish-collection facilities are located at either the powerhouse or the spillway, whichever is farthest downstream. The fish must then be prevented from migrating past this point in the river. As described in the next section, barrier dams are sometimes used for this purpose. At Baker Dam, a picketed barrier was used for many years to stop fish from migrating past the powerhouse, where the collection facilities were provided, but this system was not satisfactory. A barrier dam, which incorporates fish-collection facilities similar to those at Cleveland Dam, has recently been constructed some distance downstream from the powerhouse. The newly constructed facilities at Baker Dam have been found to be superior to the previous arrangement.

BARRIER DAMS

A fish-collection system that is probably more efficient than typical spillway and powerhouse collection systems has become more common for certain types of dams in recent years. A low dam, called a barrier dam, is constructed across the river some distance below the power dam to provide continuous, impassable velocities in mid-stream (Eicher, 1958a). The fish are thereby led in a natural way to fishway entrances on each bank, just as at natural river obstructions such as Hell's Gate.

Methods of ensuring that adult salmon will not escape over barrier dams have not yet been fully investigated. The fact that a few fish have been observed to escape over some of these dams indicates that present design standards are not entirely adequate. Either velocity or head, or a combination of the two, may be used to prevent escape of fish. However, while a vertical overfall might be adequate for preventing upstream migration, the resulting flow pattern below the dam would provide little or no guidance towards the fishway entrances. Such guidance would probably be provided by high mid-stream velocities, possibly of the order of 15 f.p.s. over a linear distance of at least 20 ft. An electrical barrier on the crest of low barrier dams might be effective in preventing escape of fish but preliminary studies have indicated that the effect of repeated electric shock on the subsequent behavior and swimming ability of the fish requires thorough investigation. Other methods that have been considered for preventing escape of fish include the use of a broad-crested weir, elimination of conditions favorable for fish jumping from tailwater, and the use of barriers or screens on the crest.

The fishway entrances at barrier dams may be equipped with telescopic weirs to compensate for river level fluctuations. If adjustable weirs are not provided, enough water must be added to the fishway flow to maintain adequate attraction velocities. Auxiliary attraction water can be obtained from the forebay of the barrier dam and introduced into the fishway entrance channels through diffusion chambers located in the floor.

A barrier, consisting of a crest dam with a maximum head of 12 ft., was completed in 1958 on Baker River 5000 ft. downstream from the Baker River hydroelectric plant. Salmon and trout destined for spawning areas in the headwaters of Baker River are trapped at the barrier dam and transported approximately 25 miles upstream by tank truck. In the first year of operation 2700 sockeye, 13,000 coho and 130 chinooks were handled (Wash. Dept. Fish., 1959). The system appeared to be successful in efficiently collecting and transporting this relatively small number of fish. The barrier dam diverts fish to a weir fishway on one bank of the river. The weir crests at the fishway entrances are automatically maintained at a fixed depth with respect to tailwater elevation. A flow of 50 c.f.s., drawn from the forebay of the barrier dam, is introduced through diffusion chambers in the floor of the fishway to provide a constant flow of attraction water at the entrance. Although no tests were conducted, observations indicated that salmon experienced little or no delay in finding the fishway entrance, swimming up the fishway, and entering the trapping compartment.

Barrier dams for collecting upstream-migrant salmon may be compared to re-regulating dams in that both can be used to alleviate some of the adverse effects of power development on small streams but their application on the Fraser River would pose tremendous problems. The cost of providing a barrier dam across the Fraser River at each power dam that has been proposed would likely be prohibitive. The problem of finding adequate foundations without having to go too far downstream might present difficulties in many cases. Further, such dams on the Fraser River would have to be immense structures to pass flood discharges and to operate at all river stages. Obviously, the practical problems involved in providing such fish-protective facilities on the Fraser River would be much more complicated than on small streams. In addition to the direct costs of construction and maintenance, a further disadvantage of barrier dams is that they may raise the tailwater elevation at the powerhouse upstream and thus reduce the power output of the hydroelectric plant.

Transportation of Adult Salmon Over Dams

GENERAL REQUIREMENTS

Fishways were being constructed in Europe at least as early as the 17th century. In 1662 in Bearn, France, a regulation was issued imposing on the proprietor of any dam or weir the duty of constructing a passage for fish suitable for both ascent and descent. The fishways constructed in France at that time consisted of steep, broad, open channels, the bottoms of which were roughened by bundles of branches. Some of these old, neglected fishways were still in existence in 1927 when the French government passed more strict regulations for the protection of salmon.

The need for fish-passage facilities became more apparent about the middle of the 19th century following the development of efficient hydraulic turbines and the consequent building of higher dams. Fishway design has progressed from crude, roughened channels into three distinct types—Denil, weir and pool-and-jet. Other methods of transporting adult salmon and trout over dams and other river obstructions were not introduced, as far as can be determined, until early in the 20th century. Gravity fish locks, or "lifts", are devices operating on the same principle as ship locks. In the pressure fish lock, on the other hand, the conduit from headwater to tailwater is full of water at all times. Fish enter a non-pressurized compartment at tailwater, a gate is then closed at the downstream end of this compartment and another gate opened to allow the fish to enter the pressurized water-filled conduit extending to the forebay of the dam. In recent years, small populations of salmon have been transported over dams by mechanical means—cableways, trucks and even in elevators. An excellent review of early fishway studies, particularly by Denil and other Europeans, is presented by Nemenyi (1941). This report includes reference to fish locks, hauling systems, and many other aspects of fisheries conservation.

To be effective, facilities for transporting adult salmon and trout over or around dams must be designed to meet complex biological requirements of all species and races of fish for which they are intended. Since these requirements are only partially known, modern transportation systems must be devised using rule-of-thumb criteria evolved over several years, largely during the design of fish facilities for Bonneville Dam. Criteria for space requirements, velocities, rates of energy dissipation, flow patterns, and rest areas have evolved as a result of the practical experience of fisheries biologists and engineers over the past two or three decades.

Recent research has revealed some of the requirements of fish-passage facilities for adult salmon. As previously mentioned, the ability of these fish to perform is related to temperature, fatigue, energy reserves, maturity and race. Experiments have shown that the swimming ability is maximal within a small range of water temperatures. Physiological studies have led to the conclusion that salmon should not be forced to swim strenuously for more than a few minutes because they are liable to suffer from extensive exhaustion, which seriously reduces their capacity to perform. Evidently, fish should be allowed to set their own pace in moving through any passage facilities. For adult coho salmon, rest areas should be provided within the passage facilities if the fish are required to swim against velocities higher than 3.5 f.p.s. (Paulik *et al.*, 1957).

Differences in the swimming ability of sockeye at various distances up the Columbia River have been demonstrated by Paulik and DeLacy (1958). Performance ability diminished as the fish approached the spawning grounds. Consideration of this feature is essential in the design of passage facilities. Racial differences further complicate the design criteria.

The behavior of migrating adult salmon and the responses of these fish to various natural stimuli are also important factors that must be adequately considered in the design of passage facilities at dams. However, very little research has been done on this aspect. It is not unreasonable, therefore, that designers of fish-passage facilities should attempt to provide an environment for the fish that is as "natural" as possible. In efforts to achieve this end, fishways are designed to avoid confinement of the fish. Facilities that operate cyclically or intermittently are generally avoided as they represent a definite departure from natural conditions. The adverse effect of sudden flow changes, such as in the tailrace of the Baker River hydroelectric plant, have been observed on numerous occasions. Upstream-migrant salmon generally retreat some distance downstream from the powerhouse following a sudden discharge reduction and do not immediately resume their upstream migration.

The effect of light on the behavior of migrating adult salmon illustrates the sensitivity of these fish to natural stimuli. As previously noted, the migration of sockeye and pink salmon under natural conditions on the Fraser River virtually ceases during darkness and is non-uniform even during hours of daylight. The pattern of daily migration, however, is similar on consecutive days, showing a progressive change during the season as the amount of daylight decreases. The daily migration pattern at Bonneville and Seton Dams has been shown to be similar to that at Hell's Gate and other points on the Fraser River system. In passing through fishways, salmon prefer shaded areas but recent experiments have shown that if fishway pools are illuminated to approximate daylight conditions, the fish will migrate continuously. Other experiments have suggested that fish move through darkened areas in a fishway more rapidly than through naturally lighted areas (Long, 1959). If light and other natural stimuli can have such profound effects on the migration of salmon, the passage of these fish at dams may be seriously affected by the hydraulic and spatial artificiality and by the numerous extraneous stimuli that are virtually inevitable at dams.

Recent experiments have indicated the necessity for excluding the odor of mammalian skin from fishways and other collection and transportation facilities. Human odors have been found to temporarily deter the upstream migration of salmon. Extracts derived from the skin of bears and seals have been found to produce the same effect. Alderdice *et al.* (1954) reported that "on detection of the repellent odor, salmon can be seen to swim excitedly in rapid circling movements in the enclosed area of a fish ladder pool, exhibiting a typical 'alarm reaction'." Fishways should therefore be designed so that manual adjustments and cleaning are not required. The raking of trash racks or other operations in or about a fishway would be expected to have at least a temporary adverse effect on the upstream migration of salmon not only because of the possible introduction of human odors but also because of the fright reactions elicited by visual response or by changes in flow.

Studies pertaining to the physiology and behavior of upstream-migrating salmon in relation to possible transportation methods are not adequate to indicate minimum design criteria, to permit predicting the behavior of fish under a given set of physical conditions, or to permit assessing the feasibility of proposed transportation schemes. In other words, the development of methods of transporting fish over dams has been largely a trial-and-error process. Very few investigations have been conducted to evaluate fishways and other transportation devices that have been installed. Current research designed to provide more complete information concerning the physiology and behavior of salmon and the requirements of fishways and other transportation methods will undoubtedly aid in the design and evaluation of these facilities.

While much information concerning passage of salmon and trout at dams has been obtained through the trial-and-error process, which has been augmented in recent years by some basic and applied research, nearly all of the practical experience with collection and transportation of fish at dams has been obtained on watersheds other than the Fraser. Since there are certain obvious differences, and possibly some subtle differences, between Fraser River and Columbia River sockeye, there is no justification for concluding that any passage facilities found to be effective on the Columbia River could also be used on the Fraser. Further, the problem of passing pink salmon over dams has seldom arisen. Satisfactory design criteria have therefore not been established for this species, even for river systems other than the Fraser. While pink salmon migrate through the short vertical-slot fishways at Seton Dam and Hell's Gate without apparent difficulty, it is generally accepted that they are not such strong swimmers as chinooks, steelhead, coho or sockeye. Accurate comparisons of swimming ability have not been made. It is considered that the behavior of pink salmon with respect to collection and passage facilities at dams would be similar to that of sockeye but thorough studies might reveal subtle differences that would necessitate important modifications in the design and operation of these facilities.

DENIL FISHWAYS

One of the earliest scientifically designed fishways was devised by Denil in 1908. It consisted of a small, sloping channel with closely spaced curved baffles along the sides and bottom (FIGURE 14). The velocity of the main flow down the center of the channel was reduced by the impingement of secondary currents produced by the side and bottom baffles. The main energy dissipation was believed to occur at the re-issue of the secondary currents as a result of the large momentum transfer and intense mixing. In more modern designs, the shape of the side baffles is simplified and, in some cases, the bottom baffles are eliminated (McLeod and Nemenyi, 1939-1940).

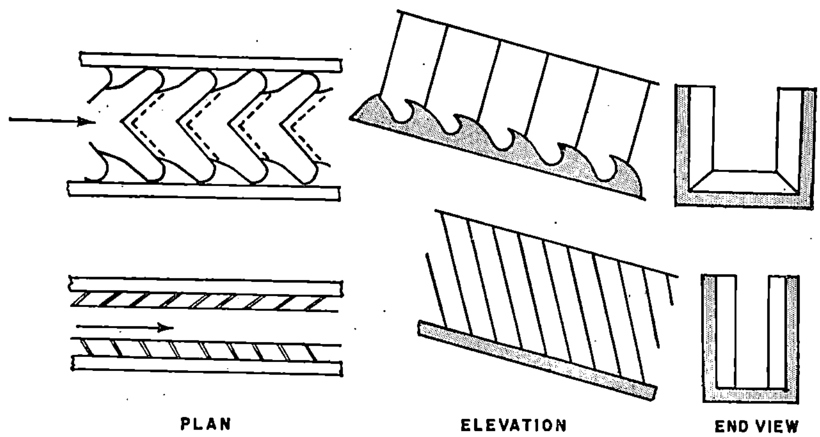


FIGURE 14—Denil fishways, showing an early design (top) and a simplification proposed by other investigators.

A trial installation of a Denil fishway at Dryden Dam on the Wenatchee River in Washington State consisted of a channel 4 ft. 3 in. wide by 7 ft. deep and 29 ft. long, built on a slope of 1:6 (Fulton *et al.*, 1953). Ten U-shaped wooden baffles spaced 2 ft. 10 in. on centers were placed along this channel, sloping upstream at a 45° angle to the floor. Clear opening between the upright portions of each single-plane baffle was 1 ft. 9 in. (FIGURE 15). This trial ladder was designed for a maximum head of 5 ft. 9 in. and was placed immediately adjacent to a 5-ft.-wide weir fishway. The most suitable operating depth of the Denil fishway appeared to be 3 ft., at which depth the discharge was approximately 30 c.f.s. With 20 to 30 c.f.s. flowing through the Denil fishway and 9 to 12 c.f.s. through the weir fishway, 89 per cent of the 1887 upstream-migrant sockeye salmon and 87 per cent of the 110 chinooks used the Denil fishway. It was noted that the increased use of the Denil fishway appeared to be due to the more attractive flow downstream from the fishway entrance. The attraction of salmon to the larger of two flows is a behavior pattern frequently observed in natural rivers.

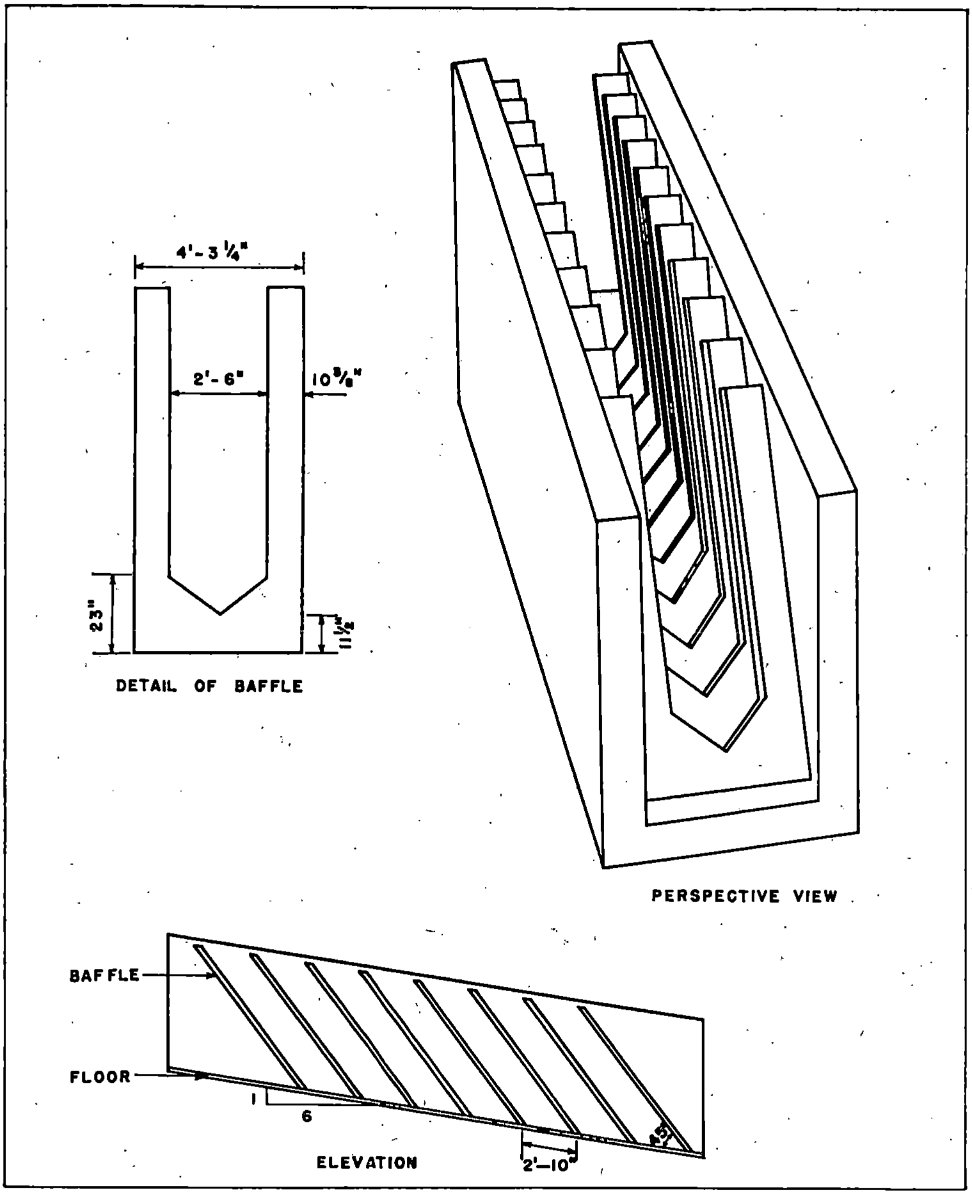


FIGURE 15—Arrangement of baffles in an experimental Denil fishway constructed at Dryden Dam. (From Fulton *et al.*, 1953.)

The flow of 30 c.f.s. at a channel depth of 3 ft. in the experimental Denil fishway at Dryden Dam produced an average velocity of about 11 f.p.s. through the restricted cross section of the channel. Salmon would be rapidly fatigued in a fishway of this type. Rest areas would be essential as the velocities far exceed the maximum sustained swimming speed for adult salmon. Paulik *et al.* (1957) reported a maximum sustained swimming speed of 3.5 f.p.s. for adult coho. The Committee on Fish Passes of the British Institution of Civil Engineers recommended that resting pools should be provided at vertical intervals of 6 to 8 ft. in Denil fishways (Committee on Fish Passes, 1942). A channel length of 30 ft. between resting pools was recommended for Denil ladders built on a slope of 1:5. The Committee further stated that the effective operating depth should be restricted between the limits of 2 to 3 ft. above the floor of the channel.

Denil fishways are not generally used on this continent for several reasons. The strenuous effort required by the fish is considered a distinct disadvantage of this type of fishway. The likelihood of sediment and floating and submerged debris interfering with the flow pattern in such narrow, baffled channels is another reason for non-acceptance. The limited range of operating depths is also a serious disadvantage.

WEIR FISHWAYS

Weir fishways are commonly used on this continent for passing salmon and trout over natural and artificial obstructions. This type of fishway consists of a sloping channel divided into a series of pools by means of transverse partitions. The water flowing down the channel passes over the partitions, or weirs. Part of the flow may also pass through orifices in these partitions (FIGURE 16). Observations have suggested that the floor slope should not be greater than 1:8 and that the drop between pools should not exceed 1 ft. Small weir fishways are frequently 6 ft. wide with 4-ft.-high weirs on 8-ft. centers. Laboratory studies have shown that an orifice at the bottom of each weir increases the stability of flow in the pools. It also provides an alternate path that is used by a substantial proportion of the fish. A one-day count of migrating sockeye at one of the weirs of a fishway at McNary Dam indicated that about

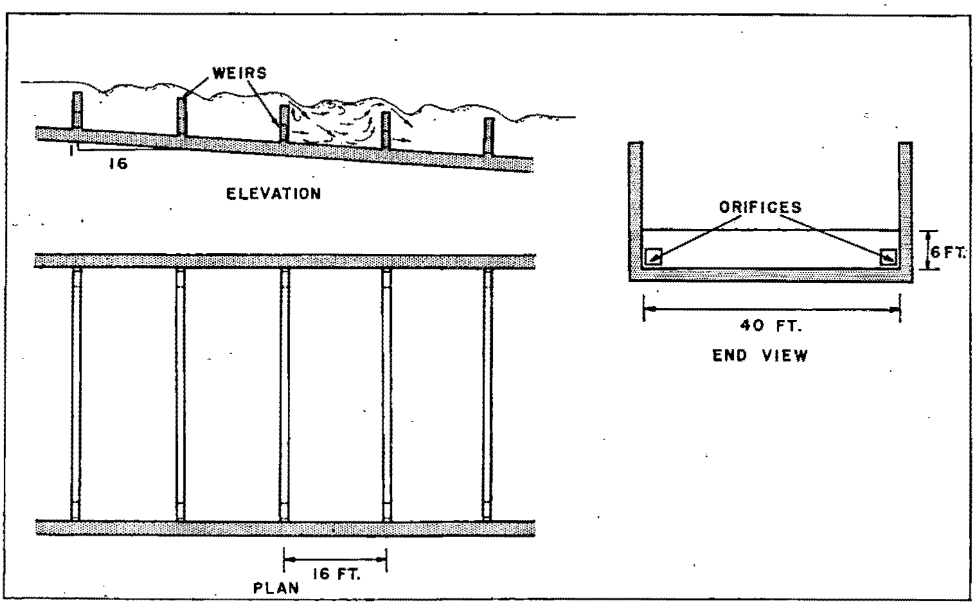


FIGURE 16—Weir fishways used at Bonneville Dam on the Columbia River.

77 per cent of the fish passed through the orifices in the weir (Corps of Engineers, 1956b). The minimum allowable flow depth over the weir crests is generally considered to be 9 in. for the efficient passage of adult salmon. Large fish, such as chinooks, may experience difficulty in passing over weirs when the water depth is less than 9 in. Holmes and Lindgren (1940), discussing possible fish-catching facilities for Shasta Dam in California, have presented a review of hydraulic requirements for weir fishways, collecting systems, fishway entrances and trapping systems for large dams.

One important disadvantage of weir fishways is that the flow pattern is dependent on the headwater elevation. For instance, weir fishways consisting of 6-by-8-ft. pools on a floor slope of 1:8, with no submerged orifices, have a stable flow pattern until the head on each of the baffles exceeds 1.1 ft. At heads of less than 1.1 ft., the flow over each weir plunges into the pool, producing a stable, upstream flow on the surface of the pool. However, when the head on the leading weir is 1.5 ft. or more, the flow over the weirs does not plunge into the pools but streams along the surface from one weir crest to the next. Between these two heads, which produce "plunging" flow and "streaming" flow respectively, there exists an unstable condition in which the flow alternates between plunging and streaming. Such a condition must be avoided because it greatly reduces the rate of fish movement through the fishway. In small fishways, passage of fish over the weirs sometimes causes the flow pattern to change and fish movement almost ceases for several minutes following such changes (Collins, 1958). Model studies have shown that this instability of flow can be minimized in several ways, most common of which are the use of submerged orifices and alterations in the shape of the weir crest to increase the contraction of the over-falling jet.

The earliest fishway designed to pass large runs of salmon over a major dam was built at Bonneville Dam, completed in 1938. Two main weir fishways were provided, each 40 ft. wide with 6-ft.-high weirs 16 ft. apart on a floor slope of 1:16. Experiments have shown that fish are delayed from 2.6 to 3.0 days in finding and ascending the fishways at this dam (Schoning and Johnson, 1956) and that salmon require about 2 hours to ascend through 35 pools (Anon., 1955). There is as yet no recorded evidence to indicate that the fish compensate for this delay by moving through the reservoir above the dam at a faster rate than through normal river velocities.

An attempt to develop more efficient weir fishways is being made by the United States Fish and Wildlife Service working under contract with the United States Army Corps of Engineers at a research laboratory at Bonneville Dam (Collins, 1958). The effects of fishway slope, water velocity and volume of traffic on the movement of adult salmon and steelhead through weir fishways are being investigated. In very short fishways, consisting of only four to six pools, it has been found that the rate of vertical ascent is about the same in fishway pools having a floor slope of 1:8 as in those with a slope of 1:16. Tests are also being conducted to determine whether the fish become fatigued more rapidly in moving through fishways with increased slope.

It is anticipated that current fishway research will yield much basic information concerning behavior and physiology of salmon and trout in passage through fishways. While the main purpose of much of the research is to obtain information that may permit the design of more economical fishways, the data will also be useful in the design of more effective fishways. Scientific fishway design is not likely to be achieved in the near future, however, especially for passage of the large numbers of fish that would be encountered at proposed Fraser River dams.

POOL-AND-JET FISHWAYS

In efforts to provide fishways that operate over wide variations in river elevation, designers have evolved various types operating on the pool-and-jet principle. These fishways consist of a series of pools from headwater to tailwater with the water flowing from pool-to-pool through orifices or vertical slots. Most if not all of the energy of the water in each jet is dissipated in the pool into which the jet issues, so that there is a minimum carry-over of energy down the fishway.

Early designs of this type of fishway included the alternate-obstacle and paired-obstacle fishways shown in FIGURE 17. The former consists of an open channel with staggered baffles projecting from the sides to about the middle of the channel. In the paired-obstacle fishway, the baffles are placed opposite each other. Thus, the tortuous flow of the alternate-obstacle fishway is avoided but the velocity of the jet is somewhat higher for the same slope. Alternate-obstacle and paired-obstacle fishways are not used at the present time for passing fish over high dams as fish sometimes have difficulty ascending them. Further, weir fishways are easier to maintain. Vertical-slot fishways, a more recently developed type of pool-an-jet fishway, combine the ease of fish passage of the weir fishway with the wide vertical range of operating levels of paired and alternate-obstacle fishways.

Vertical-slot fishways originated at Hell's Gate. The Salmon Commission has also constructed this type of fishway at three other river canyons where sockeye previously had difficulty in their upstream migration—at Yale Rapids and Bridge River Rapids on the Fraser River and at Farwell Canyon on the Chilcotin River. Vertical-slot fishways were evolved as a result of a necessity for fishways that could operate over a wide range in river elevation without manual adjustment. Although the total head through Hell's Gate gorge is only 8 to 10 ft. the water elevation has been known to change as much at 7 ft. in one day. Weir fishways would have required almost constant adjustment to compensate for changes in headwater and tailwater elevations.

Fishways of this type are provided on both sides of the river at Hell's Gate; one large fishway and a smaller, high-level fishway have been constructed on each bank. The main fishways are designed to operate over a range of 31 ft. in river elevation while the high level fishways function over a 16-ft. higher elevation. The main fishway on the left bank, which is the largest of the four,

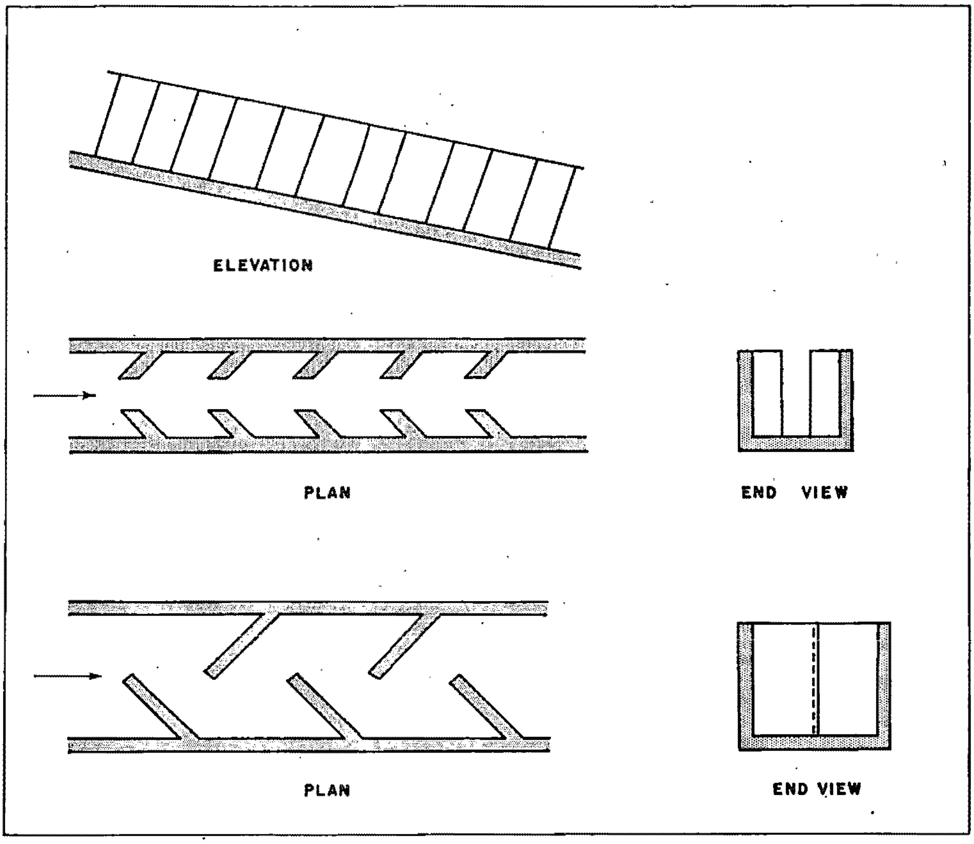


FIGURE 17—Paired-obstacle and alternate-obstacle fishways.

is 460 ft. long. The pools are 20 ft. wide, while a transportation channel at the upper end of the fishway is 12 ft. wide. The high-level fishway on the left bank is 220 ft. long and 9 ft. wide. The main right bank fishway is also 220 ft. long and is 20 ft. wide, while the high-level right bank fishway is 120 ft. long and 12 ft. wide. Both main fishways are of the double-slot type and the high-level left bank fishway is of single-slot design (FIGURE 18). The high-level fishway on the right bank is a modified double-slot design. While maximum river velocities at Hell's Gate may reach 25 f.p.s., the average velocity in the fishways is only 1.5 f.p.s., which permits easy upstream migration for all species of salmon spawning above Hell's Gate.

The Lower Adams River sockeye run was less seriously affected than other upriver sockeye populations by the obstruction at Hell's Gate. As shown by Thompson (1945), this run was able to survive because it migrated later in the year than other runs and passed through Hell's Gate at lower water levels, when the natural river canyon was normally passable. However, in both 1954 and 1958 the river was unusually high during migration of sockeye destined for Adams River and all the fish were forced to use the fishways. The following comment is pertinent:

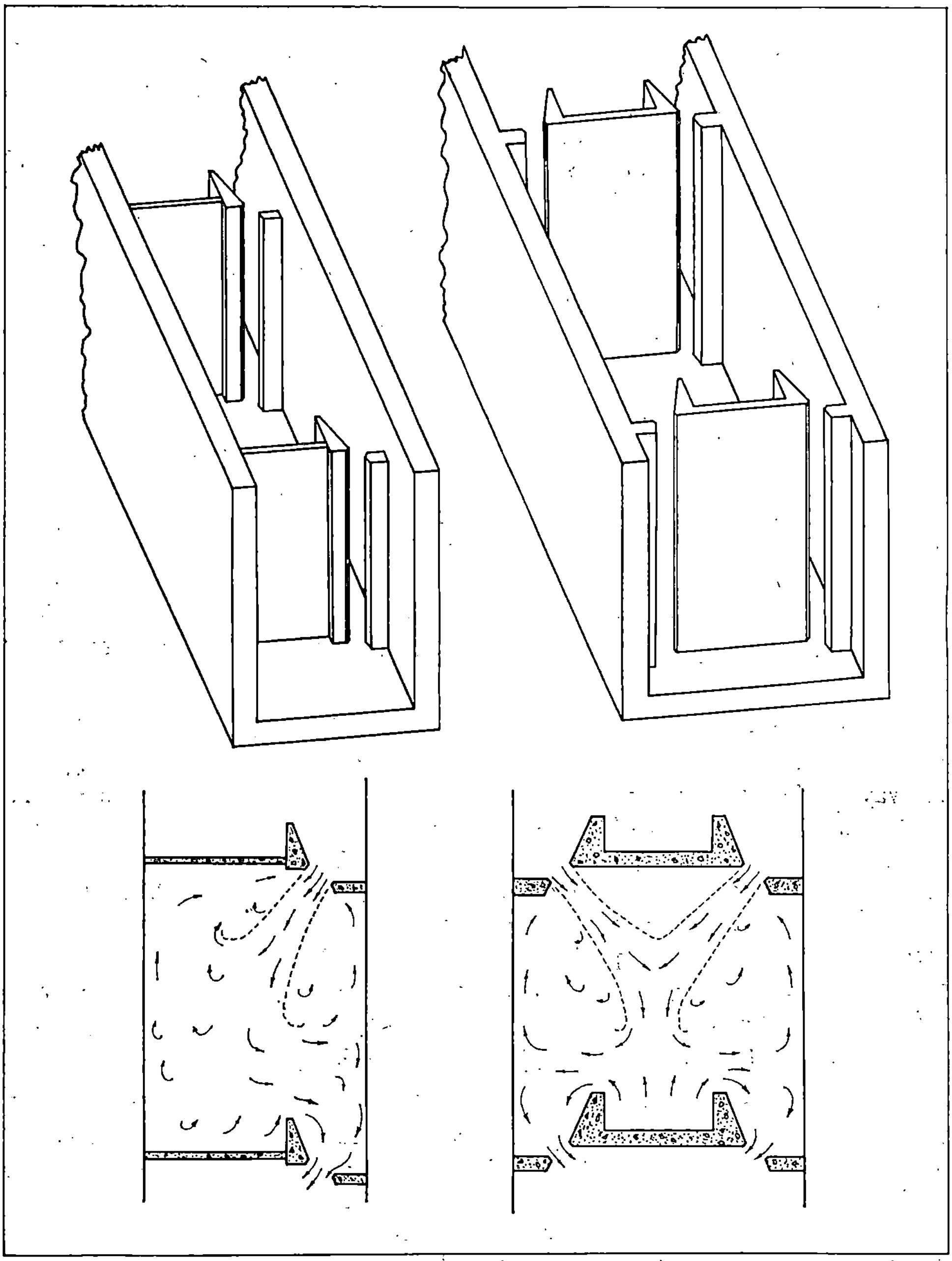


FIGURE 18—Single-jet and double-jet vertical-slot fishways.

"At Hell's Gate the unusually high water levels required the Adams River sockeye run to use the fishways for its entire period of passage from September 24th to October 4th. Normally this race, because of its late-season timing, passes Hell's Gate when the gauge-levels are below 25 feet and the natural channel is consequently passable. The 1954 Adams spawning escapement would have been substantially destroyed at Hell's Gate had the fishways not existed, and a quadrennial run worth approximately $28,000,000 would have been lost to the future resource economy of Canada and the United States. The unprecedented size of the Adams River escapement arriving below Hell's Gate on the peak day, estimated at over 1,000,000 fish, slightly exceeded the capacity of the fishways and a minor delay in upstream migration occurred. A similar effect was noted elsewhere along the Fraser and Thompson canyons where the marginal areas suitable for sockeye passage are of limited capacity." (Internat. Pacific Salmon Fish. Comm., 1955).

Vertical-slot fishways have not been commonly used for passing salmon over dams. However, the installation at Seton Dam, which is located at the outlet of Seton Lake, near Lillooet, provides an illustration of a recent trend at low-head dams. This dam operates at a head of 25 ft. with a maximum headwater fluctuation of 3 ft. An 8-ft.-wide by 350-ft.-long fishway was provided for passing sockeye, pink, chinook and coho salmon as well as steelhead and other trout. This single-jet vertical-slot fishway, provides a 16¼-in.-wide slot through which fish can swim at any depth in the fishway. The baffles are spaced 10 ft. apart on a floor slope of 1:13.33. The water depth is about 6 ft. at maximum forebay and minimum tailwater elevations. The discharge ranges from about 23 to 45 c.f.s. depending on forebay elevation.

In 1956, 9000 sockeye destined for Gates Creek migrated through this fishway from July 20 to August 20. Nineteen per cent of these passed through the fishway on the peak day. The peak hourly migration was 22.5 per cent of that day's total migration and the maximum migration in a 15-minute period was 10.7 per cent of the daily migration. The fish did not appear to be overcrowded at any time in this fishway. The average time of migration through the fishway was from 20 to 30 minutes. That is, the fish spent an average of about 48 seconds in each of the 31 pools. One fish ascended the ladder in 11 minutes and some were observed to require at least 45 minutes. An observed delay of fish at the upper end of he fishway was thought to be a result of fatigue incurred in passing through the fishway (Andrew and Geen, 1958).

A single-jet vertical-slot fishway was considered for passing salmon, steelhead, striped bass *(Roccus saxatilis)*, shad *(Alosa sapidissima)*, sturgeon *(Acipenser transmontanus* and *A. medirostris)* and other fish over low, variable-head dams proposed for construction in the Sacramento-San Joaquin area in connection with a water-conservation scheme in California. Some of the species involved, namely striped bass, shad and sturgeon, appear reluctant to use weir fishways. A test installation was constructed consisting of three baffles of a vertical-slot fishway having 12-in.-wide slots and a water depth of 6 ft. The pools were 8 ft. wide and 12 ft. long. Most of the fish were captured in gill nets and transported to the test installation by boat. Results of the experiments indicated that some individuals of all species tested used the fishway under captive conditions. However, the proportions of steelhead trout and chinook salmon using the fishway were much higher than the proportions of other species tested. Sixty per cent of the steelhead, 67 per cent of the chinook salmon, 22 per cent of the striped bass, 32 per cent of the shad and 20 per cent of the sturgeon passed upstream through the fishway (Fisk, 1959).

CALCULATED FISH-CARRYING CAPACITY OF FISHWAYS

Evaluation of the carrying capacity of fishways is of utmost importance both from an economic and a biological point of view. Methods of calculating the carrying capacities of weir and vertical-slot fishways have been suggested but they appear adequate only for obtaining rough approximations. No information is available on the capacity of Denil fishways.

It has been suggested (Anon., 1955) that data obtained at the Bonneville fishway can be used to compute the size of weir fishway required for passing a given number of fish. These computations necessitate an assumption as to the amount of fishway volume required for each fish. It was arbitrarily assumed that fish require the following fishway volumes:

Sockeye, pink and coho salmon and steelhead trout

— 4 cu. ft. per fish during active movement.
— 2 cu. ft. per fish during resting.

Chinook salmon

— 8 cu. ft. per fish during active movement.
— 4 cu. ft. per fish during resting.

No additional fishway volume was assumed to be necessary for scrap fish such as suckers and squawfish although species other than salmon and steelhead account for about one third of all fish counted over Bonneville Dam. As previously stated, salmon require an average of two hours to ascend 35 pools, or 35 vertical feet, of a weir fishway at Bonneville Dam. It was estimated that 15 per cent of the fish passed through this section of the fishway in one hour, 50 per cent in the second hour after entrance, 20 per cent in the third hour and 15 per cent in the fourth hour. Knowledge of the average rates at which sockeye enter the fishway during each day's migration, as tabulated below, therefore permits calculation of the number of fish in a 35-pool fishway at any given time.

According to this calculation, a 35-pool fishway would have 25.4 per cent of the day's fish in the fishway at one time. In other words, to pass a run of 750,000 fish in one day, sufficient space would have to be provided for 190,500 fish in the 35 pools. Since observations suggest that salmon do not sound deeper than 12 ft. when actively migrating, a maximum allowable fishway depth of 10 ft. has been specified. Thus, pools 16 ft. long and 10 ft. deep would have to be 140 ft. wide to provide sufficient volume for these fish. This calculation assumes that the 190,500 fish would be uniformly distributed throughout the 35 pools, an unlikely possibility.

The average hourly pattern of migration of sockeye during a day's migration at Bonneville Dam is shown below:

Time	Average Per Cent of Total Daily Run
4 - 5 a.m.	7
5 - 6	10
6 - 7	14
7 - 8	9
8 - 9	6
9 - 10	8
10 - 11	4
11 - 12	4
12 - 1 p.m.	5
1 - 2	7
2 - 3	7
3 - 4	8
4 - 5	7
5 - 6	4

The Bonneville data also suggest another method of calculating fishway capacity. Since salmon move through the Bonneville fishways at a rate of 35 pools in 120 minutes, fish spend an average of 3.4 minutes in each pool. In the peak hour, 14 per cent of the daily migration must be passed. At a migration rate of 750,000 fish per day, an average of 6000 fish would therefore occupy each pool during this peak hour. If a fishway volume of 4 cu. ft. is allowed for each fish, each fishway pool would have to be 150 ft. wide, 16 ft. long and 10 ft. deep regardless of the number of pools.

There are two problems involved in both of these methods of calculation. First, there is no safety factor to allow for non-uniform distribution of fish either horizontally or throughout the length of fishways. A second source of error is involved if the fish migrate at a non-uniform rate; it might be expected that the rate of movement through long fishways would be slower than through short ones. In this case, long fishways would have to be wider than short ones to pass the same number of fish. In addition, no allowance is made for unusually large numbers of fish arriving at the fishway in a short time. If the fish are to be passed with as little delay as possible, peak rates of migration rather than average rates should be taken into consideration. At Seton Dam, for instance, Andrew and Geen (1958) reported an average hourly peak rate of migration through the fishway of approximately 10 per cent of the daily total run. The individual hourly peak, on the other hand, amounted to 22.5 per cent of the daily total, while the 15-minute peak was 10.7 per cent.

Passage of fish through very long fishways introduces other problems. Because fish do not appear to migrate through fast, turbulent water during darkness at natural river obstructions, they may move downstream out of fishways at dusk. In this case, salmon would not be able to ascend fishways that were so long that they could not be negotiated during the hours of daylight of a single day. Using the data obtained at Bonneville Dam as design criteria, 65 per cent of the fish can be expected to pass through 35 pools in 2 hours. Assuming that this rate is maintained during 13 hours of daylight, 65 per cent of the fish that enter a very long fishway during the first hour of daylight could be expected to migrate through 227 pools before nightfall. At a 200-ft. dam, therefore, only those fish that entered the fishway during the first few daylight hours would reach the top of the fishway before nightfall. If the remainder of the fish migrated downstream out of the fishway, upstream passage would be greatly delayed and some fish might never reach the top of the fishway. For this reason, large resting pools at intervals throughout the length of long fishways have been proposed as a possible means of preventing the possible exodus of fish. If such resting pools were provided every 35 vertical feet, the loss of fish would presumably include only those fish that entered the fishway during the last two hours of daylight each day. Each resting pool would have to be large enough to provide 2 cu. ft. of volume for each fish in the 35-pool section of fishway immediately upstream from it. The largest resting pool, for accommodating a maximum daily run of 750,000 sockeye, would theoretically contain 25.4 per cent of the day's run or 190,500 fish. At a width of 140 ft. and depth of 10 ft., each pool would therefore have to be 270 ft. long. However, there is no proof that such resting pools would be required for long fishways nor whether they would be effective for the purpose intended. It is evident that problems involved in the use of fishways for passing salmon over high dams have not been adequately investigated.

Elling and Raymond (1959) reported on tests conducted under controlled conditions at Bonneville Dam in 1956 to determine the capacity of weir fishways. Eight tests were made involving passage of varying numbers of fish through a six-pool weir fishway, each pool measuring 6 ft. wide, 16 ft. long, 6.3 ft. average depth, with a 1 ft. differential in elevation between weirs. From 70 to 2886 fish entered this fishway in one-hour periods. The median passage time through the six-pool fishway ranged from 12 to 35 minutes. Data suggested that the maximum capacity of the fishway may have been reached in one test when an average of 51 fish entered per minute but these workers emphasized that interpretation of the results of the tests can be only tentative pending further investigation of factors controlling fishway capacity. No information is available to indicate whether this high rate of fish passage could be maintained or whether slow-moving fish would accumulate in lower pools of the fishway and limit its carrying capacity. Further, passage of large numbers of fish caused the flow pattern in the fishway to change from plunging to streaming flow and this change markedly affected the rate of passage.

Some information is also available concerning the capacity of vertical-slot fishways. The fish-carrying capacity of the two main fishways at Hell's Gate was computed by Jackson (1950). In 1944, when these fishways were being designed, it was assumed that at some time in the future they would have to provide passage for 1,500,000 or 1,750,000 fish in the peak week and that the maximum rate of arrival might exceed 250 sockeye per minute on each bank.

It was further assumed that the water depth in the fishways would be 6 ft. at the minimum stage for which the fishways were required. The pools were designed to be 20 ft. wide and 18 ft. long. Thus, at the lowest operating stage there would be 2160 cu. ft. of water in each pool. A volume of 2 cu. ft. was allowed as a minimum for each sockeye, so each pool could theoretically contain 1080 sockeye at the minimum water level. Some of this volume would be too turbulent for fish to utilize but no reduction was made on this account. Allowing an average passage time of five minutes per pool, the maximum capacity of each fishway at the minimum water level was computed to be 216 fish per minute.

Passage between pools was also considered. The jet velocity between pools is approximately 8 f.p.s. A sockeye 2.5 ft. long swimming at an estimated maximum swimming speed of 12 f.p.s. would pass through the short jet at each baffle in about one second. Since there are two jets in each of the two main fishways, the capacity for fish passing single file through the two jets would be 120 fish per minute in each fishway. However, each jet is 2 ft. wide and 6 ft. deep at minimum operating level, so the capacity of each jet is probably considerably greater than 60 fish per minute.

Rehabilitation of the upriver races of Fraser River sockeye has been so rapid that the fish-carrying capacity of the Hell's Gate fishways has already been exceeded. The 1954 run to Adams River, consisting of over 2,000,000 sockeye, entered the Fraser in a 2.5-day period and large numbers were present at Hell's Gate for at least six days. This extension of the run resulted from the limited passage provided by the Hell's Gate fishways and also from a normal spreading out in the restricted marginal areas of the Fraser Canyon below Hell's Gate. The *average* rate of passage through Hell's Gate must have been about 440 sockeye per minute, assuming that the 2,048,000 fish enumerated on the spawning grounds passed through the fishways for 13 hours each day during the observed six-day period. The *maximum* rate of passage during this period must have been considerably greater than 440 fish per minute, divided between the two main fishways.

GRAVITY FISH LOCKS

For many years small populations of salmon and trout have been passed over dams by means of fish locks, which operate on the same principle as ship locks. The fish lock at McNary Dam on the Columbia River provides an illustration of modern design of gravity fish locks (Von Gunten *et al.*, 1956). A schematic diagram of a gravity fish lock is shown in FIGURE 19. The lock at McNary Dam consists of a vertical shaft 20 by 30 ft. in horizontal section, providing for a total vertical lift of 85 ft. A diffusion chamber located below a grillage in the floor provides a uniform velocity into the lock chamber. During periods when fish are being attracted into the lock chamber, the water flows from the lock chamber over a 10-ft.-wide telescopic weir into a "lock entrance pool" or "holding basin", which is 25 by 35 ft. in horizontal section. From this chamber the water flows over a 20-ft.-wide telescopic weir to enter one of the lower pools of the weir fishway on the Washington shore of the

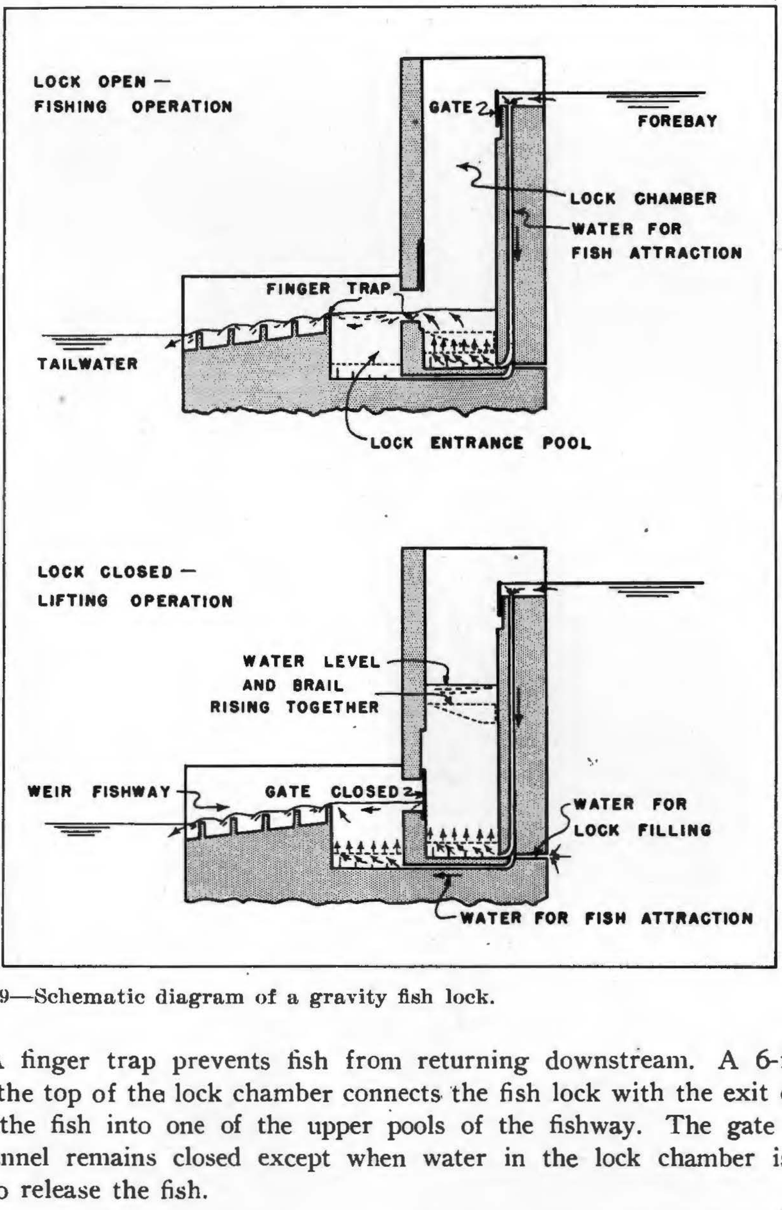


FIGURE 19—Schematic diagram of a gravity fish lock.

dam. A finger trap prevents fish from returning downstream. A 6-ft.-wide gate at the top of the lock chamber connects the fish lock with the exit channel leading the fish into one of the upper pools of the fishway. The gate on the exit channel remains closed except when water in the lock chamber is being raised to release the fish.

This fish lock was built at McNary Dam to provide an auxiliary method of passing fish in case of failure or necessary closure of the weir fishway on this bank. In addition, it was intended as an experimental facility. Since a major difficulty experienced in the operation of fish locks at Bonneville Dam was the problem of attracting fish into the lock chamber, the lock at McNary Dam was placed so that the fishway entrance and lower weirs could be used as the entrance to the lock. The lock is constructed so as to be functional either with or without the continued operation of the entire fishway. Fish can swim from the fishway entrance, past the lower weirs, through the lock entrance pool, and into the lock chamber. There they are raised, by gravity flow hydraulic lockage similar to that of a single-lift navigation lock, to forebay level.

To speed removal of fish from the lock chamber to the exit channel, a brail is used for forcing fish to remain near the water surface in the lock chamber as water in this chamber is raised to the level of water in the exit channel. This brail has a slatted floor that slopes from three sides to a small horizontal area at the exit channel. Water in the lock chamber is raised from tailwater to forebay level in three or four minutes and the brail follows this rise.

There is a constant discharge of 60 c.f.s. in the exit channel. This water is drawn directly from the forebay and, after passing through the exit channel, enters a pipe at the downstream end of this channel. This pipe connects to the lock chamber and to the lock entrance pool. During the "fishing" period, when the water in the lock chamber is at tailwater level, flow from the exit channel is directed into the diffusion chamber in the lock. During the "locking" period, when water in the lock is above tailwater elevation, this attraction flow is directed through a similar diffusion area in the lock entrance chamber or holding basin. Water for filling the lock is drawn directly from the forebay through a large conduit and, during the emptying period, the water is discharged to the river below the dam.

The Borland Hydraulic Fish Elevator, incorporated in the Torr Achilty Dam in Scotland, is a fish lock very similar in principle to that installed at McNary Dam. As shown in FIGURE 20, the lock chamber is a sloping conduit. It measures 12 ft. by 6 ft. in cross section and extends over a vertical height of 52 ft. from tailwater to forebay. The lock chamber also serves as the

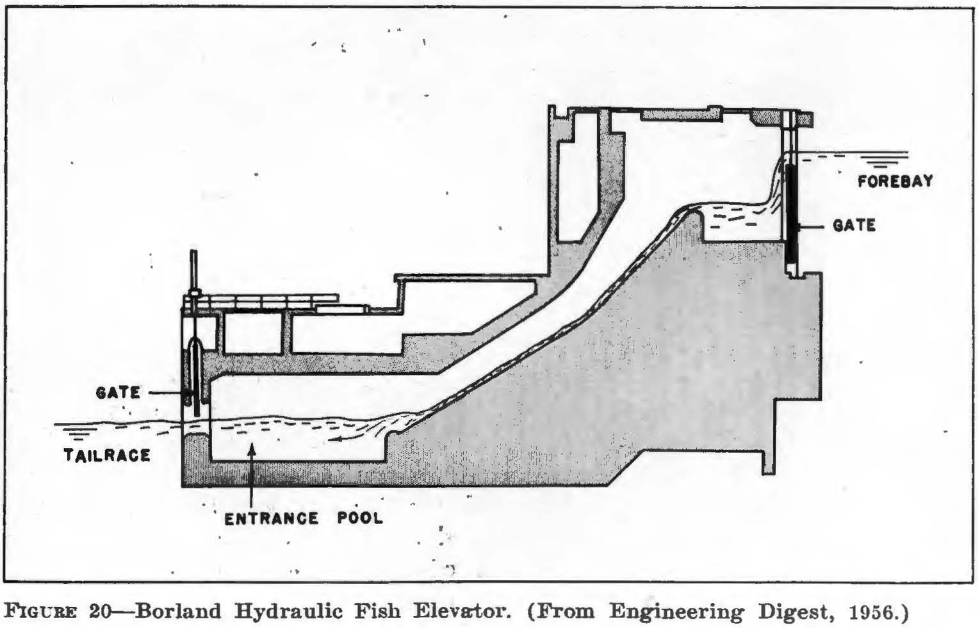


FIGURE 20—Borland Hydraulic Fish Elevator. (From Engineering Digest, 1956.)

entrance pool. There is no holding basin or entrance chamber for accumulating fish during periods when the lock is filling or emptying. The gate at the upstream end of the lock chamber consists of a 4-ft.-wide roller gate having a travel of 12 ft. Automatic controls are used to maintain the crest of this gate about 12 in. below the surface of the forebay. The discharge over this gate, about 14 c.f.s., flows into the lock chamber continuously, providing attraction water at the lock entrance, and also filling water when the gate at the downstream end of the lock chamber is closed. When the lock is filled to forebay level, a velocity is created through the lock chamber by a flow of 7 c.f.s. discharged through a by-pass valve at the downstream end of the lock chamber. This velocity is intended to provide the stimulus necessary to cause fish to swim to the exit gate of the lock chamber. Operation of this lock is on a four-hour cycle. The lower gate is open for entrance of fish for three hours, flooding of the lock chamber requires about 20 minutes, the gate at the upstream end of the lock chamber remains open for exit of fish for about 30 minutes, and dewatering of the lock chamber requires about five minutes. An estimated 3400 salmon, ranging in weight from 5 to 40 pounds, used this fish lock during an eight-month period in 1955 (Engineering Digest, 1956).

A simple type of fish lock is used for passing fish over low dams in the Netherlands (Deelder, 1958). This device, as shown in FIGURE 21, is essentially the same as the Borland Fish Elevator, except that it is not a closed conduit. Deelder recommended that inefficient types of fish passes currently used in Europe be replaced with fish locks because the effort required by the fish is minimized and less water is required for operation. He stated: " . . . . the final path to be followed by the water in a fish pass should form a right angle to the direction in which the river flows and should be situated just downstream of the point where the turmoil of the water falling over the weir (dam) finishes." This procedure is not followed in planning fish-passage facilities for Pacific salmon because observations have indicated that these fish, upon encountering a point of difficult passage, often proceed as far upstream as possible and remain there until fatigued attempting to surmount the obstacle.

The inefficient attraction of fish into locks has been frequently commented upon. Since it has not been possible to conduct the large-scale experiments necessary to investigate possible design improvements, fish locks must be considered unsatisfactory at the present time for passing large runs of Fraser River sockeye and pink salmon. It has often been suggested that attraction and collection of fish would be expedited if short Denil fishways were used between the locks and tailwater level at dams. For instance, McGrath (1958) in discussing the inefficient attraction of fish to locks, maintained that "much benefit would result if it were possible to combine a Denil type pass outlet with a Borland pass main unit." It is also conceivable that a system could be devised to speed the entrance of fish into locks by using moving screens in a long approach channel to force fish to enter the lock chamber. Such devices,

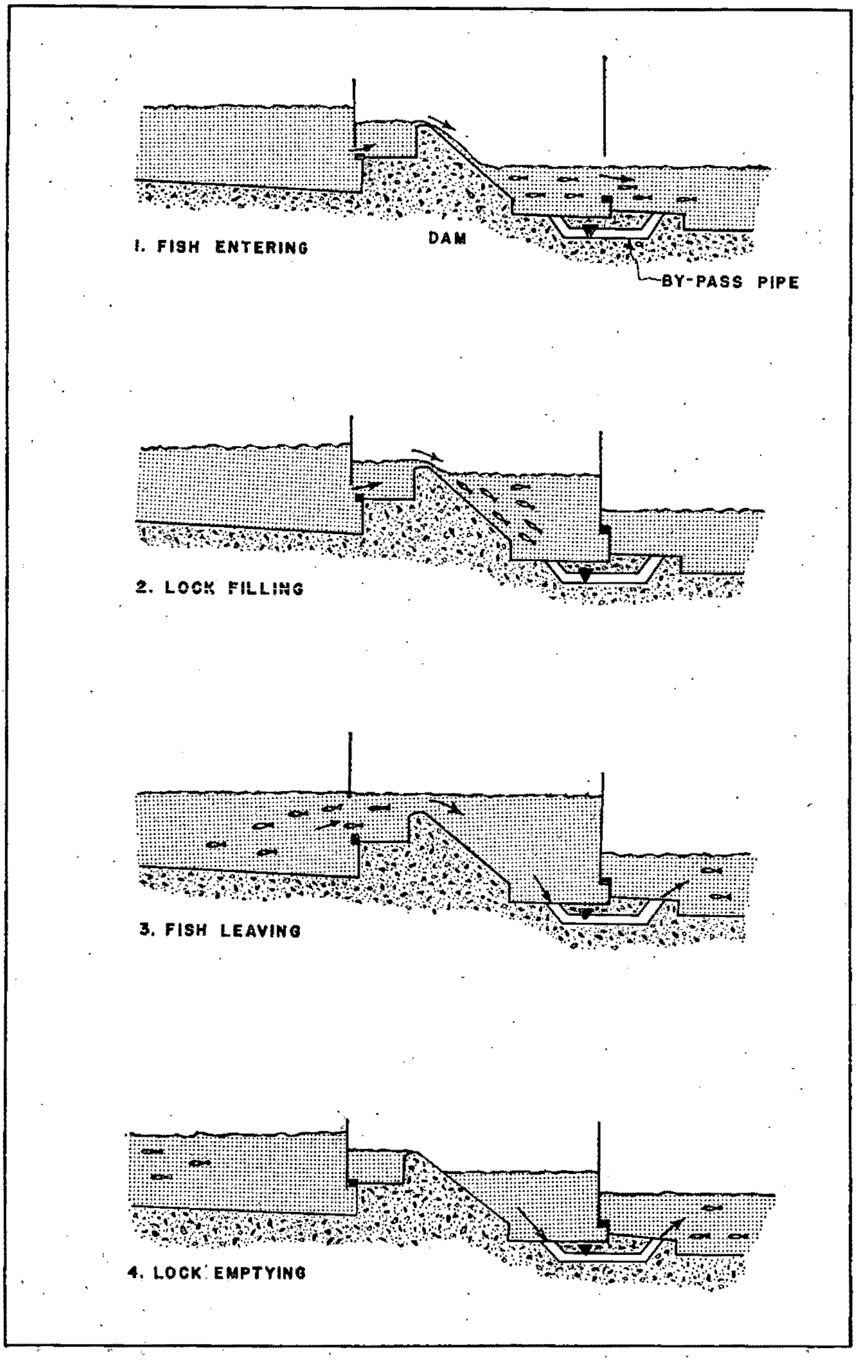


FIGURE 21—A simple gravity fish lock used at low dams in the Netherlands. (From Deelder, 1958.)

however, would probably impose additional stress on the fish and might cause physical injury. Further, the previously described problems of attracting fish to fishway entrances at dams would still exist.

The Borland Fish Elevator and the pressure fish lock, both of which operate without a brail, have the additional disadvantage that some fish remain in them for long periods of time, sometimes for several operational cycles. While this disadvantage may not be significant with respect to passage of Atlantic salmon or some species of Pacific salmon and steelhead trout, it would have serious consequences with respect to passage of Fraser River sockeye and pink salmon in that the capacity of the transport system would be reduced and the fish would be delayed.

The limited capacity of fish locks is a major disadvantage. Even if a system could be devised to overcome the apparent reluctance of salmon to pass through fish locks without delay, the problem of providing locks large enough to pass large runs of salmon over a dam on the Fraser River would not be easily solved. It has been shown that fish facilities at such a dam would have to be capable of passing, in a single hour, at least 14 per cent of the maximum daily migration of 750,000 fish. That is, 105,000 salmon may be expected to arrive at any dam on the Fraser River below Prince George in a single hour. If the loading and unloading of fish could be done mechanically by means of forcing screens and brails it might be possible to operate the fish lock on a two-hour cycle at a low dam, possibly 50 ft. high. For continuous operation, at least two lock chambers would be required, operating in sequence.

No criteria are available to permit the design of such a facility but some comprehension of the minimum physical size of such a structure can be obtained by assuming an operational cycle of one hour, with three locks operating sequentially so that each would be capable of passing one third of the maximum number of fish expected in the peak hour. Volume requirements for each fish are not precisely known. Unpublished studies of the passage of salmon through locks have indicated that the fish exhibit a state of alarm or "uneasiness" when confined in volumes that allow less than 20 cu. ft. per fish. However, even applying the same volume requirements as used for resting areas in fishway design, fish locks for passing Fraser River sockeye would be extremely large. If it is assumed that a volume of 2 cu. ft. would be sufficient for each fish, each of the three locks would have to contain 70,000 cu. ft. of suitable resting areas. Since salmon are known to congregate near the surface, depths greater than 12 ft. are not considered suitable as rest areas. Therefore, the cross section of each lock chamber would have to be at least 5830 sq. ft. or about 76.4 ft. square. Assuming that one third of the maximum hour's migration, or 35,000 fish, could be loaded into each lock in 30 minutes and that the other operations—filling the lock to forebay level, unloading the fish, and emptying the lock to tailwater level—could each be completed in 10 minutes, the filling and emptying discharges for a vertical lift of 100 ft. would be 970 c.f.s. If each fish required 20 cu. ft. of volume instead of 2 cu. ft., the lock would have to be 10 times as large in cross-sectional area and the discharge would be 10 times as great. It is very unlikely that the fish lock described by these theoretical calculations would be practical because, for one thing, the operational cycle would probably have to be considerably longer to allow entry of the fish and to complete the other phases of the operation. More lock chambers would therefore be required. It can be seen that the structures required would be very large and that the amount of water consumed would be substantial, even for a low dam. More important, however, is the fact that operating experience with gravity fish locks at Columbia River dams does not encourage optimism concerning their possible use in passing large numbers of salmon over proposed Fraser River dams.

PRESSURE FISH LOCKS

The pressure fish lock is another type of facility specifically designed for passing fish over dams. In operation, it is very similar to a gravity fish lock; the same entrance systems can be used, and the lock chamber consists of a vertical or sloping shaft extending from tailwater to forebay. The lock chamber may extend to the water surface of the forebay or it may pass directly through the dam, in which case fish are released below the surface of the forebay. A schematic diagram of the pressure fish lock installed at McNary Dam is shown in FIGURE 22. After fish enter the lock chamber, a gate is closed at the downstream end of this pool and another gate is opened at the upstream end. The fish are therefore subjected to a sudden pressure increase proportional to the head on the dam. A small discharge is passed through the pressurized lock chamber to provide a velocity that is intended to induce fish to swim from this conduit into the forebay.

The experimental pressure fish lock installed at McNary Dam operates under a gross head of 92 ft. (Von Gunten *et al.*, 1956). The entrance to this facility consists of a short weir fishway, from which fish enter the lock chamber by swimming over a finger trap mounted on the crest of a telescopic weir. The lock chamber has a cross section 12 ft. by 8 ft. and a 4-by-6-ft. tunnel extends about 22 ft. from this chamber to the forebay. This exit tunnel, which is gated at midlength, leads to two openings into the forebay, one through a 60-ft.-long vertical shaft to the forebay surface and the other a continuation of the deeply submerged exit tunnel direct to forebay. Water to attract fish into the lock chamber is introduced through a grating in the floor of the chamber. When the lock chamber is filled or fish are being discharged, this water supply is shifted to a diffusion area in the floor of the upper end of the approach fish ladder to provide a constant flow down the ladder.

Preliminary experiments have been conducted to evaluate possible biological effects of pressure fish locks on migrating adult sockeye salmon (Harvey and Pyper, MS.). Tests on 110 Cultus Lake sockeye in 1958 were designed to measure effects of duration of pressure and rates of application and release of pressure. Pressures of 300 p.s.i., which would correspond to pressures in the fish lock of a 700-ft. dam, caused only one immediate mortality. This fish

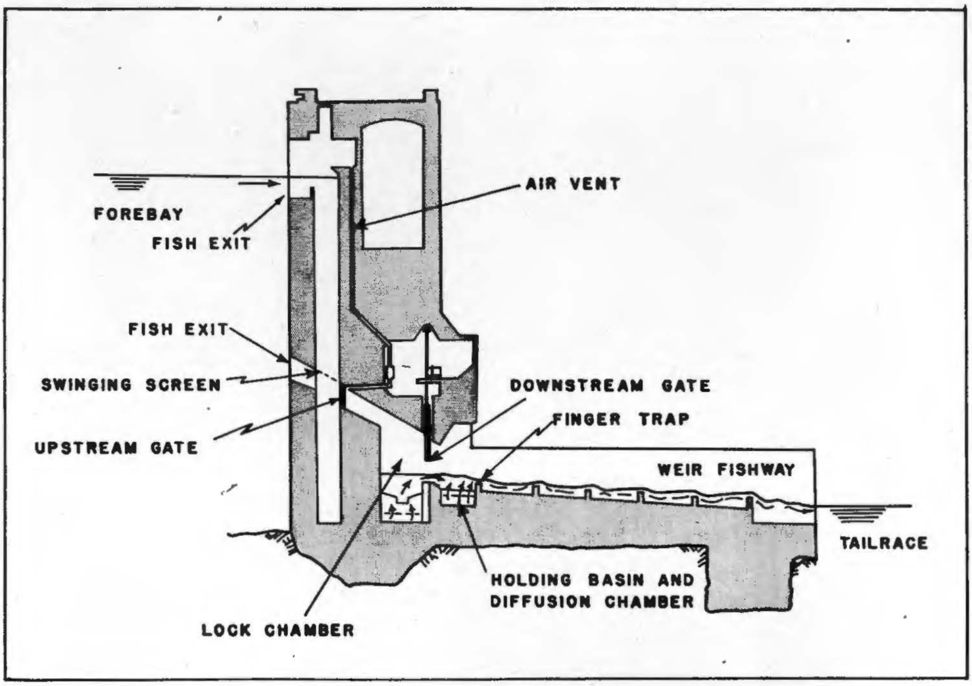


FIGURE 22—Schematic diagram of the experimental pressure fish lock at McNary Dam on the Columbia River. (From Von Gunten *et al.*, 1956.)

died of internal hemorrhage. A higher mortality among pressurized females was observed during a two- to three-week retention of test and control fish. Fish that died during the retention period were unspawned but the viability of eggs of the pressurized females surviving to maturity was not affected. These studies were expanded in 1959 to explore the effects of lower pressures. Results based on 60 fish indicated a mortality prior to spawning of approximately 10 per cent among females exposed to 50 p.s.i. or 300 p.s.i. No control mortalities were observed. It appeared that the ability of adult sockeye to cope with the stresses imposed by retention may have been reduced after the fish had been subjected to pressure. While adult sockeye do not appear to be seriously affected by pressure or pressure change, their ability to cope with additional stresses of the environment may be significantly reduced. Further studies are required before pressure fish locks can be adquately evaluated for passing adult salmon over dams.

From an engineering point of view, pressure fish locks have certain advantages over gravity fish locks. Two distinct advantages are immediately apparent: first, the water requirements are considerably less and second, the fish can be released directly into the forebay without transporting them to the water surface. However, attraction of fish into the lock, a problem that has become apparent in the use of gravity fish locks, is not improved. Further, the capacity of pressure fish locks may be even more restricted than that of gravity fish locks because experience with the experimental lock at McNary Dam has shown that some fish remain in the pressurized lock chamber for several hours before moving out into the forebay.

MECHANICAL TRANSPORTATION

Another method that is sometimes used for passing small runs of salmon and trout over dams consists of mechanical transportation by truck, aerial cableway, railway or elevator. The mechanical trapping and transporting facilities at Cleveland Dam have already been described. A similar installation on the White River in the State of Washington has been operating since 1940. This installation was built to provide upstream passage for salmon and trout at Mud Mountain (Stevens) Dam, a flood control project. A maximum of 15,653 salmon and steelhead have been transported in one year (Wash. Dept. Fish., 1959). Fish are collected at a low diversion dam some distance downstream from Mud Mountain Dam. From this impassable barrier, a weir fishway leads the fish to a holding basin. Without being removed from the water, fish are forced, by means of a sloping brail, to enter a second chamber. A funnel-shaped bucket at the bottom of this chamber is then raised, containing the fish and an adequate volume of water. A gantry crane then transports the bucket to a loading bay, where the fish and water are transferred to a tank truck. The tank is filled with water before the fish and water in the bucket are loaded. A drain on the tank is opened and the fish and water then pass into the transport tank. The fish, therefore, remain in water at all times and are not dropped freely into the tank. The fish are hauled about seven miles before release.

From 1926 to 1956, a unique aerial cableway was used for passing salmon and trout over Baker Dam. Since the head on this dam is 250 ft., conventional fishways were considered impractical and a mechanical method of transporting the fish was therefore provided. Fish were stopped in their upstream migration by means of a picketed weir across the river at the powerhouse and diverted into two traps, one in the center of the weir and the other at the upstream end of the tailrace channel. They were brailed from these traps, which had a cross section about 3 by 5 ft., in water-filled buckets and dumped into a 50-cu.-ft. transport tank running on a narrow-gauge railway. This tank was pulled up an incline to a holding pool about 50 ft. above the tailrace elevation. The fish were dumped into the holding pool and subsequently loaded into a 20-cu.-ft. tank that was hauled on an aerial cableway to the crest of the dam. There the fish were dumped into another tank, a sliding gate in this tank was opened, and the fish were carried through a 50-ft.-long wooden pipe and fell freely through air from the end of this pipe to a barge in the forebay of the dam. As fish were sometimes swept downstream over the spillway, they had to be barged several hundred yards up the reservoir before being released. This method of transporting fish over Baker Dam was injurious and inefficient. The weir occasionally washed out, the traps were not efficient and the fish were often injured in transferring them into and out of the several tanks.

However, it did serve to preserve a segment of the original run of sockeye and coho for 30 years. The maximum number of fish hauled in any one year consisted of 19,637 coho, 3522 sockeye and 219 steelhead trout, pinks and chinooks. In recent years the run has consisted of about 8200 coho and 2400 sockeye. Even when operated at the maximum rate, only 60 fish could be hauled over the dam in 15 minutes.

The inefficient transporting system at this dam had to be replaced in 1958 because another dam was being constructed upstream and it was desirable to trap fish downstream from the lower dam and transport them 25 miles to above the upper dam. A barrier dam was therefore constructed and a fishway and loading system very similar to that at Mud Mountain Dam was installed so that fish trapped at this location could be loaded into tank trucks.

Fish are also transported over dams by means of elevators. The same system as described at White River, or Mud Mountain Dam, can be used for trapping fish below a dam and hauling them in water-filled buckets directly to forebay level. This transport method is used at the 60-ft.-high Beechwood Dam in New Brunswick (Trade News, 1958). At this plant, the fish are attracted to a collection system constructed along the face of the powerhouse. Fish swimming into this collection system from the tailrace follow along a transverse channel to a 10-ft.-square "V"-mouth trap. This trap also serves as an elevator carriage, which is drawn to the crest of the dam by means of a cable and winch arrangement. Before the carriage moves from its lower position the "V" entrance is closed, as is the fish passage approaching the trap. On arrival at the top of the dam, the carriage is tipped, releasing the fish to continue their journey up the reservoir. Raising, emptying and lowering the carriage takes approximately five minutes. Only 1127 salmon were passed over the dam in 1957, the first year of operation. Passage was delayed for a considerable period because the fish did not readily enter the trap. However, it was thought that this problem could be rectified in subsequent years after the plant was completed.

Mechanical transportation of salmon and trout over dams appears to be satisfactory, under certain conditions, for passing small numbers of fish. It has the advantage that the capital cost of the installation is relatively low. Biologically, one advantage is that fish may be transported over high dams in a short period of time without requiring a large energy expenditure for swimming. However, the possibility of stress and physical injury resulting from excitability of the fish is a serious disadvantage of all mechanical means of transport. When adult salmon were hauled from Rock Island Dam on the Columbia River during the salvage operation following construction of Grand Coulee Dam (Fish and Hanavan, 1948), chemical analyses showed that pronounced changes affecting the quality of the water occurred during transport. In this operation, eight trucks were used, each carrying a 1000-gallon tank through which aerated water, ice-cooled if desired, constantly recirculated at the rate of 125 gallons per minute. The dissolved oxygen concentration dropped rapidly after the fish were placed in the tanks and then slowly returned to the point of saturation. This drop reflected the restless behavior of the fish during the first 30 minutes of confinement in the tank. Following this period, the fish became less active and, as a result, the dissolved oxygen content of the water increased. The bicarbonate alkalinity also showed a slight rise. The free carbon dioxide increased to 10 or 15 times the initial concentration of approximately 2 p.p.m. with an accompanying decrease in the pH. It was found that the carrying capacity of each tank varied with the size of the fish and the temperature of the water. During the peak of summer hauling, the maximum capacity was considered to be 25 large chinook (700 lbs.) or 300 sockeye (900 lbs.). The capacity for carrying salmon and trout had to be further limited to compensate for the weight of scrap fish that entered each load.

One of the most thorough reviews of the methods, equipment and problems of tank truck transportation of fish has been presented by Norris *et al.* (1960) These authors review the history of fish transportation and give much valuable information concerning the techniques used in modern practice, including tank design, capacities, circulation and filtration. They point out that the carrying capacity of modern tank trucks is generally considered to be about 0.5 to 1.5 pounds of fish per gallon of water.

Black (1956) pointed out that mortality of fish during and following transportation is a common experience of the fish culturist. Horton (1956) reported mortality rates as high as 93 per cent. Often death is due to a lowered or complete lack of oxygen, or adverse temperature, or to a combination of these factors. Metallic poisoning, especially from zinc brought into solution by the action of dissolved carbonates or by carbon dioxide of metabolic origin, is another important cause of death. Black (*ibid.*) cited evidence to show that the delayed planting mortality, which has been reported by several investigators, may be caused primarily by physiological disturbances resulting from severe muscular activity in the transportation tank. As a result of vigorous activity, the stores of glycogen in muscle are converted to energy available for the performance of work by the contracting muscles, and to various metabolities, chief of which is lactic acid. For two-year-old Kamloops trout, an eight-fold increase in lactic acid content of the blood has been observed following 15 minutes of vigorous activity. Furthermore, the lactic acid level did not subside to approximate resting conditions for 6 to 12 hours. A high sedimentation rate of blood and clotting within the blood vessels was occasionally noted following vigorous activity. Previous work had also shown that after three minutes of vigorous exercise the swimming ability of yearling Kamloops trout was reduced from 10 m.p.h. to 2 m.p.h.

Black demonstrated a significant increase in the lactic acid level of fish following transportation in tank trucks and concluded that "the lactic acid production and other correlates of muscular activity may be implicated in the death of salmonoids following transportation." He stated that adequate oxygen was provided during these transportation experiments but if the level had dropped to one third of air saturation, previous experiments had shown that the lactic acid production might increase two- or three-fold even at moderate activity. Furthermore, if zinc should be released from the container during transportation the blood level of lactic acid would increase due to incomplete oxygen uptake. In summary, he concluded: "The variability in mortality during and following transportation must be comprised of several factors including the initial condition of the fish, the excitability of the species in question, the excitation induced by the shape of the tank, the nature and duration of the transportation, the manner of oxygenating the water, the clearance of acid metabolites, temperature, metabolism of the fish, buffering capacity and pH of the water, freedom from toxic agents. To these factors and agents may be added the endogenous production of lactic acid from muscular activity."

Black and Barrett (1957) noted that increases in lactic acid were associated with even minimal handling such as transporting fish from outside ponds to inside hatchery troughs. Significant increases in blood levels of lactic acid were noted following transportation in a tank truck. In a later paper, Black (1958a) stated: "Hyperactivity as a lethal factor in fishes is of very great significance in problems of fisheries management. The consequence of severe muscular activity is important in every aspect of handling of fishes, for example, live transport of fishes, tagging, construction of fishways, etc. Death occurs in fishes under certain circumstances following severe muscular activity. The conditions described include struggling in a live box, responding to vigorous chasing, swimming through swift passages of water, and struggling on a trolling line. Death has been observed under these conditions for both fishes such as salmon, striped bass and shad in fresh water, and fish such as two-year-old sockeye salmon, nearly mature chinook salmon, and codfish and flatfish in sea water."

Parker *et al.* (1959) preesnted evidence which suggested that mortality rates resulting from severe muscular activity of adult salmon are less severe in fresh than in salt water. Adult coho salmon did not appear susceptible to fatigue to a lethal degree in fresh water whereas a mortality rate of 44 per cent was estimated for severely exercised individuals in salt water. It was postulated that, in fresh water, the lack of feeding resulted in slower mobilization of energy reserves and therefore restricted the rate of energy expenditure by the fish. Lack of feeding was viewed as a protective mechanism of survival value for adult Pacific salmon. Transportation of adult sockeye and pink salmon over dams might therefore not result in mortalities caused by physiological disturbances associated with strenuous activity. Juvenile salmon would be expected to suffer from the serious adverse effects of extensive fatigue, however, because they feed during their fresh-water migration.

It is apparent that holding, handling, and mechanical transportation of fish should be avoided if possible. The problem of physiological disturbances affecting the swimming ability and possibly the survival of fish arises in all phases of the capture, holding and transporting operations regardless of whether the fish are transported in truck-mounted or track-mounted tanks. The effectiveness of mechanical transport systems, which must necessarily involve trapping and confinement of the fish, will remain in doubt until it can be conclusively shown that such transport methods do not affect the survival and reproductive ability of the fish.

DOWNSTREAM PASSAGE AT DAMS

One problem, not frequently encountered, arises from the behavior of certain races of salmon that migrate beyond their spawning areas and subsequently move back downstream to spawn. Consequently, a dam constructed between a spawning ground and the limit of upstream migration would require a safe and ready means of downstream passage for unspawned adult salmon.

The productivity of pink salmon spawning in Seton Creek near Lillooet is probably reduced to some extent by the obstructing effect of Seton Dam, constructed near the upstream end of the spawning area. Significant numbers of pink salmon pass upstream through the fishway at this dam and a large proportion of these remain in the forebay of the dam (Andrew and Geen, 1958). Some pass downstream through the turbulent and probably injurious fish-water sluice, some spawn in the very restricted area immediately upstream from the dam and others migrate further upstream to spawn in Portage Creek at the upper end of Seton Lake.

Similar and possibly more serious problems would arise in the protection of sockeye salmon if a proposed dam was built at the outlet of Chilko Lake. A substantial portion of the adult sockeye arrive in Chilko River in an immature condition and migrate into Chilko Lake, where they mature. They then move downstream into Chilko River to spawn. The provision of a suitable environment for maturation of these early arriving adults is considered important for the maintenance of this race of sockeye. Free access to and from the lake may be necessary. If the proposed low dam was constructed at the lake outlet, fishways could be provided that would probably be adequate for the upstream migration of these fish but there could be no assurance that the fish would migrate *downstream* through the fishways or over the spillway to reach their spawning grounds. Similar problems could arise if dams were constructed at the outlet of Adams or Francois Lakes as sockeye also migrate into these lakes prior to dropping downstream to spawn.

Passage Through Reservoirs

The effect of long slow-moving reservoirs on the upstream migration of salmon is one facet of the fish-power problem that remains almost completely unknown. Some races of sockeye and pink salmon in the Fraser River system migrate through lakes to reach their spawning grounds and although it is difficult to appreciate how odor or other stimuli could be effective in guiding fish through relatively still water, the forthright migration of these fish suggests the existence of some sort of navigational cues. The fish may be directed in their journeys by environmental cues that are related in a precise and reliable fashion to their goal. However, so little is known on this subject that the mechanism has not been elucidated nor is it known whether all races of Fraser River sockeye and pink salmon are genetically adapted to navigate through relatively still bodies of water.

Evidence that adult sockeye utilize some characteristic of the water as a navigational cue was obtained in a transplantation experiment in the Quesnel-Horsefly system in 1953 (Internat. Pacific Salmon Fish. Comm., 1954). Sockeye fingerlings that had been hatched and reared in the Quesnel Field Station on Horsefly Lake were transported by air and released in Quesnel Lake. Extensive observations showed that well over 90 per cent of the surviving jacks and adults returned to the outlet of the rearing ponds at Horsefly Lake even though they had not previously traversed the 15 miles of lakes and rivers between Quesnel Lake and the hatchery. Apparently some attractive factor that originated while the fish were in the hatchery was responsible for the return of the adults to the incubation and rearing area rather than to the spawning grounds of the natural population. Navigation by olfactory perception has been indicated by Hasler (1954) and it seems apparent that some characteristic of the water was utilized as a navigational cue in the 15-mile migration from Quesnel Lake to the hatchery. Possibly such navigational cues would be dissipated to such an extent in reservoirs that the fish would not be able to find their home stream.

There can be no doubt that construction of dams and creation of reservoirs result in profound changes in the natural environment. As previously mentioned, the physical structure of reservoirs is generally quite different from that of lakes. The complex flow patterns, density currents, and thermal patterns have been described previously. Much basic research on fish navigation is required before the effects of environmental changes on navigational cues can be evaluated.

Some evidence has been obtained to indicate a significant loss of adult salmon in passage through reservoirs. Ward (1927) made some of the first observations. In studying the migration of adult sockeye through Lake Shannon, the nine-mile reservoir above Baker Dam near Concrete, Washington, he observed a loss of fish between the dam and the spawning grounds. He stated:

"Now the records for the summer of 1926 and for the past summer (1927) show that a considerable portion of the sockeyes lifted over the dam failed to reach Baker Lake. This is the normal spawning ground of this species; it is located 20 miles upstream from the dam. Thus 3578 fish were put over the dam in 1926 and only 2823 were caught at the lake. As a fish trap closes the entire channel where the river leaves the lake, the record is hardly open to question. During the past year 4158 fish were put over the dam and only 1328 reached the lake. Part of this difference is to be accounted for by the fact that some of the fish which were put over the dam were physically incapacitated and probably perished before they could have completed the upstream trip. On the other hand, it is clear that such an explanation is not adequate to account for the entire difference."

On the basis of the observed behavior of migrating adult salmon, Ward postulated that a large part of this loss of spawners could be explained by the reduction in current and the creation of a subsurface zone of cold water which "trapped" the fish. The following excerpt from his report is pertinent:

"In other streams when red salmon have entered a lake with deep cold water, they rest and ripen in that water, continuing there until they rise to the shore zone to spawn. It is evident that in this deep cold area of Lake Shannon the fish would not be subject to a current stimulus such as under earlier conditions would have impelled them to continue the migration upstream and the temperature stimulus would tend to hold them in place since movement in any direction would bring them into warmer water. It is, of course, evident that such part of the fish as might continue along shore waters or through the upper water strata would find the river at the upper end of the lake and be impelled by the current stimulus to continue their ascent of the stream. These would then ultimately reach Baker Lake and the normal spawning grounds. Those fish which were trapped in the deep cold basin and ripened there would probably not find suitable spawning grounds or in the event that they did select some new place, the considerable variation in water levels in the new lake would imperil and very likely destroy the eggs in the course of the winter."

The causes of diminishing numbers of salmon reaching successive dams on the Columbia River are not known. Apparently, however, in some years the number reaching upriver dams is so small in relation to the number counted over lower dams that the difference cannot be accounted for by known spawning populations, commercial catch, and numbers taken at hatcheries. For instance, the apparent disappearance of sockeye and fall chinooks on the Columbia River has received special mention (Corps of Engineers, 1955). In 1954, 100,499 fall chinook salmon were counted through the Bonneville fishways but only 9682 of these fish were counted through passage facilities at McNary Dam, 147 miles upstream. The report states: "Considering the number of fish taken by hatcheries, and spawning in the main river and tributaries, the number of fall chinooks which ascended McNary Dam was much less than the most conservative estimate. The most probable explanation is perhaps the heavy fishing of fall run chinook above Bonneville Dam."

Reports of the Washington State Department of Fisheries have repeatedly expressed concern about the loss of upstream-migrant salmon at Columbia River dams. In a discussion of the successful rehabilitation of a sockeye run on the Snake-Salmon River system following removal of a dam, it has been stated (Wash. Dept. Fish., 1954): "Concern is felt, on the other hand, over the apparent disappearance of a major share of the 1953 sockeye escapement over Bonneville Dam. Of the 235,000 counted through Bonneville fishways, about 9000 were taken in the Celilo Indian fishery, 6000 appeared at the Redfish

Lakes to spawn, and 152,000 were counted over Rock Island Dam. Of the 152,000 counted over Rock Island, 67,000 went into the Okanogan River and 20,000 into the Wenatchee River, leaving 64,000 unaccounted for of those passing over Rock Island Dam. While the various upriver counts and estimates are conservative, the difference is too great to be explained by error in calculation. Whether or not the accumulative problems of fish passage through three successive dam structures are responsible remains to be evaluated." Thus it is seen that salmon are lost in the Columbia River not only between Bonneville and Rock Island Dams but also above Rock Island Dam where no commercial fishing is permitted. While there may be many adverse conditions for fish passage at the dams and in the reservoirs, Gangmark and Fulton (1952) postulated that the loss of fish is due primarily to three factors: "(1) low water conditions and resulting higher temperatures causing mortality, (2) natural mortality of fish infected with disease or otherwise in a weakened condition, and (3) straying into other streams."

Part of the unexplained loss of fish between Columbia River dams might result from mortalities suffered by fish attempting to migrate over the dams. Such mortalities could occur in the back-roll and violent turbulence in the energy-dissipating areas below spillways or by pasage downstream over spillways. Schoning and Johnson (1956), in studying delay of adult salmon at Bonneville Dam, reported that some fish tagged in one of the fishways and released in the forebay passed downstream over the dam. Other reports have mentioned injury and mortality of adult salmon below Bonneville Dam. Several injured and one decapitated fish were observed below this dam in 1953 (Corps of Engineers, 1954). An earlier report mentioned dead and dying fish below Bonneville. Examination of some of these fish revealed blood-filled trauma in the body muscles (Corps of Engineers, 1952), suggesting that death had been caused by severe physical injury. A more recent study, the results of which have not yet been published, indicated that during an 11-day period in 1955 the number of dead chinook salmon in the area downstream from Bonneville Dam was approximately 20 per cent of the number that passed upstream through the fishways at this dam. There was a direct relationship between spillway discharge and mortality rate.

Any delay suffered by upstream-migrant salmon at dams does not appear to be compensated for by an increased rate of migration through low-velocity reservoirs. There is some evidence to suggest that salmon migrate more slowly through forebay pools on the Columbia River than through normal river velocities (Anon., 1955). While a more complete study of the problem is certainly required, available information suggests that salmon delay in reservoirs and that some do not find their way through reservoirs to the spawning grounds.

The extent of delay and loss of fish may be related to the magnitude of velocity changes and alterations of physical and chemical characteristics of the water. These changes can be extensive, as demonstrated by Sylvester (1958). Changes in the physical and chemical characteristics of rivers are likely related to flushing rates of reservoirs, depths of reservoir outlets, upstream storage, and other water uses. Until such time as more information is available concerning factors related to upstream migration of adult salmon, a complete evaluation of the effect of reservoirs on the productivity of these fish is not possible.

To avoid the possible hazards involved in migration of adult salmon through reservoirs, transportation of these fish around reservoirs has been considered. The hazards and limited capacity of mechanical transport methods have already been described and it appears that such transport methods would be impractical at proposed Fraser River dams. The physical and biological problems involved in transporting large runs of Fraser River sockeye and pink salmon over dams and around reservoirs by truck, barge, flume or other means appear insurmountable.

Conclusions Concerning Effects of Dams on Migration of Adult Salmon

Dams on the Fraser River and its tributaries would introduce many hazards to the safe, undelayed upstream migration of adult sockeye and pink salmon. Maximum productivity requires that adult salmon reach their respective spawning grounds in suitable condition and at the optimum time for effective spawning. Dams may adversely affect both the condition of the fish and their time of arrival on the spawning grounds by altering estuarial and river conditions, by delaying and fatiguing fish, and by creating reservoirs in which environmental conditions may not be favorable for successful migration.

Some of the requirements for successful migration of Fraser River sockeye and pink salmon are being studied. Biological changes occurring within the fish during migration and the relationship between the fish and the natural environment are not well understood. It is therefore impossible at the present time to determine the total effect of proposed dams on upstream migration of these fish.

Migration of adult salmon is known to be dependent on energy stores accumulated during ocean residence. Since sockeye salmon do not have a large energy reserve on completion of spawning, undue energy expenditure or inefficient utilization of energy during migration might prevent successful completion of the spawning act.

Salmon are also known to be adversely affected by fatigue. Strenuous activity causes an accumulation of metabolic waste products and the animal must then rest before resuming normal activity.

Several obvious changes in the river environment are known to affect salmon migrations. River discharge, for instance, is apparently associated with the timing and pattern of upstream migration. There is some evidence that upstream migration of Adams River sockeye is more favorably timed, in relation to environmental conditions on the spawning grounds, in years of high spring and summer discharge of the Fraser River. Since flood control and hydroelectric developments would reduce the average discharge during spring and summer months, such developments could reduce sockeye productivity. Temperature changes would also occur if dams were constructed on the Fraser River. Reduced velocities in reservoirs result in increased heating of the surface water during spring and summer months while deeply submerged outlets at dams draw cold water from subsurface layers. The net effect on downriver temperatures is a function of the relative amounts of surface and subsurface discharge. Construction of a high dam on the Fraser River would probably result in a temperature reduction during the summer and an increase during the fall months. Changes in water temperature affect the rate of energy utilization, swimming ability and disease susceptibility of salmon. Construction of dams could produce extreme temperature changes that would seriously reduce the reproductive potential.

More subtle environmental changes may also occur. For example, the water quality may be altered in some way. This might have some influence on upstream migrants but possible changes and their effects have not been investigated. Decreased discharge would, of course, increase the significance of any pollution. A multitude of changes, as yet not fully understood or appreciated, might have important effects on upstream migration.

Proposed Fraser River dams would not only cause environmental changes in downstream areas but would also create reservoirs that might have serious adverse effects on upstream migration of salmonids. There have been several reports of the disappearance of significant numbers of salmon migrating through reservoirs. Very little is known concerning migration of salmon through reservoirs but it is obvious that reservoirs represent a radical departure from the natural migratory environment and that the changed velocities, temperatures, depths and other factors might interfere with upstream migration.

Collection of migrating adult salmon for transportation over dams presents many problems. Since delay and fatigue during migration may have serious consequences with respect to reproductive ability, it is obviously important to provide facilities at dams that enable fish to find and enter transportation facilities without undue exertion and delay. However, the artificial flow patterns below dams and the spatial and discharge restrictions of collection facilities impair upstream migration. Artificial stimuli for guiding salmon to collection facilities would have doubtful practical value. Barrier dams, which provide high mid-stream velocities to lead fish to collection facilities on each bank, are probably more effective than spillway and powerhouse collection systems, which merely provide multiple entrances in locations where fish are most likely to accumulate.

Several methods have been used for transporting adult salmon over dams. Attempts on the part of designers to provide passage facilities in which conditions for migration approximate those found in nature stem from a lack of basic data concerning the requirements and capabilities of migrating salmon. Thus, weir fishways, simulating a series of low falls, are generally used for passing salmon over dams. Pool-and-jet fishways have recently been used in some instances because this type of passage facility does not require adjustment to compensate for changes in reservoir elevation. Hauling systems and fish locks have also been used in some instances but the capacity of such devices is limited and fish are often hesitant to enter them. They probably would not be practical for passing large numbers of salmon at proposed Fraser River dams.

In some respects, salmon populations of the Fraser River are unique. The numbers of fish that would be affected by any main-stem development would far exceed the numbers influenced by any previous developments on salmon rivers. The necessity to handle an unprecedented volume of traffic poses unprecedented problems in the rapid collection and upstream passage of the fish. Further, some races of Fraser River sockeye are particularly susceptible to the adverse effects of delay during upstream migration. Short delays of only a few days are known to reduce the productivity of some races.

In summary, it appears that large-scale dam construction and related storage on the Fraser River watershed would alter the natural environment to such an extent that the productivity of sockeye and pink salmon could be adversely affected. Dam construction would cause extensive environmental changes, not only in the sections of river downstream but also at the dams themselves, in the fish-passage facilities and in the reservoirs. It seems unlikely that all of the possible adverse effects could ever be predicted. While scientific research may solve many of the problems that would be created by dam construction on the Fraser River, it is likely that at least some of the inevitable environmental changes would adversely affect upstream migration of adults and thus reduce their productivity to some extent.

SPAWNING AND EGG INCUBATION

There are numerous ways in which dams and diversions proposed for construction on the Fraser River watershed could reduce the productivity of sockeye and pink salmon by adversely affecting spawning, egg incubation and fry emergence. For instance, diversion of flow or flooding of spawning streams would obviously be detrimental to maximum production. There are more subtle effects that could be equally harmful, however. Before the effects of proposed alterations in the natural environment can be assessed, complete knowledge of spawning behavior, range of environmental factors suitable for successful spawning of each race and species of salmon, and the environmental conditions necessary for successful egg incubation, fry emergence and subsequent fry survival is essential. While information collected by the Salmon Commission during its 22 years of work on the Fraser River system is extensive, it is far from adequate for predicting all possible effects of environmental changes on the spawning, incubation and emergence of the numerous races of Fraser River sockeye and pink salmon.

Spawning, egg incubation and fry emergence are critical phases in the life cycles of salmonids. Since each species has become adapted over a period of many generations to certain optimum environmental characteristics, it is not unusual to observe reduced survival rates when adverse conditions occur in the natural environment. Nine years of study at Chilko Lake by the Salmon Commission have shown sockeye egg-to-fry survival rates ranging from 4.5 to 11.9 per cent. Neave (1953) showed that the survival rate of pinks and chums *(Oncorhynchus keta)* from egg deposition to fry entering the ocean seldom exceeded 10 per cent. Average fresh-water survival of pink salmon in three streams for which several years of data were available were as follows: McClinton Creek, 13.15 per cent; Hooknose Creek, 5.07 per cent; Sashin Creek, 1.61 per cent. The maximum observed survival rate in these three streams was only 23.8 per cent and in one instance the survival rate from eggs deposited to fry entering the ocean was only 0.2 per cent. For chum salmon, survival rates of 0.08 per cent to 6.03 per cent are recorded for Nile Creek and 0.99 to 15.09 per cent for Hooknose Creek. From these data and from the work of other investigators, it is apparent that egg and alevin survival rates are generally at a low level and show much variation. Since survivals are low, any adverse environmental conditions brought about by hydroelectric development could virtually eliminate populations of sockeye and pink salmon by reducing fry production to such low levels that natural population controls, such as predation, would assume even greater importance in regulating population size.

Salmon spawn at a certain time each year which, under average conditions, provides a favorable temperature cycle for egg development and results in fry emergence at a time corresponding to the advent of favorable growing conditions in the spring. Water velocities in which salmon prefer to spawn occur at sufficient depth that the proportion of incubating eggs exposed to drying and freezing during the winter low-flow period is relatively small. Further, the velocities chosen by spawning salmon are generally associated with a rather coarse type of gravel that provides the relatively high rate of percolation essential for survival of eggs and alevins. Relationships between environmental conditions and fry production are not well understood but it appears certain that indiscriminate alteration of the natural environment would have an adverse effect on fry production.

Spawning Behavior

Many workers have published observations on spawning behavior of various salmonids. It appears that spawning behavior of the various species is remarkably similar. Mathisen (1955) made an extensive study of the spawning behavior of sockeye salmon. Schultz (1938) published observations on spawning behavior of kokanee *(Oncorhynchus nerka)*, maintaining that breeding behavior of all salmonids was very similar. Briggs (1953) discussed spawning behavior of coho and chinook salmon and steelhead trout. Greeley (1932) outlined spawning behavior of brook, brown *(Salmo trutta)* and rainbow trout, while Shapovalov and Taft (1954) observed spawning behavior of steelhead trout and coho salmon. Burner (1951) studied spawning habits and characteristics of spawning nests of four species of Pacific salmon—chinooks, coho, chum and sockeye. He described the spawning act as follows:

"Redd building may be divided into three stages, prespawning, spawning and postspawning. During the prespawning stage, the female salmon is green, that is, the eggs are neither ripe nor loose in the ovaries. Males are seldom in attendance, and are frightened away by the female, who repels all intruders of either sex. The female digs the redd as she turns on either side, at an angle of about 45° to the current, head upstream, body arched, and makes a series of violent flexions with body and tail. The tail strikes the gravel occasionally and the strong-boiling current created carries gravel and silt a short distance downstream. This material spreads out in a flat semicircle at first; then, as the digging upstream proceeds, it collects into a loose pile called the tailspill. With more digging, the redd assumes a long oval shape about twice the length of the salmon and several inches deep. The prespawning digging of the redd may go on for as many as 5 days.

"At the beginning of the spawning stage, the nest is ready for the eggs. All loose gravel and fine material have been removed from the pot, or centre of the redd, whose shape is such that any current in the bottom flows upstream then upward and outward. Usually there remain in the pot large stones too heavy for the fish to move far, and the crevices between these rocks provide excellent lodgment for the eggs. Males are constantly present now. The female alternately digs at the redd and settles back into the depression to release eggs. A male then moves quickly alongside the resting female, curves his body against hers, and releases sperm in a small milky cloud that settles briefly in the bottom of the redd where the eggs are lodged. The newly deposited eggs are thus surrounded by sperm and eventually fertilized. Excess sperm is carried slightly upstream along the bottom of the redd and gradually carried away by the current. During the spawning stage the redd increases considerably in length and depth, and appears to move upstream as a result of the continued digging at the upstream wall and the filling in of the tailspill area.

"The postspawning stage begins after the female finishes depositing her eggs. Males are no longer attentive. The female is gaunt and spent, but she continues to dig at the gravel with ever-weakening efforts until she dies. This postspawning digging, which may continue for 10 days, becomes shallow, off-center, and ineffective. The area of the nest is increased without (after the first day at least) adding to the protection of the eggs."

Nesting and spawning of salmon under natural conditions involves an intricate series of movements extending over a period of several days. Hoar (1956, 1958), in summarizing the principles of salmon behavior, has stated that the salmon's behavior consists of a hard core of fixed stereotyped movements. The number and form of these movements are fixed by genetic constitution and are characteristic and consistent. These movements are triggered by specific stimuli from the external world (releasers). Some are released only when the animal is in a certain physiological state, which depends on the blood levels of the hormones, food reserves and so forth.

It is apparent that successful reproduction is not ensured by arrival of the two sexes on the spawning grounds. Each spawning movement or sequence of movements is triggered by an environmental releaser and these movements are released in the appropriate order only when environmental releasers appear in the right order and only when the fish are in the proper physiological state. Salmon that are delayed or exhausted on the migration route, either by obstructions or by adverse physical conditions, may not attain the proper physiological state at the proper time or they may not find the appropriate environmental conditions to trigger the complex series of behavior movements that are essential to successful reproduction.

An additional factor that can influence salmon productivity is the ratio of the two sexes on the spawning grounds. Any environmental alteration that might affect one sex differentially requires thorough consideration. Experiments have been conducted by the Commission on various races of Fraser River sockeye to evaluate the effects of different sex ratios on the success of spawning. Six females, along with one, two, four, five or six males, were placed in pens on the spawning grounds. More eggs were consistently retained by the females when males were scarce. Further, substantially fewer live eggs were found in the gravel when there was a scarcity of males.

In assessing effects of environmental changes on spawning of Fraser River sockeye and pink salmon, it is important to realize the precise timing of the spawning migration and the spawning act. In general, each race begins its fresh-water migration on the average date that will permit it to reach the spawning grounds and spawn when temperatures are most likely at an optimum level for spawning and subsequent egg and fry survival.

Although very little is known concerning the mechanisms that initiate migration, some information is available concerning chronological order of the various segments of a run during migration, spawning and death. It has been established that, in general, the order in which fish of a given run of Fraser River sockeye enter the river is maintained during migration and spawning (Killick, 1955). In Forfar Creek, as in many other spawning areas of the Fraser River watershed, sockeye spawn about seven days after arrival. The average life span on the spawning grounds is about 13 days for females and 12 days for males. Analysis of the time of death of Adams River sockeye for the years 1946, 1950, 1951 and 1954 revealed that life-spans were shorter at the ends of the runs in 1946 and 1951 when migration into the Fraser River extended for the usual period of about 30 days. In 1950 and 1954, however, when the main concentration of Adams River sockeye entered the river in 2.5 and 5 days, mean times of death on the spawning grounds were the same throughout all parts of the run. A hypothetical calculation, which took into consideration the effect of chronological dispersion during migration and spawning, indicated that 82 per cent of the sockeye migrating up the Fraser River during a three-day closed fishing period would spawn within a nine-day period.

The time spent by adult salmon in migration and spawning is a function of the amount of stored energy in the body tissues. Since feeding ceases before sockeye enter the Fraser River estuary, the amount of stored energy, which must be sufficient for both migration and spawning, is an important determinant of the life span of each fish. If the time and energy expenditure required for migration were increased because of delay or difficult passage en route, the time available on the spawning grounds would be reduced. Thompson (1945) and Talbot (1950) found that tagged sockeye did not reach the spawning grounds if they had been delayed at Hell's Gate more than 12 days. Killick found that average life spans on the spawning grounds varied from 12 to 19 days. It is probable that some sockeye delayed less than 12 days during migration were able to reach the spawning grounds but were unable to spawn successfully because of the reduced time of life remaining. The larger returns-per-spawner since the Hell's Gate fishways were built in 1945 indicate that the former long delays at this site reduced spawning efficiency, even among those sockeye that did reach the spawning grounds.

Ward (1959) found, for Fraser River pink salmon, that the number of days spent en route and on the spawning grounds was approximately the same for all early migrating races (Seton Creek, Thompson River and main-stem Fraser River) but was considerably longer for the two late races (Harrison River and Chilliwack-Vedder River). Those races spawning upstream from Hell's Gate spent an average of 14.0 to 16.5 days on the spawning grounds compared with 21.5 to 28.9 days for races having a shorter migration distance. Populations of pink salmon that would have to migrate past proposed Fraser River dams spend the shortest time on the spawning grounds and appear to arrive at the spawning areas in a mature condition, without delaying en route, and spawn soon after arrival. Spawning efficiency of these fish would probably be adversely affected if they suffered extensive delays during migration.

Water Temperature

Water temperatures during spawning, egg incubation and fry emergence have a profound effect not only on success of spawning but also on egg and fry survival. Consequently, temperature changes that would result from proposed dam construction upstream from spawning areas require thorough study. The ways in which dams can alter the normal temperature cycle have been described previously.

Data collected by the Salmon Commission show that temperature is an important factor controlling the productivity of sockeye salmon. Fraser River sockeye and pink salmon spawn on the falling portion of the annual temperature cycle. Spawning temperatures of sockeye range from 55° to 45°F with peak spawning generally occurring at about 50° F. Spawning of pink salmon also shows a peak at about 50°F but the upper and lower limits appear to be more widely separated. Spawning time of each race appears to be closely related to timing of the environmental cycle in the reproductive area, with pinks possibly less critically adjusted than sockeye. Pinks arrive on the spawning grounds over a longer period of time and spawning occurs over a wider temperature range.

Other studies on the spawning temperatures of Pacific salmon indicate that spawning usually occurs in about the same range of temperatures as for Fraser River sockeye and pink salmon. Burner (1951) reported spawning temperatures of four species of salmon as ranging between 40° and 62° F. Most spawning of Columbia River salmon occurred at temperatures ranging from 44° to 55° F. Chambers (1956) reported that spring chinooks spawned between 40° and 55°F while fall chinooks spawned in the declining portion of the temperature cycle between 56° and 41°F. Sockeye and coho salmon also spawned on the falling portion of the cycle at temperatures ranging from 55° to 47°F and 51° to 40°F respectively. Spawning temperatures of chinook and coho salmon in a small California stream were reported by Briggs (1953) as ranging from 52° to 48°F and 56° to 46°F respectively.

Temperatures in excess of 55°F during the spawning period of Fraser River sockeye appear to increase the number of females that die unspawned. Data from Raft River, a tributary of the North Thompson River, indicate the adverse effects of high temperatures (TABLE 2). In many years, the high temperatures in this river result in many fish dying before they have completed spawning. Data from Middle River, the outlet stream from Takla Lake, provide further evidence to illustrate adverse effects of high temperatures on spawning efficiency. In 1953, when water temperatures at peak of spawning ranged from 55° to 60°F, spawning success was only 45 per cent. That is, many females died unspawned or partially spawned so that only 45 per cent of the available eggs were deposited. In most spawning areas of the Fraser River watershed, egg deposition usually varies between

TABLE 2—Mean temperatures of the Raft River during the peak of spawning of sockeye salmon in relation to the proportion of available eggs deposited.

YEAR	MEAN DAILY TEMPERATURE		MEAN TEMPERATURE DURING PERIOD	EGG DEPOSITION
	Minimum °F	Maximum °F	°F	Per cent
1950	59	61	60.0	45.2
1951	57	59.5	58.4	72.5
1953	57	60	58.3	75.7
1956	54.5	60	57.0	93.8
1955	55	58.5	56.9	89.3
1952	55	57	56.2	77.6*
1954	51.5	55	53.3	98.6
1957	49	55	52.0	99.3

* In 1952, high temperatures occurring before the peak of spawning caused high mortalities in the early part of the run and may also have affected spawning efficiency at the peak of the run.

90 and 99 per cent. Extremely low water temperatures are seldom encountered during the spawning season and their effect on egg deposition has therefore not been determined. There is some indication, however, that low temperatures also reduce the proportion of eggs deposited.

Water temperatures are also known to have a profound influence on incubating eggs. Studies conducted by the Commission have suggested the importance of incubation temperature on productivity. Vernon (1958b) demonstrated a significant inverse relationship between Fraser River water temperatures from December through February, a period roughly corresponding to hatching and early alevinage of pink salmon, and the subsequent return of adult pink salmon two years later. Mean temperature over the extended period from September to March also showed a significant inverse relationship to catch two years later. Analysis of five years of data from Weaver Creek have also indicated an inverse relationship between incubation temperatures and survival of sockeye eggs to the fry stage. Relationships such as these should be regarded with caution, however, as the underlying cause or causes have not yet been determined.

Fry emergence is possibly related to the time of availability of suitable environmental conditions for rearing. It may be that higher-than-normal incubation temperatures cause the fry to hatch earlier and migrate to lake- or ocean-rearing areas, as the case may be, at a time when conditions are less favorable for survival. Subtle effects such as these are difficult to detect and measure but there can be no doubt about their importance in salmon production.

While information concerning the specific effects of water temperature on incubating eggs is far from complete, certain initial indications from several studies that have been conducted by the Salmon Commission are suggestive and reveal the necessity for more complete knowledge. Survival rates of Fraser River sockeye eggs that commenced incubation at temperatures of 45°, 50°, 55° and 60°F have been measured in several experiments. In an experiment with Cultus Lake stock in 1949-1950 and Horsefly Lake stock in 1953-1954, eggs that commenced incubation at 45°F suffered much higher mortalities than those initially incubated at temperatures of 50°, 55°, and 60° F. An experiment conducted at Horsefly River in 1953-1954 provided information pertinent to the upper temperature tolerance limits for sockeye eggs. The results indicated that eggs exposed to temperatures of 60° to 62°F for short periods of time suffered severe losses during the period of exposure but little or no delayed effect was evident. Exposure to temperatures of 62° to 65°F caused extensive egg loss both during and following exposure to such temperatures.

These experiments suggested that survival of eggs and fry in the gravel was related to the stage of development attained by the embryo prior to the onset of cold winter temperatures, the mortality rate being inversely proportional to the stage of development attained at the onset of near-freezing temperatures. While the experiments are incomplete, they are indicative of a problem requiring precise evaluation.

Seymour (1956) studied the effects of temperature on incubation of chinook salmon eggs. He observed high egg and fry survival rates at constant temperatures of 50°, 45° and 40°F, lower survivals at 55° and 57.5°F, and very low survivals at higher temperatures. Eggs exposed to 60°F at the start of incubation, and thereafter to more moderate temperatures, suffered minor losses. Continued exposure to temperatures of 62.4°F resulted in a loss of 78 per cent of the eggs and temperatures of 64.6°F produced an almost complete loss of eggs. Seymour reported no survival among eggs exposed to 34°F for the entire incubation period. Eggs incubated in water of 55°F for 3½ weeks and thereafter at 34° suffered only 3 per cent loss while eggs incubated at 55°F for only two weeks and then at 34°F suffered a 42 per cent mortality. Some period of incubation at warmer temperatures is apparently required before chinook eggs can tolerate low temperatures.

Combs and Burrows (1957) reported that chinook eggs incubated at constant temperatures showed high survival rates within the temperature range of 42.5° to 57.5°F. All eggs died at a constant incubation temperature of 35°F and high mortality rates were suffered even at 40° F. These experiments suggested that eggs of salmon spawning in cold, headwater streams late in the fall when water temperatures are falling rapidly have a much reduced chance of survival.

Hayes *et al.* (1953) and Hubbs (1922) studied the effect of temperature on embryonic development and showed that the order of appearance of anatomical features in the embryo and certain meristic characteristics of fishes are dependent on temperature of incubation. The time of development of the digestive system and the skeleton are advanced, in relation to other anatomical features, at low temperatures. Premature hatching is also likely to occur at low incubation temperatures. High temperatures, on the other hand, promote early completion of a functional circulatory system and external features such as fins and pigment. In addition to their effect on the chronological order of development of anatomical features in the embryo, abnormal incubating temperatures increase the proportion of abnormal fry produced. The vertebral count, for instance, has been shown to be dependent on incubation temperature. The severe dislocation of the order of differentiation caused by changes in temperature may result in mortality.

As with many other phases of the fish-dam problem, fundamental research concerning spawning, egg incubation and fry emergence is in an early stage. Much more data must be obtained before predictions of the effects of altered temperature conditions can be made. There can be no doubt that egg survival is closely related to water temperature and that dams upstream from spawning areas could alter the thermal pattern and consequently the survival of eggs and alevins. Since rate of development of eggs is dependent upon water temperature, a water-use project that changed the thermal pattern might cause fry to hatch and emerge from the gravel at a time when environmental conditions were not conducive to maximum survival.

Data collected on the Fraser River system suggest that the time of fry emergence is related to the period of temperature increase occurring in the early spring months. Extensive data from Weaver Creek show that an increased rate of emergence of sockeye fry occurs in periods of high discharge or with increased water temperature. The pattern of fry emergence is altered in years of a freshet, when emergence occurs over a shorter period than in years when no freshets occur. Emergence of fry at the Horsefly artificial spawning ground has also been associated with increased water temperatures. Studies on pink salmon in the Fraser River watershed in 1958 indicated that emergence of fry was associated primarily with water temperature. Increasing and decreasing temperatures were associated with respective increases and decreases in the number of fry captured in sampling gear. No relationship between discharge and emergence was noted except in the Vedder-Chilliwack system where an increase in discharge was associated with a decrease in the number of emerging fry. However, the discharge increase was inversely related to water temperature and in view of the lack of an emergence-discharge relationship in other systems, it seems probable that pink salmon emergence is primarily a function of water temperature.

Throughout this report, the relationship between salmon production and environmental conditions is stressed. While the total effect of specific temperature changes on spawning, egg incubation and fry survival cannot be predicted at the present time, available data suggest that this problem deserves thorough consideration.

Water Depth and Velocity

Water depth and velocity in spawning areas both appear to be of significance not only for successful spawning but also for maximum egg survival. Velocity appears to be most important, with depth of secondary importance in that suitable velocities are generally available only within a certain depth range. Spawning in streams occurs at depths of less than 1 ft. and greater than 24 ft. (Chambers, 1956). Lake spawning has been observed at depths over 70 ft. (Can. Dept. Fish., 1959). Despite the observed wide range of spawning depths, the range of bottom velocities at selected river spawning sites is quite limited.

Extensive surveys on the Chilko River have been made in an attempt to relate density of spawning sockeye in specific study areas to physical features of the environment. Thirty-four sample areas, each 30 by 15 ft., were marked out on the stream bed and the density of spawners on these areas, which included a wide range of depths and velocities, was determined. During three years of study, there was a wide range in size of the spawning populations and significant differences in stream flow. In spite of these variations, a consistent relationship was evident between the density of spawners and some physical factors measured at each sample area. The depth of water over the Chilko spawning area is greater than that found in many other sockeye spawning areas. Depth, however, does not appear to exert a major influence on the choice of spawning site. Gravel beds that go dry and are exposed to freezing during the winter low-flow period are never heavily populated, nor are they the first choice of spawning salmon. As shown in TABLE 3, areas of heavy egg deposition were found over almost the whole range of available depths.

Table 3—Abundance of sockeye spawners in sample density areas in Chilko River in relation to water depth and velocity.

	Conditions Available in Density Areas Used by Fish			Conditions Available in Three Areas of Highest Spawning Density				Conditions Available in Three Areas of Medium Spawning Density				Conditions Available in Three Areas of Lowest Spawning Density			
	Average	Max.	Min.	1	2	3	Average	1	2	3	Average	1	2	3	Average
	1949 — 59,000 spawners — 25 density areas utilized														
Density Area Number				31	16	26		23	12	29		21	19	1	
Depth of Cover (ft.)	4.4	5.5	3.4	4.2	4.4	3.5	4.0	4.1	4.1	4.5	4.6	4.1	4.0	4.8	4.3
Average Velocity (f.p.s.)	1.8	2.8	1.1	2.0	1.7	2.8	2.2	1.8	1.6	1.1	1.5	1.7	1.4	0.9	1.3
Bottom Velocity (f.p.s.)	1.1	1.8	0.6	1.4	1.1	1.8	1.4	1.2	1.0	0.7	1.0	1.0	0.9	0.6	0.8
	1950 — 30,000 spawners — 15 density areas utilized														
Density Area Number				20	26	16		12	27	22		18	28	15	
Depth of Cover (ft.)	4.8	5.8	3.8	5.0	3.8	4.7	4.5	5.4	3.9	4.7	4.7	5.8	5.1	5.3	5.4
Average Velocity (f.p.s.)	1.9	2.8	1.2	2.2	2.8	1.7	2.2	1.6	2.8	2.0	2.1	1.8	1.2	1.4	1.5
Bottom Velocity (f.p.s.)	1.1	1.8	0.7	1.3	1.8	1.1	1.4	1.0	1.5	1.2	1.2	1.1	0.7	0.8	0.9
	1951 — 118,000 spawners — 25 density areas utilized														
Density Area Number				24	26	22		12	15	31		19	5	28	
Depth of Cover (ft.)	4.3	5.4	3.3	4.4	3.4	4.3	4.0	5.0	4.9	4.1	4.7	3.9	5.0	4.7	4.5
Average Velocity (f.p.s.)	1.8	2.8	1.1	1.9	2.8	2.0	2.2	1.6	1.4	2.0	1.7	1.4	1.2	1.2	1.3
Bottom Velocity (f.p.s.)	1.1	1.8	0.7	1.1	1.8	1.2	1.4	1.0	0.8	1.4	1.1	0.9	0.8	0.7	0.8

Notes:

— The stream bottom consisted of approximately 45% boulders 6 in. and larger, 40% coarse gravel, and 15% fine gravel and sand.
— 34 areas, each 50 sq. yds., were used as sample areas for density measurements.
— "Average velocity" measured at four tenths of depth measured from bottom.
— "Bottom velocity" measured 0.3 ft. above stream bottom.

The average velocity was an important factor associated with the choice of spawning area. Whereas average velocities of 1.1 to 2.8 f.p.s. were recorded, the greatest spawning density occurred near the upper range of available velocities in areas having an average velocity of 2.2 f.p.s. Areas having an average velocity of 1.3 f.p.s. were frequently utilized by the fish but the density in these areas was much less than in areas having velocities of 1.7 f.p.s. or higher. An even better relationship was evident between density of spawners and the bottom velocity, which was measured 0.3 ft. above the stream bottom. The highest spawning density occurred in areas having bottom velocities of about 1.4 f.p.s. Multiple regression analyses of the Chilko data indicated that the density of spawners in the study areas was directly and significantly related to the water velocity 0.3 ft. above the river bottom. No significant relationship between gravel size or water depth and density of fish was noted.

The characteristics of the spawning areas of the various races of Fraser River sockeye vary considerably and any proposed alterations of the natural environment would probably have to be reviewed in terms of the requirements of the particular race in question. It should be noted that the particular conditions of the spawning area in Chilko River did not permit observations in high water velocities. There is no doubt, however, that high velocities would limit the choice of spawning areas in many other streams.

Other workers have presented data on the velocity and depth requirements of spawning salmon. Briggs (1953) reported that, in a small stream, chinook and coho salmon chose spawning areas where the water depth was 10 to 16 in. and 5 to 8 in. respectively. Burner (1951) reported chinook, coho, chum and sockeye spawning in water only 2 in. deep. Chinooks spawned in depths up to 48 in., coho up to 26 in., chums up to 30 in., and sockeye up to 37 in. Average spawning depth of sockeye was about 12 in. In the streams surveyed, the average water velocities at the redd sites ranged from 1 to 2 f.p.s. with an average velocity at sockeye spawning areas of 1.6 to 1.8 f.p.s. Chambers (1956) considered water velocity to be more important than depth in choice of spawning sites. He stated:

"Because the salmon must hold themselves at the site while the nest is being excavated and the eggs deposited, the water velocity is an important factor in determining where spawning takes place. The amount of dissolved oxygen available to the eggs is also dependent upon the rate of flow of water through the nest. Velocity was found to play a more important part in the selection of a spawning site than was depth. Whereas nests were observed in water depths down to 24 feet in the Columbia River, very little spawning occurred in water faster than 3 feet per second. The size of the fish also determined how shallow the water could be for spawning. Sockeye, the smallest species, used water of less depth than the chinook or silver salmon. However, it is interesting to note that the velocities over the sockeye spawning areas were comparable to those used by the larger salmon." The ranges of depth and velocity most utilized by the salmon in these studies were as follows:

Species	Depth - ft.	Velocity - f.p.s.
Spring Chinook	1.25 - 2.25	1.50 - 2.50
Fall chinook—Columbia River	4.00 - 6.50	2.75 - 3.75
Tributary Rivers	1.25 - 2.25	1.00 - 1.75
Coho salmon	1.00 - 1.50	0.25 - 2.00
Sockeye salmon	0.75 - 2.25	1.25 - 2.50

Hourston and MacKinnon (1957), in analyzing the depth-velocity preferences of spawning pink salmon in a small, controlled-flow spawning channel in Jones Creek on the Fraser River watershed, observed that the sections of the channel that were not selected as spawning areas by the first 100 pairs of spawners were considerably shallower and faster than those areas that were occupied. The average velocity available was 2.1 f.p.s. but the first day's fish selected an average velocity of 1.6 f.p.s. and the first 100 fish selected an average velocity of 1.9 f.p.s. Similarly, whereas the average depth available for spawning was 1.20 ft., the first day's fish chose an average depth of 1.38 ft. and the first 100 fish chose an average depth of 1.28 ft. It must be noted, however, that depth and velocity are inversely related in this spawning channel and if fish select the lower velocities, they must necessarily spawn in deeper areas.

Water depth and velocity at redd sites are also important for successful egg incubation. Unless sufficient water depth is available, incubating eggs are exposed to drying and freezing during the winter low-flow months. The slope of the water surface of a stream is an important determinant of both the surface velocity and the subsurface percolation flow, which supplies oxygen to incubating eggs and removes the waste products of metabolism.

Sporadic discharges downstream from either spillways or powerhouses at hydroelectric installations could have an adverse effect on spawning and egg incubation. High discharges increase the velocity and depth and may carry spawning salmon away from partially completed redds. Low discharges, on the other hand, may reduce the percolation flow and expose redds. An abnormally high discharge during the period of incubation may kill many eggs and alevins by causing bed load movement with consequent destruction of redds and deposition of silt.

Proposed dam construction on the Fraser River system would involve development of storage on main-stem rivers as well as increasing the storage capacity of existing lakes. Inundation of river spawning areas would, on the basis of present knowledge, alter the environment to such an extent that successful propagation of the affected populations would be unlikely. Large velocity reductions, increased silt deposition and alterations of other important environmental conditions would not permit successful spawning and egg incubation. Lake-spawning areas could be destroyed if the lakes were utilized as major storage reservoirs. Spawning sockeye in Great Central Lake have been reported to a depth of 70 ft. (Can. Dept. Fish., 1959). More recent data have shown that this depth does not represent the maximum limit to which sockeye can spawn. Available data do not permit an evaluation of the effects of increased depth of water over lake spawning grounds but temperatures, light and possibly currents would be altered, all of which may be important to the success of spawning. Any utilization of newly inundated areas by spawning salmon would be of questionable value in view of the extensive annual draw-downs characteristic of reservoirs.

Since it is apparent that depth and water velocity on spawning areas are of great importance for successful spawning and incubation, water-use projects that inundate spawning areas, reduce or increase the flow over natural spawning areas, or cause sporadic fluctuations in this flow could have a serious adverse effect on salmon production.

Gravel Size and Composition

Spawning salmon exhibit a decided preference for certain types of substrate material. Detailed documentation of the characteristics of spawning areas for each species and each race is of importance in evaluating effects of changed environments or in planning rehabilitation work.

Several authors have outlined some of the characteristics of salmonid spawning areas. Hobbs (1937) studied the spawning sites of chinook salmon in New Zealand waters. The majority of the gravel was less than 3 in. in diameter. Redds were frequently made in reaches where gravel was interspersed with boulders. In fast rivers, spawning was confined to low-velocity marginal areas. Hobbs (1940) showed that trout start to dig redds when the gravel is of an appropriate size but completion of the redd depends on the degree of consolidation and the gradient of the stream bottom. Hoar (1956) suggested that tactile releasers were indicated from this work.

Fabricius and Gustafson (1954) carried out a series of aquarium observations and maintained that coarse gravel consisting of stones of roughly walnut size was favorable nest material for char *(Salmo alpinus)*. Rocky material was preferred to sand and sand in turn was utilized before flat, disc-like stones. Observations and experiments by these workers indicated that spawning activities were visually released. Female char carried out typical nest-digging movements on a horizontal glass plate that covered a section of preferred gravel in the aquarium where observations were made. Visual and tactile responses may very well both be involved in the selection of suitable spawning substrate.

Chambers (1956), in studying the characteristics of spawning nests of Pacific salmon, observed that "the gravel forms a protective cover in which the eggs develop. It must be of a size that can be moved by the fish, and the current, in building the nest. Therefore, the size of the fish will determine how large the gravel can be for spawning. It must be small enough to retain the eggs and large enough to permit a free flow of oxygenated water to pass over them." Whereas ½- to 2-in. gravel was the most common size range in all spawning areas studied, samples obtained from chinook salmon nests contained a large proportion of gravel larger than 2 in. in diameter. Sockeye, the smallest species, preferred gravel less than 2 in. in diameter. The mean percentage composition by weight of the various sizes of gravel obtained from spawning redds of each species of salmon are given in

TABLE 4. The ⅛- to 6-in. gravel was computed on a 100 per cent basis; the fines were calculated on the basis of the entire sample less than 6-in. size. Construction of the nest altered the size composition of the gravel by reducing the proportion of fines and smaller sizes.

Many samples of gravel have been obtained from some of the most important sockeye and pink salmon spawning areas of the Fraser River system. There is no assurance that these samples represent preferred gravel types or that they provide high egg survival rates. However, they were obtained in areas of heavy egg deposition, where egg survival may be expected to be relatively high. Data from some spawning streams are summarized in the grading curves shown in FIGURE 23.

Hourston and MacKinnon (1957) stated that the acceptable range of gravel sizes for the Jones Creek artificial spawning channel was determined from a composite plot of the grading curves of gravel from the Adams River, Okanagan River and Jones Creek spawning areas. When it was found that the grading curve of the natural gravel in the channel did not fall within the specified limits, shown in FIGURE 24, washed and graded gravel ranging in diameter from ¼ to 1½ in. was placed in the channel to a depth of 12 to 18 in.

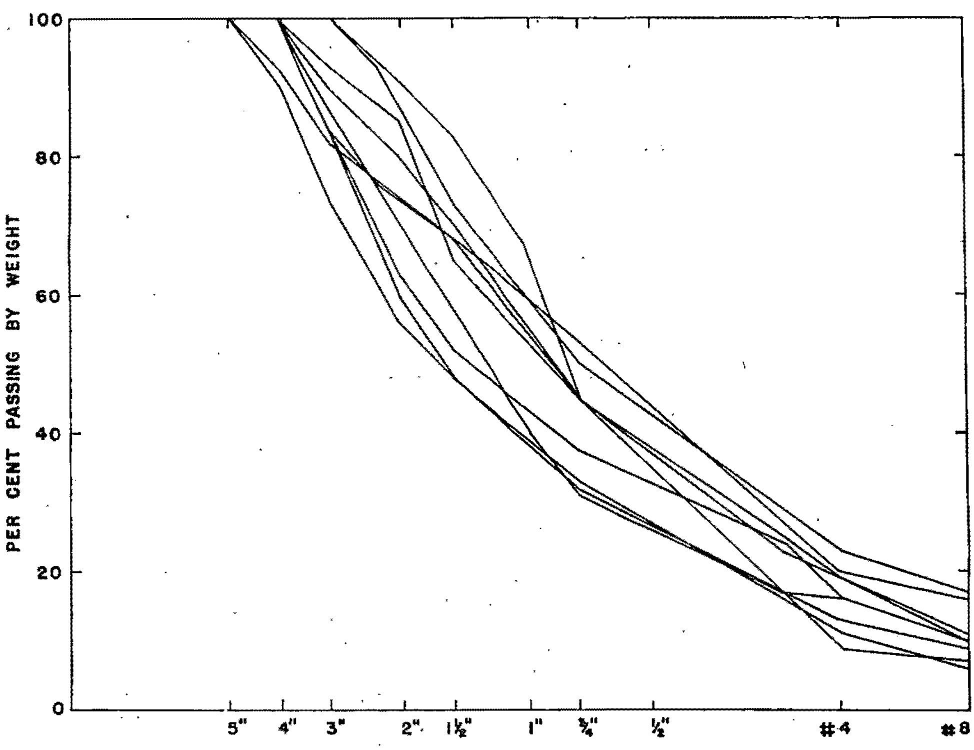


FIGURE 23—Composition of stream bed material in spawning areas of sockeye (Adams, Chilko and Stellako Rivers; Weaver and Boise Creeks) and pink salmon (Fraser, Harrison, Chehalis and Chilliwack-Vedder Rivers; Seton Creek).

TABLE 4—Average size composition of gravel obtained from redds of Pacific salmon (from Chambers, 1956).

GRAVEL SIZE	SPRING CHINOOKS	FALL CHINOOKS	COHO	SOCKEYE
	Per cent	Per cent	Per cent	Per cent
Fines	7.05	10.94	9.14	13.73
⅛- to ½-in.	20.59	20.77	25.64	26.76
½- to 2-in.	40.70	41.80	46.40	58.07
2- to 4-in.	24.88	23.74	24.99	13.28
4- to 6-in.	13.81	13.70	3.02	1.91

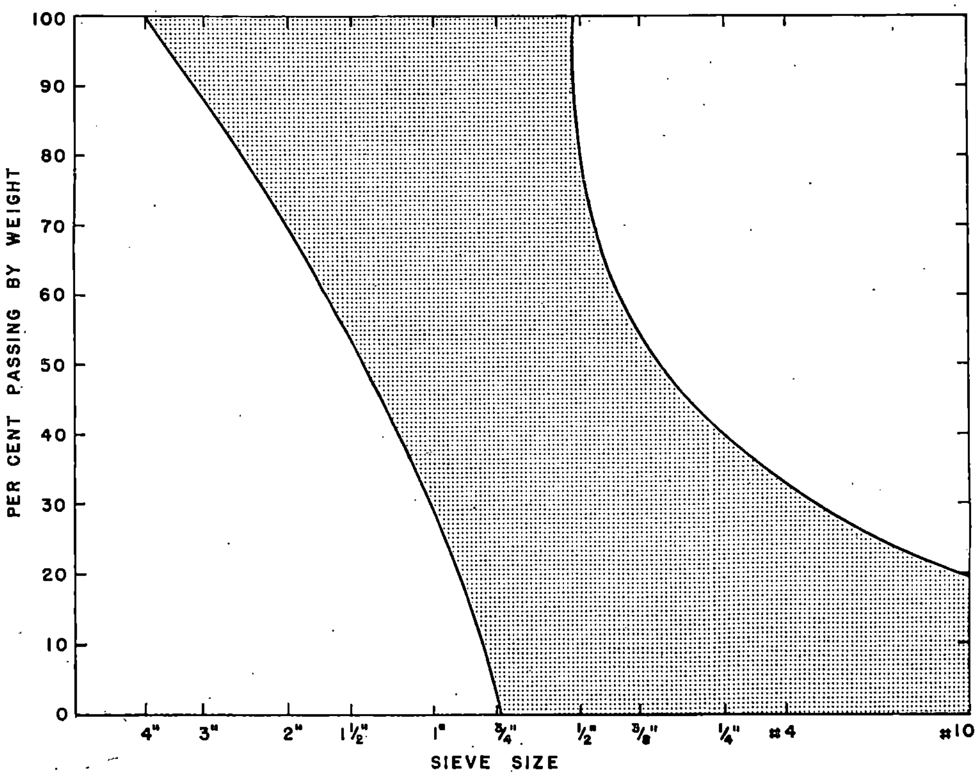


FIGURE 24—Acceptable range of gravel sizes chosen for design of Jones Creek artificial spawning channel. (From Hourston and MacKinnon, 1957.)

Burner (1951) found that salmon generally chose areas of stream bed composed of gravel less than 6 in. in greatest diameter. Redd size was inversely proportional to the amount of cementation and to gravel size. Firmly cemented gravel was avoided. Areas free of mud and silt were preferred. Nearly all of the exposed gravel in spawning nests of Columbia River sockeye was less than 6 in. in diameter; less than one per cent was over 6 in. in diameter and not more than 11 per cent of the exposed redd area contained mud, silt and sand. Redd size was directly related to the size of the fish. The largest fish, summer and fall chinooks, built redds that averaged 6.1 square yards while sockeye had redds averaging 2.1 square yards.

Briggs (1953) noted that the mean gravel diameter of coho salmon spawning areas was 3.7 in. while that of chinook salmon and steelhead trout was 4.2 and 3.2 in. respectively. Shapovalov and Taft (1954) noted that coho salmon and steelhead spawned in areas of small to medium gravel. All workers appear to be in agreement that spawning areas of salmon generally consist of certain substrate materials, which vary for species and size of fish.

Since success of spawning and egg incubation is related to gravel size and composition, effective deposition and incubation occurs only in particular areas. Water-use projects that change the gravel composition or render natural spawning gravel inaccessible can be expected to have an adverse effect on salmon production. Further, the natural flood discharges may have an important effect in washing gravel and removing fine material and other deleterious matter. Eliminating these flood discharges, by construction of dams for flood control or hydroelectric purposes, may therefore adversely affect spawning areas downstream.

Subsurface Flow

A flow of oxygenated water through the gravel of spawning nests is essential for survival of eggs and may also be an important factor influencing salmon in their choice of suitable spawning areas. Experiments have shown that gravel consisting of a large proportion of fine material permits less percolation than the coarse gravel most often utilized by spawning salmon. Salmon remove much of the fine material from the nest during redd-digging. The shape of the redd also contributes to increased percolation.

The oxygen-bearing subsurface flow is of prime importance to the survival of salmon eggs during incubation. Pyper and Vernon (MS.) reported a series of experiments on the oxygen demand of sockeye eggs and alevins in the gravel. They noted a progressive increase in oxygen consumption from the pre-hatching stage through emergence. At the pre-hatching stage 0.0049 mg./egg/hr. was used while 0.03245 mg./egg/hr. was required by emerged fry. Oxygen consumption during the pre-hatching stage was of the same order of magnitude as that found by Alderdice *et al.* (1958) for chum salmon eggs at the same stage of development. Wickett (1954) presented data on the oxygen consumption of chum, pink and coho salmon eggs. Oxygen consumption of the eggs of Atlantic salmon has been determined by Hayes *et al.* (1951) and Lindroth (1942). Their results compared favorably with those obtained in studies of Pacific salmon eggs.

Alderdice *et al.* (1958) subjected chum salmon eggs to low levels of dissolved oxygen at various stages of incubation and computed "critical" levels that appeared to define the minimum oxygen levels above which respiratory rate is unmodified by oxygen availability. These critical levels ranged from about

1 p.p.m. in early stages to over 7 p.p.m. shortly before hatching. Eggs compensated for extremely low oxygen levels by reducing the oxygen demand and rate of development. Very low oxygen levels at early incubation stages resulted in the production of abnormal fry. Low dissolved oxygen levels just prior to hatching caused eggs to hatch prematurely at a rate dependent on the extent of oxygen deficiency.

In nature, the supply of oxygen available for incubating eggs is a function of the velocity of the subsurface flow and the oxygen level of this water. Wickett (1954) has shown that the supply of water to the gravel is derived from the stream flow and the groundwater flow from the banks of the stream. The latter flow is of lower oxygen content and therefore modifies the level of oxygen ultimately available to the eggs. Wickett (1958b) presented data that indicated that egg-to-fry survival of pink and chum salmon in four coastal streams was directly related to the permeability of the gravel.

Chambers (1956) showed that the amount of dissolved oxygen in water flowing through salmon redds was somewhat less than that in the flowing stream above the redds. In one instance, the stream contained 8.15 p.p.m. of dissolved oxygen while at a depth of 0.4 ft. below the stream bed the oxygen content was 7.40 p.p.m. At 0.8 ft., the oxygen level had decreased to 6.82 p.p.m. and at 1.2 ft. it decreased still further to 2.65 p.p.m. Percolation water drawn from the forward slope of the tailspill of a salmon redd, where the eggs were deposited, consistently contained more dissolved oxygen than did samples taken from (1) the identical spot prior to spawning, (2) undisturbed gravel beside the nest, and (3) other parts of the nest. Chambers tabulated the range of dissolved oxygen in subterranean water collected from spawning grounds as follows:

	Spawned Areas (p.p.m.)	Unspawned Areas (p.p.m.)
Chinooks	5.70 - 9.10	0.10 - 6.75
Coho	1.90 - 7.85	0.00 - 4.85
Sockeye	1.40 - 7.25	0.30 - 2.60

The results of unpublished experiments conducted by the Salmon Commission to measure the survival of eggs in relation to the rate of flow through typical sockeye spawning gravel have shown the importance of an adequate water supply. FIGURE 25 shows the results of experiments that were conducted under controlled conditions where the average rate of percolation could be accurately measured. Subsequent studies have shown that the rate and distribution of flow through gravel beds can be improved by the removal of particles less than ¼ in. and over 2 in. in diameter. It has been established that most of the water that supplies oxygen to incubating eggs comes directly from the flowing stream above the gravel surface. Laboratory tests have also shown that the percolation flow is substantially increased by the tailspill or mound of gravel at the downstream edge of salmon redds.

Shelton (1955) measured the survival of eggs incubated under simulated stream conditions. Plastic screen bags containing chinook salmon eggs were

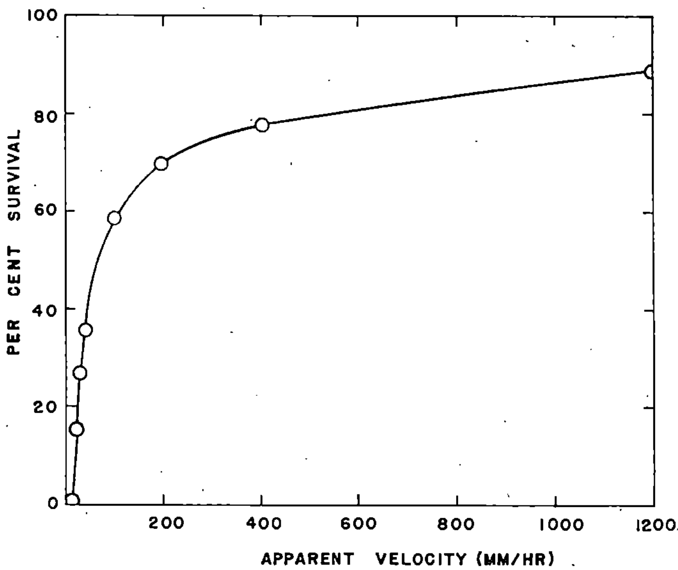


FIGURE 25—Survival of sockeye eggs from eyed stage to emergent fry, in relation to water velocity through a typical spawning gravel. (From Pyper and Vernon, MS.)

planted at various depths and in various gravel sizes. In beds of small gravel, only 13 per cent of the eggs emerged as fry but in coarse gravel the efficiency increased to 87 per cent. In fine gravel, the survival was much higher when the eggs were buried 3 in. below the gravel than when buried 6, 12 or 18 in. but in coarse gravel the depth of deposition had little effect on hatching efficiency.

Very little information is available concerning lake spawning of salmon. The Cultus and Taseko Lake races of sockeye in the Fraser system spawn on the beach areas of their respective lakes. Significant numbers of sockeye also spawn on certain beach areas of Chilko Lake. Apparently spawning in such situations occurs only where water from some groundwater source percolates up through the gravel. However, no information on rates of flow is available at present.

The importance of an adequate supply of oxygenated water percolating through the gravel of salmon spawning areas and the hazards involved in reducing this flow as a result of flow regulation, stream bed erosion, silt deposition, gradient reduction, and so forth, are evident. It is also important to note that water quality may affect salmon production. Organic decay in reservoirs has been known to deplete oxygen in the lower layers. Toxic gases may accumulate as a result of this organic decay. The use of deeply submerged outlets that draw off such water could be expected to have serious effects on migrating and spawning salmon, as well as on incubating eggs. McGrath (1958) records instances where fish have been killed as a result of the discharge of high-temperature, silt-laden, oxygen-deficient water when reservoirs are flushed out. Silt deposition substantially reduces the capacity of reservoirs and it is occasionally necessary to flush out this deposited sediment to avoid interference with the normal operation of the dam. For instance, occasional flushing is required at a low dam located on the Middle Shuswap River upstream from a salmon spawning area. Silt and debris could be deposited in the river downstream, with consequent adverse effects on spawning and egg incubation.

Conclusions Concerning Effects of Dams on Spawning and Egg Incubation

Dam construction on the Fraser River system would produce a multitude of environmental changes that could affect spawning efficiency, the survival of incubating eggs, and the emergence of newly hatched fry. Successful spawning and egg incubation can occur only within certain ranges of environmental conditions. Studies of the spawning behavior of salmonids has indicated a core of stereotyped movements, each of which is released by a certain stimulus or combination of stimuli. The necessary stimuli are often environmental factors such as temperature, velocity and nature of the substrate. Alteration of these environmental factors may therefore adversely affect spawning.

Hydroelectric and flood control developments would cause important changes in the annual discharge pattern. Quite apart from the physical loss of spawning areas, reductions in flow could reduce the subsurface flow that supplies oxygen to incubating eggs and removes the waste products of metabolism. Velocity changes resulting from sporadic or extended discharge changes could alter the gravel composition of spawning areas and lead to increased silt deposition, which would affect spawning and egg-to-fry survival. Sporadic discharges would probably have a serious effect on spawning behavior. Alterations of the normal discharge cycle could also reduce the availability of preferred spawning velocities and depths.

Water temperatures would also be changed following dam construction. Reductions in discharge would result in climatological conditions having a greater influence on water temperatures. Temperatures would also be altered by storage of water and by discharge from subsurface outlets at dams. Temperatures higher than 55°F generally result in some sockeye dying unspawned or only partially spawned. Abnormal temperatures during the incubation period may cause a high rate of egg mortality and may cause premature or delayed hatching and emergence.

Dams could increase the water depth over lake and river spawning areas to such an extent that spawning would either not occur or would be ineffective. Inundation of river spawning areas would likely preclude successful spawning. The effects of increasing the storage on lakes in which sockeye spawn could have serious effects because light, temperature and percolation flow would probably be changed.

Subtle environmental changes could have serious effects on spawning and egg incubation. For instance, the quality of water discharged from reservoirs may be very important. Toxic materials, such as the products of organic decay in reservoirs, could have serious effects. Silt flushed out of the forebays of dams could be deposited on spawning beds downstream and reduce the percolation flow to incubating eggs. A complete assessment of the effects of dams and reservoirs on spawning, egg incubation and fry emergence requires considerably more information than is currently available concerning environmental changes that would occur, optimal spawning conditions, and the tolerances of spawning salmon and incubating eggs to various environmental changes.

FRESH-WATER REARING OF SOCKEYE

After emerging from the gravel, Fraser River sockeye fry migrate to a lake where they spend usually one and sometimes two years before migrating to the ocean. That fresh-water rearing is essential for survival of Fraser River sockeye is indicated by the fact that analysis of the scales of the returning adults consistently shows at least one year of fresh-water rearing (Clutter and Whitesel, 1956) even though observations indicate that some fry go directly to sea after emerging from the gravel. The importance of the lake rearing area in determining the ultimate production of adult sockeye salmon has been shown by Foerster (1954), who demonstrated that the percentage return of adult sockeye to Cultus Lake was directly related to the size at which the yearling migrants left the lake for the ocean. Thus, any factors that alter the productivity of the lake environment would be expected to influence the ultimate production of sockeye salmon.

The production of sockeye in a fresh-water rearing area is influenced not only by the density of the population but also by the productivity of the rearing area. Rawson (1958) attributed productivity of a lake to the climatic, morphometric and edaphic features of the environment. Lake productivity may be influenced by flood control or hydroelectric power developments in two main ways: (1) By construction of a dam at the outlet for storage and flow regulation and (2) By diversion of water into the lake from a foreign drainage system. As these two types of developments present several unique problems, they will be considered separately.

Effects of Damming a Natural Rearing Lake

Habitat modifications occasioned by the construction of a dam at a lake outlet are exceedingly complex. In many cases a lake may be so changed that an entirely different environment will be formed for the original flora and fauna (McMynn and Larkin, 1953). While, as these workers maintained, it may be feasible to predict conversion of a lake from eutrophic to oligotrophic, with the attendant relative decrease in productivity, it is most difficult to forsee more subtle changes in ecology that might determine the suitability of an area for a particular species of fish. So many variables are involved that prediction must be made for each individual situation and only a few broad generalizations are justified.

Raising the lake level will produce varied results depending on the topography and edaphic characteristics of the surrounding terrain. Changes in shoal areas may be favorable to one species of fish and not others, with a consequent shift of the species composition of the area. Increasing the depth and volume of water may also be viewed as being of some significance in the nutrient economy of a body of water, especially where a relatively shallow lake is inundated to considerable depths. Wind-induced circulation and recovery of nutrients from the lake bottom could be reduced. This in turn might lead to a reduction in plankton production. The temperature regime within the lake might also be altered, depending on the nature of the original lake. A shallow eutrophic lake, possibly with no appreciable stratification, might be converted to a typical oligotrophic lake with the usual pattern of summer stratification. Prediction of the expected temperature regime would be an individual problem and would vary depending on the location of the outlets.

Since storage for hydroelectric purposes is obtained during months of peak run-off and is utilized during periods of low flow, a certain amount of draw-down is inevitable. Cuerrier (1954) reported an obliteration of littoral fauna of Lake Minnewanka in Alberta as a result of drawn-down. The bottom fauna initially decreased to 50 per cent of its original weight and after 10 years increased to 75 per cent of the original weight. Changes in species composition were also noted. Rawson (1958) suggested that bottom fauna in shallow areas would likely be destroyed by fluctuating water levels and that this loss of food would undoubtdly affect production of trout and other non-migratory fish that feed on aquatic insects and other shallow-water forms.

McMynn and Larkin (1953) evaluated the possible effects of water utilization in the Campbell River area involving increased storage on three lakes. In this instance, it appeared that the morphometry of all three lakes would be favorably affected by increased storage. The flushing rate would be reduced and the area of shallow, productive zones increased. These workers felt, however, that these benefits would be counteracted by adverse effects of the extensive annual draw-down. Larkin (1951) reviewed possible effects of increasing the water storage on Trout Lake, a typical oligotrophic body of water located near Kootenay Lake in British Columbia. Bottom fauna in shallow areas would be reduced by draw-down but in view of the sparse quantities of bottom fauna in this lake it was felt that total fish production would not be seriously affected. It was felt that plankton production would not be affected .

As previously mentioned, various proposals for flood control and hydroelectric power development on the Fraser River watershed involve increasing the storage capacity of several large sockeye rearing lakes. For example, Stuart Lake would be raised 28 ft., Adams Lake 34 ft. and Quesnel Lake 20 ft. As far as temperature and dissolved oxygen are concerned, the effects of changes that would occur under surface spill condtions might be relatively small. Since the discharge cycle would be altered, however, the temperatures in the epilimnion would be altered. Storage during the spring and summer months would result in the epilimnion reaching summer temperatures earlier in the season. Temperatures could be higher than normal in the surface layers during the summer months. The depth of the hypolimnion would be increased but since the lakes are already oligotrophic and generally display no oxygen deficiency none would be anticipated with an increased depth. While the extensive draw-down characteristic of storage reservoirs would have deleterious effects on bottom fauna, plankton production might not be seriously affected. Cuerrier (1954) reported no apparent decline in plankton production in Lake Minnewanka following an increase in storage capacity. Both Larkin (1951) and Withler (1956) felt that plankton production in large oligotrophic lakes would not be seriously affected by increasing the depth. Since planktonic organisms form the bulk of the diet of young sockeye, the anticipated faunal changes might not seriously affect these fish.

More complex changes are to be anticipated when water is discharged from reservoirs through deeply submerged outlets. The temperature regime in the lake and the annual temperature cycle of downstream areas would be altered. Tailwater temperatures could be lower in summer and higher in winter than was previously the case. Higher summer temperatures in the upper, productive layers of the reservoir might contribute to an increase in plankton production. However, since fingerling sockeye display certain temperature preferences, increased plankton production in the unusually warm surface layers might, in effect, be unavailable to them. Furthermore, heating of the lake might create adverse conditions for sockeye fingerlings while creating an improved environment for predatory and coarse fish. If the depth of sockeye rearing lakes was greatly increased and the flow was discharged through subsurface outlets, both the surface and subsurface layers might reach temperatures much higher than normal. Furthermore, the duration of annual temperature stratification would probably be increased. The circulation of available nutrients from subsurface layers to the productive zone might also be reduced. Such changes could be visualized as contributing to decreased productivity of plankton-feeding fish such as sockeye.

The effects of artificial impoundments on plankton-feeding fish have not been adequately explored. Runnstrom (1951, 1952, 1955) described the reduction in growth of char and brown trout associated with regulation of a lake and attributed the reduction to a decline of the bottom fauna utilized by these fish for food. Nilsson (1958) noted a change in the diet of two species of whitefish (*Coregonus pidschian* and *C. peled*) in a lake in Sweden following regulation but this condition was not interpreted in terms of growth of the coregonids and was further complicated by the utilization of several types of food organisms. A basic study on the effects of impoundments on plankton production and plankton-consuming organisms is required before predictions are possible. Interspecific relationships must also be investigated. Cuerrier (1954), for instance, showed a decline in growth of lake trout following the damming of Lake Minnewanka. He attributed this to an ecological separation of the prey and predator species of fish. The lake, formerly a producer of large trout, is now inhabited by a dense population of small lake trout.

Effects of Diversion of Foreign Flow to a Natural Rearing Lake

Hydroelectric power can be developed in many regions of British Columbia by diversion of water from one drainage system to another at a lower elevation. In fact, this method of development is most common in this province at the present time (Hourston, 1958). As Vernon (1958a) has pointed out, admixture of water from adjacent drainages may greatly alter the temperature, chemical characteristics and turbidity of the water receiving the diversion flow. Such changes may have a profound effect on the production of plankton and bottom fauna used as food by economically important species of fish. The probable effects of a proposed diversion of Taseko Lake water to Chilko Lake have also been discussed (Internat. Pacific Salmon Fish. Comm., 1949). It was suggested that if the turbid waters of Taseko Lake were diverted to Chilko Lake, the resulting mixture would be less favorable for the production of young sockeye as turbid water reduces the penertation of sunlight, thus limiting the growth and abundance of phytoplankton and zooplankton.

Effects of introducing turbid water to a salmon-rearing lake have been studied by Geen (MS.). This investigation dealt with the effects of diverting cold, turbid water from Bridge River to Seton Lake, which is a rearing area for one and possibly two races of sockeye salmon. In this instance, lake temperature was reduced following diversion. Turbidity of the lake and outlet stream increased markedly. Direct data on plankton production and the total mineral content of Seton Lake prior to diversion were not available but a comparison of the present condition of Seton and Anderson Lakes, which lie in the same valley and are quite similar morphometrically, edaphically and climatically, revealed that the mineral content was slightly higher in Anderson Lake and plankton production was several times greater than in Seton Lake. This was in contrast to the pattern observed in several natural chains of large lakes where the total dissolved solids, temperatures and productivity generally increase from the upper to lower lake of the series. All indications were that the plankton production and mineral content of Seton Lake had been reduced by the addition of turbid Bridge River water. The flushing rate was also increased by addition of this foreign water to the lake. However, as the time required to replace the entire volume of Seton Lake was approximately one year, it was felt that the increased flushing rate had not been of major significance in reducing productivity. Growth of juvenile sockeye in Seton Lake was examined but the data were not adequate to permit definite conclusions. On the basis of growth in some other turbid lakes, however, it was anticipated that a reduction of the former high rate of growth could occur. The low zooplankton production was apparently caused by the reduced light penetration, resulting in unfavorable conditions for growth and production of phytoplankton and therefore adversely affecting the abundance of the zooplankton populations.

Changes in temperature of sockeye rearing lakes may adversely affect sockeye production. Diversion of foreign flow from surface layers of a reservoir may increase the average temperature of the receiving lake. A summer temperature reduction would generally be anticipated, however, because the water entering the lake would probably be drawn from a reservoir by means of deeply submerged outlets. Further, diversion of water into a lake increases the flushing rate, thus tending to lower the average temperature during the productive summer months. Geen (MS.) observed a significant reduction in the average temperature in the productive zone of Seton Lake following diversion of water from the Bridge River hydroelctric plant into this lake. This temperature reduction was caused primarily by the low temperature of the incoming water, the increased flushing rate apparently being of very little importance. Donaldson and Foster (1941) have shown that temperature has a pronounced effect on the growth, food utilization and mortality rates of fingerling sockeye salmon. Young sockeye exhibit a preference for temperatures similar to those found near the thermocline in natural lakes during summer and early fall months. The temperature of surface layers of Skaha Lake, British Columbia, was found to be much too high for optimum growth, survival, and efficient food utilization. Sockeye were unable to tolerate water temperatures of 78°F for more than a fews days and were merely able to maintain their body weight at temperatures of 70°F. Temperatures of 45°F or less produced poor growth with low food conversion rates. From these data, maximum food utilization, growth and survival appear to occur at about 55°F. Any water utilization project that results in changes in the temperature of the productive upper layers of the lake may reduce sockeye production.

Alteration of the environment by diversion of foreign water may have profound effects on resident fish populations. Increased or decreased oligotrophy of salmon-rearing lakes may favor certain species of fish at the expense of economically important species. Much information is available to show that species changes are frequently associated with environmental alterations. For instance, Swingle (1954) reported large changes in the species composition following impoundment of rivers in Tennessee. Various authors, including Eschmeyer and Manges (1945), have also reported extensive migrations of fish precipitated by drastic changes in stream systems draining from reservoirs. In view of these studies and other previously mentioned in the section on impoundment of natural lakes, it seems apparent that changes in species composition, though of a more minor nature, could result from diversion of foreign flow to sockeye-rearing lakes.

Lindsey (1957) has outlined other aspects of the problem of diverting water from one system to another. He discussed the problems that could result from diverting water from the Peace River in British Columbia to the Fraser River. Fish distribution would be altered by such diversions. He suggested that any diversion of water over the Continental Divide would introduce pike *(Esox lucius)* into coastal drainages. Not only are pike voracious fish eaters but they are also the definitive host for the tapeworm *(Triaenophorous crassus)*. While the parasite does not affect man, the cysts formed in the musculature of fish render the flesh less attractive and may therefore reduce its market value. Whitefish, Arctic grayling and salmonids are known to act as intermediate hosts. Lawler and Scott (1954) reported the co-existence of anadromous salmonids and pike in the Wood River system in Alaska, where the salmonids are infested with *Triaenophorous* cysts. Burgner (1958) reported that the average incidence of this parasite in smolt samples from the Wood River system for the years 1948 to 1957 was 71 per cent. The plerocercoid stage of this cestode has been found on occasion to be detrimental to other species of fish, including rainbow and brook trout and Atlantic salmon, and it might adversely affect young sockeye. Such relatively subtle changes as these require careful consideration in the preservation of economically important species of fish.

Conclusions Concerning Effects of Dams on Fresh-Water Rearing of Sockeye

The foregoing review of problems associated with diverting foreign flow into and damming sockeye rearing lakes illustrates some of the more subtle complexities of fish-power problems. While the analysis is by no means complete, it is apparent that marked environmental changes can occur and that the changes can have profound effects on fish populations. Increasing the storage and controlling the discharge may alter the trophic status, often changing a lake from eutrophic to oligotrophic. Such a change may affect the species balance within the lake. The temperature regime may be altered by reduced summer discharge and use of subsurface outlets. Draw-downs, which are characteristic of such storage areas, reduce the bottom fauna and rooted aquatic vegetation. Draw-downs, which are characteristic of such storage areas, reduce the bottom fauna and rooted aquatic vegetation. Draw-downs might also seriously affect the survival of eggs and alevins of lake-spawning sockeye. Increased inundation might eliminate most lake-spawning areas because of changes in temperature, light and percolation flow. Present evidence suggests that plankton production would not be seriously affected by increasing storage.

Power is frequently developed in British Columbia by diverting water from one drainage system to another system at a lower elevation. The nature of the resulting mixture of waters depends on the physical and chemical characteristics of the components. Frequently, the diverted flow is colder, often of glacial origin and having a lower dissolved mineral content than the receiving body of water. The subsequent reductions in temperature, total dissolved solids and transparency in the receiving water would be expected to create less favorable conditions for plankton and fish production. The physical changes that occur could also differentially affect the various fish species in the system. Further, diversions may result in the introduction of new species of fish and parasites to the receiving system.

MIGRATIONS OF JUVENILE SALMON

Upstream Migration of Sockeye Fry

Most races of sockeye spawn in streams tributary to lakes, with the result that the fry move downstream to the lake rearing area after hatching. However, certain races of sockeye in the Fraser River watershed must migrate upstream, as recently emerged fry, to reach their rearing lake. For example, nearly all of the Chilko sockeye spawn in the Chilko River immediately below Chilko Lake. In this area, when the fry emerge from the gravel during the spring months, they are carried downstream by the water current until they reach a low-velocity area. After a period of approximately 10 days in this area they migrate upstream, following marginal areas of the stream, to enter Chilko Lake.

Fry produced in Little River follow a similar pattern. These fry move downstream through Little River, the outlet stream of Shuswap Lake, and enter Little Shuswap Lake. They remain in this lake for a few weeks before migrating up Little River to Shuswap Lake, which is the natural rearing area for this population. Fry produced in Adams River are carried downstream by high velocities and enter Shuswap Lake near its outlet. Possibly some of these fry are also swept downstream through Little River. Sockeye fry produced by spawning in the South Thompson River below Little Shuswap Lake pass upstream through this lake and, after swimming upstream through Little River, enter Shuswap Lake.

Sockeye fry hatched in Weaver Creek in the Harrison River system follow an even more complex pattern of migration. After being swept downstream by the high velocities in Weaver Creek, these fry swim downstream through a small lake and a low-velocity stream to the Harrison River. They then swim upstream through this river to Harrison Lake, their rearing area.

Conclusive evidence is not available concerning factors responsible for these patterns of migratory behavior. It is likely that migratory behavior is directly related to such environmental factors as temperature. Keenleyside and Hoar (1954) have shown that differences in rheotactic response are associated with temperature. According to Northcote (1960), both the size of fish and certain environmental factors are important in determining the migratory response of young rainbow trout. His study was based on a population of trout that spawn in both the outlet and inlet streams of Loon Lake, British Columbia. Migration of juvenile fish to the lake therefore requires that those hatching in the outlet swim up into the lake and those from the inlet move downstream into the lake. He demonstrated that, as a general rule, these fish continued their migration *towards* the lake even when transferred from the outlet to the inlet stream and vice versa. This observed difference in the migratory behavior of juveniles was associated with water temperature, upstream migration being associated with a certain temperature range and downstream migration with slightly lower temperatures. Northcote suggested that environmental changes brought about by hydroelectric development could alter the migratory behavior of this species. While data are not available to justify extrapolation from trout to sockeye, it is probable that much the same mechanisms are operative and that serious consequences could result from artificial environmental changes.

Quite apart from environmental alterations that might occur, a major problem would exist if the fry in Chilko River had to migrate past a dam at the outlet of Chilko Lake. As far as can be determined, there is no precedent for passage facilities for recently emerged sockeye fry. Even if such precedent did exist, the large numbers of fry in Chilko River would create a major problem in adapting any known techniques to this location. In eight years of observations, the maximum number of fry was produced in 1957. In this year, the total run was estimated, on the basis of photographic enumeration, to consist of 55,000,000 fry. In the peak hour, 277,000 fry migrated upstream on the left bank. Sample counts showed that, on the average during this year, 38 per cent of the fry followed the left bank and 62 per cent migrated along the right bank. On this basis, it might be expected that the peak hourly migration on both banks would consist of 730,000 fry. Methods of handling such large numbers of fish have certainly not been proven.

These fish, which are little more than one inch in length, are not strong swimmers. Observations of shoreline velocities and the movements of fry in Chilko River indicated that for a distance of 1.0 ft. the maximum swimming speed is about 1.4 f.p.s. For a distance of 2.0 ft., the maximum swimming speed is less than 1.0 f.p.s. Sockeye fry migrating upstream in the Chilko River characteristically swim in a narrow band of shallow water extending not more than 1.5 ft. from shore. They progress upstream at an average rate of 0.26 f.p.s. against average shoreline velocities of about 0.54 f.p.s. The migration in Little River, into Shuswap Lake, has been observed as far as 8 or 10 ft. from shore in velocities of 1 or 2 f.p.s. but this was in early summer after the fry had reared for some time in Little Shuswap Lake. Recently emerged fry, on the other hand, remain very close to shore and migrate upstream at a maximum rate of about 0.2 f.p.s. in shallow water where the velocity ranges from 0.3 to 0.6 f.p.s. It is considered, therefore, that in any river where sockeye fry are required to migrate upstream to their rearing lake, continuous marginal paths in which the velocity does not exceed 0.5 f.p.s. for a distance of 1.5 ft. from shore should be available.

Two methods have been proposed for passing fry upstream at low dams such as that proposed for the outlet of Chilko Lake. The first method, the use of fishways, locks, or some mechanical transportation system, must be rejected at the present time because of the complete lack of design criteria and operational experience for such devices. The second proposal involves reduction of head on the dam before the commencement of fry migration so that the fish would not encounter velocities in excess of 0.5 f.p.s. in migrating past the dam site. Large spillway gates on the dam would be opened so that the river would be restored to substantially the same slope and cross-sectional area as before the dam was built. After the fry migration was completed, the gates would be closed so that water could be stored for the following winter low-flow period. This proposed dam and scheme of operation would involve a great number of problems, both engineering and biological. The fry migration occurs in May and June, when the run-off is high. Since it is difficult to predict the run-off pattern, there is the possibility that in some years the lake might not be adequately drawn down to restore flow in the river to the pattern commonly occurring during the upstream migration. The high discharge that would result might cause the fry to be blocked below the dam for extended periods. Such delayed fish might be weakened or otherwise adversely affected and might be swept so far downstream that it would be impossible for them to migrate upstream to reach Chilko Lake. Further, to pass such a dam, fish would have to swim upstream in much deeper water than along the natural river bank. Being forced to leave the protection of the shallow, shoreline areas, they might be subjected to increased predation. Alternately, marginal areas around the abutments of such a dam might be created to meet the depth and velocity requirements but extensive experimental work would be essential before the design of such passage facilities for fry could be attempted.

Effects of Reservoirs Created on Sockeye Rearing Lakes on Normal Migrations of Juveniles

When a lake is used as a reservoir for hydroelectric purposes, the normal outflow of that lake is altered. Flow regulation usually involves storage of water, or reduction of outflow, during the spring high-flow months and increased outflow during the winter low-flow months . Since the migrations of sockeye yearlings out of their rearing lakes coincide, in general, with the onset of the spring run-off, the increasing discharge may have some effect in initiating or directing the migration. On this assumption, it is possible that storage of the early portion of the spring run-off would adversely affect the migration.

Diversion of water from a sockeye rearing lake for power generation on another watershed might reduce the value of the lake as a sockeye producer. Regardless of what factors direct the migration of young sockeye out of a lake, a second outlet some distance from the natural outlet would also attract fish. Thus, the hydroelectric developments proposed for the Chilko watershed, which involve diversion of water from Chilko Lake to coastal streams leading to Bute Inlet (FIGURE 4), would alter the flow patterns and possibly many other characteristics of Chilko Lake. Unpublished observations made at Sproat Lake on Vancouver Island, where a screened, secondary outlet drawing only 90 c.f.s. from the lake attracts a large number of sockeye smolts, indicate that many of the Chilko smolts would be expected to seek exit from the large secondary outlets that have been proposed for Chilko Lake. Since the physical structure of the lake would be altered, many fish might not reach either outlet. Fish could collect in the vicinity of a deeply submerged power intake but might not sound to enter it. Although it might appear possible to trap these fish and transport them to the natural lake outlet, a successful method of collecting sockeye smolts has not been devised. Further, there is no precedent for transportation of large numbers of smolts over such a distance. Transportation by boat or barge would not be feasible because Chilko Lake is sometimes ice-covered during the first part of the smolt migration. If the fish congregated in the vicinity of the power intake until after the normal migration period had passed, they would likely remain in the lake for a second year, experiencing an additional year of mortality, competing with underyearlings for food, and perhaps preying on underyearlings. If only a proportion of each year class reached the natural lake outlet during each spring migration, total production would be further reduced.

Damming the outlet of a sockeye rearing lake to provide additional storage could also affect water temperatures in the lake. Submerged outlets, drawing cold water from subsurface layers, may result in the surface layers warming up more quickly than normal during the spring months. Increasing temperatures have been associated with the cessation of smolt migration. Any alterations that resulted in earlier warming of a lake might tend to inhibit smolt migration. Foerster (1937) found that the period of migration of young sockeye from Cultus Lake each spring was inversely correlated with temperature conditions during the months immediately preceding the migration period. Commencement of migration coincided with the vernal rise in lake temperature, with the threshold migration temperature being about 40°F. Cessation of migration appeared from these studies to be related to the setting up of a "temperature blanket", with the surface layers warming up to such an extent that young sockeye remained in deeper, cooler layers. Sockeye that were thus "trapped" in the lake apparently remained there until the following spring, growing relatively slowly during this additional year of lake residence. Ward (1932) proposed that downstream-migrant salmon, in moving through a reservoir, encounter a temperature barrier at the dam that causes them to remain in the reservoir. He maintained that the "landlocking habit" among *Salmo* and *Oncorhynchus* was caused primarily by temperature and attributed large populations of kokanee in reservoirs to landlocking of anadromous species.

Effects of Reservoirs Created on Migration Routes of Juvenile Salmon

Indications are that the production of sockeye and pink salmon would be reduced if the juveniles of these species were forced to pass through one or more reservoirs on their seaward migration. Research concerning the passage of downstream-migrant salmon through large impoundments is inadequate, however, to permit accurate predictions as to specific effects of changes in the migratory route. Possible changes as they might affect downstream migration are discussed below.

VELOCITY REDUCTION

In addition to the possible adverse effects of the "temperature blanket" described above, one of the obvious effects of the formation of reservoirs is the marked reduction in water velocity. Under natural conditions, sockeye smolts move downstream in rivers at about the same rate as the average water velocity. This has been demonstrated by experiments conducted on Chilko River, where the migration speed of sockeye smolts was found to be about 30 miles per day. Whereas migration through natural, high-velocity rivers appears to be a passive movement, migration through lakes appears to be more active, with fish migrating at a speed greater than the water velocity. Experiments have indicated that the average speed of sockeye smolts moving through Cultus Lake is about 0.7 miles per day and through Seton Lake one or two miles per day. A low-velocity reservoir created on the migration route would therefore be expected to result in a significant reduction in the speed of downstream migration.

The proposed Moran Dam would create a reservoir about 170 miles long. During the period of smolt migrations through this section of river, the recorded discharges in the Fraser River at the proposed dam site range from a minimum of 13,000 c.f.s. to a maximum of 266,000 c.f.s. On the basis of river cross-sections and average river slope for the reach, it is estimated that under present river conditions water travels this 170-mile reach of river in about 45 hours at the minimum discharge for April 15. At maximum river flow during the smolt migration, the travel time is only 18 hours. Therefore, if sockeye smolts travel through this reach of the Fraser River at about the same rate as the average water velocity, as they were observed to do in the Chilko River, the migration time would be only 18 to 45 hours.

Calculations indicate that in an average water year the time required for water to pass through the proposed Moran reservoir during the period of smolt migration would be about 60 times as long as through this reach of the river under natural condiions. The estimated travel times, calculated on the basis of average flow, distributed over the entire cross-section of the reservoir, with storage of surplus flow, and assuming minimum reservoir elevation on April 15, are shown in TABLE 5.

TABLE 5—Calculated travel rate of water through proposed Moran reservoir in an average water year.

Starting Period	Reservoir Elev. at end of period (ft.)	Average Inflow (c.f.s.)	Average Outflow (c.f.s.)	Average Storage (c.f.s.)	Elapsed Time Through Reservoir (days)
April 15-20	1410	43,000	43,000	0	67.0
21-30	1420	55,000	43,500	11,500	64.0
May 1-15	1440	73,700	43,500	30,200	59.4
16-31	1490	113,000	43,500	69,500	57.0
June 1-10	1515	121,000	43,500	77,500	59.7
11-30	1540	113,500	61,100	52,400	67.5
July 1-15	1540	101,500	101,500	0	93.8
16-31	1540	85,000	85,000	0	116.0

Sockeye smolts entering the reservoir at the upstream end during the peak of the normal migration period, May 16 to 31, would reach the dam in about 57 days if they traveled at the same rate as the average water velocity. That is, their average water speed would be about three miles per day. But the previously mentioned experiments in Seton and Cultus Lakes suggest that, in low water velocities, smolts actively swim downstream at a rate of about one mile per day. Smolts would therefore be expected to move through the proposed Moran reservoir at the approximate rate of four miles per day. On this basis, their normal migration would be prolonged about 40 days. Possible biological effects of such fresh-water delays are discussed in a later section.

TEMPERATURE CHANGES

Reaches of the Fraser River converted into major reservoirs would have their temperature regime altered considerably. As previously mentioned, many factors contribute to significant temperature changes in reservoirs. During the period of seaward migration of juveniles, the surface layers of reservoirs attain temperatures that are somewhat higher than in the undisturbed river. This increased heating results from the reduced velocity, which allows climatic conditions to exert a greater influence on the water mass, and from thermal stratification and draw-off of cold subsurface layers. Temperature affects activity and behavior of fish and may affect the seaward migration of young salmon.

During downstream migration, young salmon encounter certain naturally occurring temperature changes but measurements and calculations of existing temperature conditions on the Fraser River watershed suggest that these changes are relatively minor. For instance, three years of concurrent temperature data obtained at Hell's Gate and the outlet of Chilko Lake (Figure 26) indicate that young sockeye leaving Chilko Lake would be subjected to a temperature increase of not more than 10°F in this 275-mile migration distance. These fish leave Chilko Lake during the period April 15 to June 15, with annual peaks of migration occurring in late April, early and mid-May. It has been estimated that they reach Hell's Gate within a week. Migrants from other upriver rearing areas such as Quesnel, Stuart, Fraser and Francois Lakes may be subjected to similar temperature changes.

An indication of the temperature changes that fish would be subjected to in passing through major reservoirs on the Fraser River can be obtained by using the proposed Moran Dam as an example. As a result of the greatly increased time required for water to travel through the reservoir, surface temperatures would be higher than the temperature of the existing river. The great depth and slow velocities probably would result in temperature stratification at least at certain times of the year. Since little work has been done in analyzing the effects of river flow and climatic and limnological conditions on thermal stratification in reservoirs, a lengthy study of existing reservoirs would be necessary to obtain sufficient background information for an evaluation of thermal conditions in the reservoir that would be formed by the proposed dam. However, an indication of the probable conditions in the reservoir can be obtained by referring to measurements available from Roosevelt Lake above Grand Coulee Dam on the Columbia River.

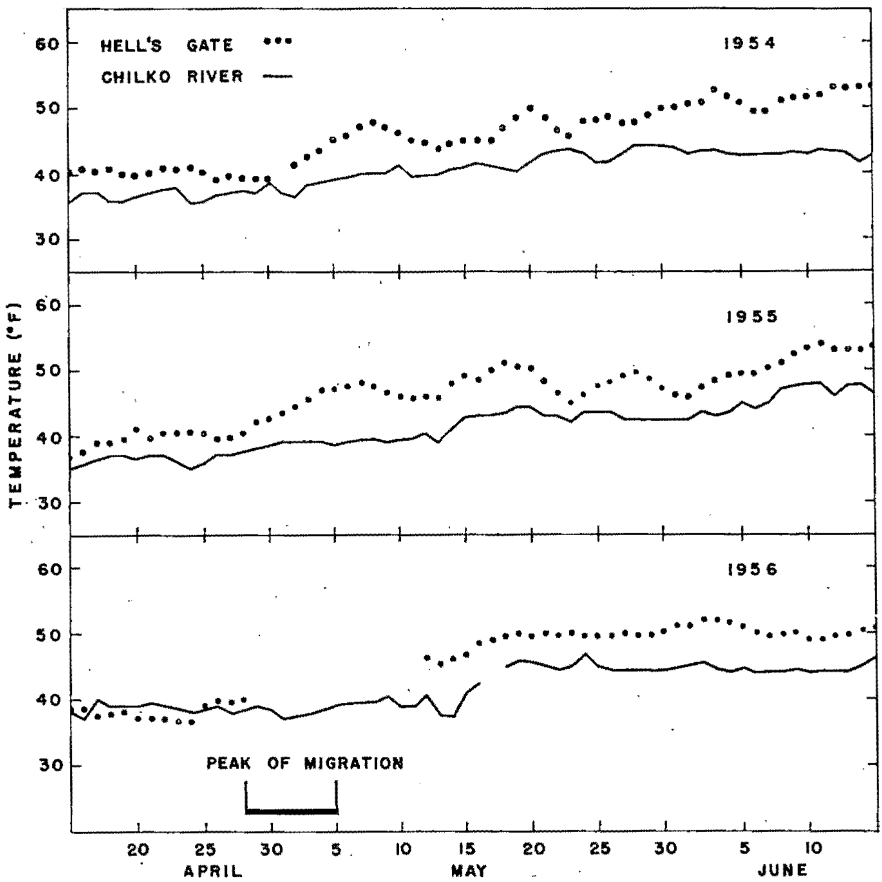


FIGURE 26—Water temperatures at Chilko Lake and Hell's Gate during times of migration of seaward-migrant sockeye from Chilko Lake.

TABLE 6 lists the various characteristics of the two dams and reservoirs. It will be seen that the two reservoirs are similar with respect to longitude and elevation and while they are 3° apart in latitude, they are both located in the continental climatic zone east of the Cascade Mountains and thus would have approximately similar exposures to climatic conditions, the one important difference being that Roosevelt Lake runs generally east to west, whereas the Moran reservoir would run from north to south. Moran Lake would have a 37 per cent larger volume than Roosevelt Lake and a mean annual outflow 55 per cent less than Roosevelt Lake. Average water velocity in the proposed Moran reservoir would be only about one third of that in Roosevelt Lake. Consequently, there would be much greater opportunity for heating and thermal stratification in Moran Lake than in Roosevelt Lake.

FIGURE 6 presents some data on depth-temperature relationships in Roosevelt Lake at several locations for the period May to October. There are definite periods of stratification in May, August and September. In May, the stratification is similar to that occurring in natural lakes but in August and September

TABLE 6—Comparison of characteristics of Roosevelt Lake and the proposed Moran reservoir.

	Roosevelt Lake	Moran Lake
Latitude of Dam	48° N.	51° N.
Longitude of Dam	119° W.	121° 52′ W.
Reservoir Elevation	1290 ft.	1540 ft.
Drainage Area	74,100 sq. miles	50,000 sq. miles*
Average River Flow	104,150 c.f.s.	48,300 c.f.s.*
Maximum River Flow	637,800 c.f.s.	266,000 c.f.s.*
Mean Annual Run-off	77,200,000 a.f.	34,480,000 a.f.*
Head at Dam	348 ft.	720 ft.
Dam Crest Width	4173 ft.	3200 ft.
Draw-down	80 ft.	200 ft.
Draw-down Per cent of Head	23%	27.8%
Reservoir Area	85,000 acres	65,000 acres
Reservoir Length	151 miles	172 miles
Average Width	4650 ft.	3140 ft.
Reservoir Volume	9,700,000 a.f.	13,300,000 a.f.
Active Volume	5,165,000 a.f.	9,000,000 a.f.
Per cent Active Volume	53%	67.5%
Average Cross Section (estimate only)	530,000 sq. ft.	640,000 sq. ft.
Velocity at Average Section at Maximum Flow	1.2 f.p.s.	0.42 f.p.s.
Average Turbine Discharge	65,000 c.f.s. (1950)	37,400 c.f.s.

* After deducting Nechako River diversion.

it is modified by the displacement of cold water, the displacement taking place during the freshet period. By October, continued turbine withdrawal of the colder waters results in nearly isothermal conditions but at a much higher temperature than would occur in the normal river at that time due to the time lag in passage of water. During May there can be as much as 15°F temperature difference between the surface and bottom of the reservoir at Grand Coulee Dam. It can therefore be predicted that a differential of at least this amount would occur during May in the proposed Moran reservoir. Surface water temperatures in the Moran reservoir would be determined by the interrelationships of all the climatic and hydraulic conditions affecting the reservoir but there is strong circumstantial evidence that they would be at least as high as those in Roosevelt Lake and certainly higher than in the normal river.

Judging by temperature measurements in Shuswap Lake (FIGURE 27), it appears that the surface layers of the proposed Moran reservoir might reach temperatures as high as 60°F during the normal period of smolt migration. A 40-day delay of smolts in the reservoir would result in some fish still being present in July, when the surface layers could reach temperatures as high as 70°F. This would be about 15°F warmer than temperatures normally encountered by smolts during their seaward migration.

The effect of such higher temperatures on the behavior and general condition of migrants will require careful study since any change could affect the ability of the smolts to migrate through reservoirs. It is possible that the surface water temperatures would not be suited to or preferred by the fish during their downstream migration, in which case they might alter their behavior to obtain such temperatures.

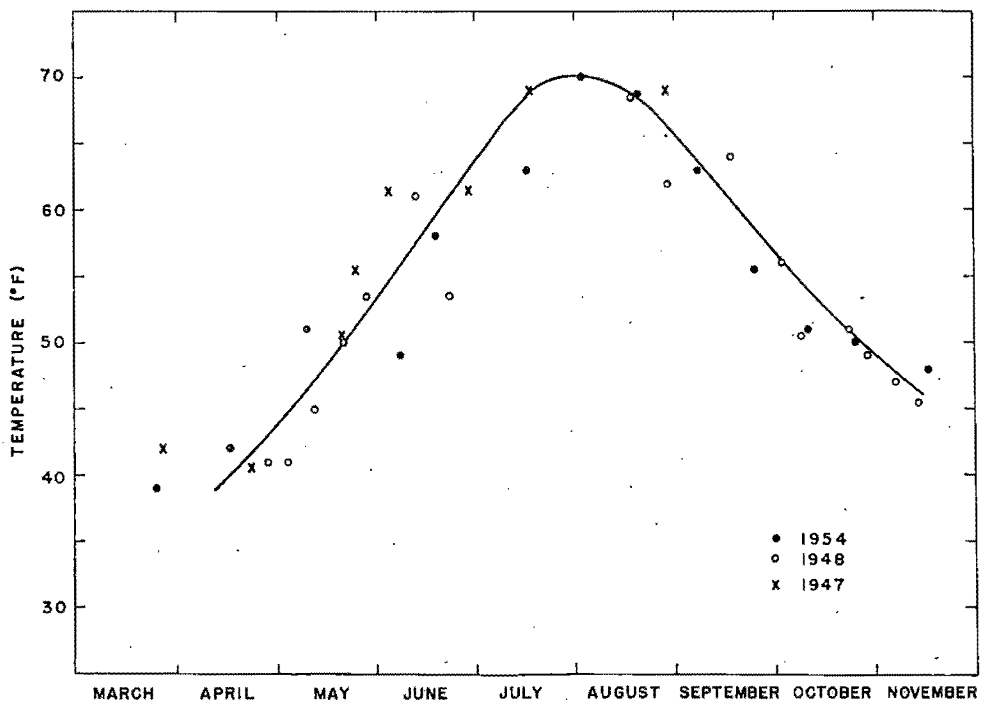


FIGURE 27—Surface water temperatures in Shuswap Lake, 1947, 1948 and 1954.

CHANGES IN OXYGEN, TURBIDITY AND PLANKTON

The possibility of other physical and chemical changes in river water impounded in a reservoir must also be considered. For example, in some of the Tennessee Valley Authority reservoirs in the eastern United States, studies have disclosed that currents of extremely low dissolved oxygen content pass through a reservoir between 40 and 60 ft. below the reservoir surface. In some instances, the dissolved oxygen below 60 ft. of depth is almost entirely depleted. These depletions are the result of high water temperatures and the oxygen demand of water-borne materials entering the reservoir (Wiebe, 1940). Fish mortality could occur as a result of fish entering the strata of low oxygen content. Robeck *et al.* (1954) have studied the dissolved oxygen levels in Roosevelt Lake. They noted a gradual depletion of oxygen in the deeper layers in a downstream direction. However, there was no depletion below concentrations considered safe for salmon, nor was there any indication of oxygen-deficient density currents. The Fraser River in its natural state is generally saturated with oxygen and the previously mentioned oxygen demand that is caused by minor pollution in certain areas is quickly satisfied by turbulence and re-aeration. If low-velocity reservoirs were constructed in these reaches of the river, however, a serious situation could conceivably result because of the oxygen deficiency and the presence of other toxic materials.

Considerable clarification of water in any large reservoir on the Fraser would be expected. Turbidities in Roosevelt Lake were less than 7 p.p.m. in September, 1952 compared with 19 p.p.m. in the incoming Columbia River (Robeck *et al.,* 1954). Reduced water velocity is accompanied by a decrease in the load of suspended materials. Although clarification of waters impounded in a reservoir tends to increase biological productivity, it may also provide an increased opportunity for predators to feed on migrating smolts and fry.

Plankton production in Roosevelt Lake has been shown to be extremely poor (Gangmark and Fulton, 1949). Bottom fauna was also sparse, owing to the large winter draw-downs and deposition of silt. While some food and game fish were present in this reservoir in relatively low numbers, squawfish, chub, suckers and carp were quite abundant. These authors concluded that the low productivity of Roosevelt Lake was caused by deposition of sediment, frequent replacement of water, sparsity of littoral areas and large winter draw-downs. It is quite likely that any reservoirs constructed on the Fraser would also have a low level of productivity and primarily support undesirable species of fish.

EFFECT OF A SERIES OF RESERVOIRS

Many reservoirs have been proposed for construction on the salmon migrations routes of the Fraser River watershed. The reservoir of the proposed Moran Dam has been used to illustrate the possible adverse effects on downstream migrants because the environmental changes would probably be more pronounced in this reservoir than in any of the other reservoirs that have been suggested. However, if a series of small reservoirs was created, the adverse effects might be even more serious than in the single large reservoir proposed for Moran Canyon. Downstream migrants subjected to the stresses involved in passing through reservoirs and over the spillways or through the turbines of even low dams may exhibit pronounced behavior changes that would preclude their migration through successive reservoirs.

PASSAGE OF PINK SALMON FRY THROUGH RESERVOIRS

Recent behavior studies suggest that pink salmon fry are not adapted to migration through large impoundments. MacKinnon and Brett (1955) described an experiment in which pink, sockeye, chum, coho and chinook fry were released at the upstream end of a 2.4-acre impounded water basin. Only one quarter of the pink and chum fry moved through the impoundment during a nine-day period when recapture gear was operated at the outlet. Since the fry of these species normally migrate directly to sea after emerging from the gravel in which they are hatched, the very low recovery of these species in this experiment suggests a serious loss caused by the impoundment. None of the sockeye, coho or chinook salmon fry were recovered but this is not surprising since the fry of these species do not migrate directly to sea. Hoar (1951) has shown that pink salmon fry emerge from the gravel at night, swim rapidly downstream with the current, and retreat into the gravel again at dawn. However, on reaching deep, slow-moving water they fail to find shelter under stones and subsequently gather in schools. They then remain in schools and exhibit typical feeding behavior rather than actively continuing their seaward migration (Hoar, 1954, 1956). Thus, an artificially created area of deep, slow-moving water on the migration route of pink salmon fry could alter their behavior pattern to such an extent that they might not reach the sea. However, the reservoirs of those low dams that have been proposed for construction on the Fraser and Thompson Rivers below the spawning grounds of the present commercial runs of pink salmon would probably provide sufficient velocity to carry pink fry to sea with little delay.

BIOLOGICAL EFFECTS OF FRESH-WATER DELAY

Delaying the downstream migration of sockeye smolts could seriously affect their survival. There is some evidence that fresh-water delay results in increased residualism. The ability of smolts to make the transition to sea water might also be reduced if the fish were delayed in fresh water beyond the usual migratory period. Any additional stresses imposed on the fish, such as increased temperatures in reservoirs or passage over dams, might further affect the ability of sockeye smolts to make the transition to sea water.

It has been estimated that sockeye smolts would be delayed about 40 days as a result of passage through the proposed Moran reservoir. A delay of this magnitude is almost certain to have a profound effect on their survival. It is considered that the downstream migrations are timed to the environmental cycle and that complex physiological changes occur in the fish before and during their migrations that prepare them for the ocean environment. Each race of downstream migrants is probably adapted to the environmental characteristics of its particular seaward migration route. That is, the Stuart races are probably adapted to long migrations through lakes such as Stuart and Trembleur. Other races such as Chilko, Stellako and Horsefly do not encounter lakes on their migration. It is probable, however, that even those races that migrate through lakes during their seaward migration would not be adapted to passage through a 170-mile-long reservoir created where a fast-flowing stretch of river previously existed. The migrants would be delayed for extensive periods and their survival might be substantially reduced.

There is some evidence that sockeye smolts feed during their seaward migration. Smolts captured in the Chilcotin River were found to contain insects. Since seaward migrants would be present in reservoirs for much longer periods of time than in natural rivers, the question arises as to their ability to obtain adequate food to support their energy requirements for active swimming. Reservoirs would contain more food than fast-flowing rivers but the supply could be quite limited in such reservoirs, and might soon be depleted by the large numbers of sockeye smolts that would be present during periods of seaward migration.

Recent experiments indicate that juvenile salmon exhibit a preference for salt water prior to, during, and after the normal period of downstream migration. Baggerman (1959) has suggested that the disposition for seaward migration of juvenile Pacific salmon is directly related to this observed salt-water preference. The tendency for these fish to migrate seaward may therefore be expected to diminish with increasing periods of fresh-water delay. It could well be that migratory activity would be much diminished before the fish reached the lower end of a large reservoir such as that which would be created behind the proposed Moran Dam.

When appropriate fresh-water conditions are available, sockeye can successfully complete their life cycle githout going to the ocean. Landlocked sockeye or kokanee are fresh-water forms of the anadromous species. They complete their life cycle in many lakes that also support substantial populations of sockeye. Ward (1932) observed that the construction of Baker Dam in the State of Washington produced a substantial population of landlocked sockeye in Lake Shannon, the 9.5-mile-long reservoir immediately above this dam. He attributed the appearance of these fish to an observed delay, and consequent residualism, among downstream-migrant sockeye at the dam. Ward concluded that sockeye smolts were delayed or blocked at Baker Dam primarily because of the heating of the surface layers of the reservoir. Presumably the fish sounded to cooler water and therefore did not find the surface spillway exit. While the actual cause of landlocking may or may not have been determined by Ward, the formation of a substantial population of landlocked sockeye above Baker Dam has been demonstrated. After considering the problem of landlocking of sockeye populations in reservoirs, Hoar (1956) concluded: "With fish as well adapted to fresh-water as the kokanee the prospect does not seem happy for commercial sockeye. There is every reason to expect sockeye—perhaps also coho and spring salmon—to remain in fresh water when they encounter one or more vast impoundments of water in their normal route of migration."

Data from experiments conducted in Cultus Lake in 1958 may illustrate other possible adverse effects of reservoirs. Sockeye smolts captured in the outlet stream below Cultus Lake were transported to the upper end of the lake, released, and those that migrated through the lake were captured and counted at a weir across the outlet stream. One group consisted of 1000 sockeye captured and released near the peak of the downstream migration period and the second group consisted of 1500 sockeye taken 12 days later near the end of the main migration period. Nearly all of the first group migrated through the lake a second time but only 80 per cent of the fish in the second group were counted at the weir. The 20 per cent loss of fish in the second group may have been due to residualism. The average time required for passage through the lake was about 4.5 days for both groups. If the loss was caused by residualism, passage through long, low-velocity reservoirs could be expected to cause significant losses. The fact that only the second group showed a significant loss in the lake may be associated with the changing intensity, during the migratory period, of environmental and physiological factors that initiate and control migratory activity. Presumably, these factors are related to endocrine activity and can be expressed in terms of "salt-water preference" as described by Houston (1957) and Baggerman (1959).

These preliminary experiments were continued at Cultus Lake in the spring of 1959. Further information was obtained to indicate harmful effects of delaying smolts in fresh water beyond the normal migratory period. Sockeye captured at the lake outlet and released at the upper end of the lake appeared at the lake outlet again in a few days. Fish that were not artificially delayed before release showed a peak of recovery at the lake outlet in about five days. However, fish that were delayed for 16 days showed a peak recovery only two days after release. That is, delayed fish migrated through the lake more quickly than undelayed fish although delayed fish that were released late in the season were recovered at the lake outlet in smaller percentages than fish released earlier. The migration rate in a large reservoir might increase after a period of delay but it is probable that some reduction in numbers of migrants would occur.

The ability of sockeye smolts to survive an experimental transition from fresh to salt water also appeared to be related to the period of delay in fresh water. Since either premature or delayed entry into salt water appeared to reduce the survival rate, it is possible that physiological changes occurring within the fish enabled them to make the transition to the ocean environment at a relatively fixed time after smolting. While these studies are still in an exploratory stage, they suggest that delaying of sockeye smolts in fresh-water reservoirs could adversely affect production. Further study is required for predicting the extent of delay in reservoirs and the total effect of this delay.

Downstream Passage at Dams

PASSAGE OVER SPILLWAYS AND THROUGH TURBINES

Injuries suffered by downstream-migrant salmon passing over spillways and through turbines at dams generally cause a significant mortality, which may destroy the economic value of a salmon resource. Since no method has yet been devised for collecting downstream migrants in the forebays of major dams, these fish are subjected to hazardous conditions in the only migration routes available to them—over the spillway or through the turbines.

Hoar (1956) has given an excellent summary of the phsyiological problems generally involved. He pointed out that the skin forms an active barrier between the external environment and the internal fluid environment of the living cells and that injury to this delicate surface results in:

(a) flooding of tissues with excessive amounts of osmotic water,
(b) liberation of toxic materials from injured tissues, and
(c) ready penetration of pathogenic organisms.

In addition, injuries suffered by downstream-migrant salmon at dams frequently extend to internal organs.

When fish are in fresh water, there is a continuous flow of water into the body through the gills and mucous membranes of the mouth. The kidney must therefore function continuously to filter relatively large volumes of water. Its capacity is limited, however, and greatly increased volumes of water entering through injured skin cause an abnormal accumulation of watery fluids within the tissues and may lead to death.

Studies of the reactions of other vertebrate animals have shown that injured tissues frequently liberate histamine-like materials which are toxic and which markedly increase tissue permeability. Although this reaction has not been demonstrated in fish, it is likely that similar types of reactions occur. An increase in tissue permeability would accentuate inflow of water and loss of vital tissue constituents such as salt and plasma protein.

One of the external effects of skin abrasions and cuts is a fungus infection of the injured area. Within a few days after receiving cuts or skin abrasions, seaward-migrant salmon may be attacked by fungi that obtain a foothold at minute skin perforations or even where the protective layer of mucous is scraped off. The fungus attaches to the fish by means of small, root-like filaments that penetrate the skin and in late stages of the disease may invade the underlying musculature. As the filaments grow through the skin, they cause the death of surrounding tissues and may eventually lead to the death of the fish. Fungus inhibits healing and adversely affects the animal. Fungus-infected fish probably have a reduced chance of survival in passage through reservoirs or through river areas having higher-than-normal temperatures.

In addition to its immediate reaction to physical injury, the animal attempts to adapt to the strain placed on its physiological machinery as a result of stress or physical injury and mobilizes reserves from many sources. Many adverse effects are now reasonably well described in the mammal (Selye, 1949) and it may be presumed that fish make comparable adaptive changes (Hoar, 1957). If the damage is extensive, vital organic compounds, such as some of the hormones, are exhausted and death quickly follows.

Brett (1958) proposed that stress could be defined as "a state produced by any environmental or other factor which extends the adaptive responses of an animal beyond the normal range, or which disturbs the normal functioning to such an extent that, in either case, the chances of survival are significantly reduced." He further suggested that a significant feature of stress applied to downstream migrants by passage through turbines is that it is likely to be indiscriminate. All fish passing through a turbine are subjected to virtually the same pressure change; differences in survival may simply be according to the distribution of resistance within the population. Any lethal stress that has reached the stage of causing immediate death of some of the fish may be approaching the catastrophic level for the whole population. Small additional stresses could result in total mortality. It seems likely that passage through turbines, however, also involves discriminate stress because all of the fish are probably not subjected to the severe conditions of localized pressure change and cavitation.

Since all of the fish are subjected to a certain indiscriminate stress in passing through a turbine or over a spillway, fish that are not killed may be affected to the extent that their ability to perform is impaired. Chances of survival would be reduced not only because of decreased tolerance to other stresses usually encountered during fresh-water migration but also because of the reduced ability to cope with the necessary transition to sea water. This transition may subject fish to considerable stress, even under natural conditions. Whereas fish must remove relatively large amounts of osmotic water from their system while in a fresh-water environment, they must prevent dehydration while in a sea-water environment. This change from a hypotonic to a hypertonic medium necessitates extensive changes in the metabolic processes and a period of several hours is required for adaptation (Houston, 1959). Black (1951) has shown that, under experimental conditions, transfer of chum and coho fry to sea water results in an increase in chloride content and that a significant mortality among the coho fry, apparently resulting from an accumulation of salts in the tissues, is a consequence of this change. Changed density and water content were also observed following transfer of chum and coho fry to sea water. Chum fry showed very little mortality whereas nearly all of the coho fry died within 24 hours. Houston (1959) demonstrated that the swimming ability of chum salmon fry was greatly reduced for at least 30 hours following entry into the sea water. Thus it is apparent that the transition of juvenile salmon from fresh to salt water imposes an osmo-regulatory stress. Current studies suggest a direct relationship between survival of Fraser River sockeye smolts in the Georgia Strait - San Juan Islands area and the spring discharge of the Fraser River at the time of smolt migration. While temperature and salinity also seemed to be related to survival, these factors are in part a function of river discharge. Although the underlying mechansms are not understood, it is possible that any reduction in spring discharge would adversely affect sockeye survival. The adverse effects of flow reduction might be accentuated if the fish were subjected to injury or stress by passage over spillways and through turbines during their seaward migrations.

Causes of Injury in Spillways and Turbines

A great deal of evidence has been obtained in the last few years which shows that downstream migrants suffer mortalities in passing over spillways and through turbines. No experiments have been conducted at a dam as high as the proposed 720-ft. Moran Dam. However, at Baker Dam, which is 250 ft. high, 64 per cent of the sockeye yearlings were killed in passage over the spillway and 34 per cent in passage through the turbines (Hamilton and Andrew, 1954). One of the main reasons for not constructing passage facilities for adult salmon and trout at Grand Coulee Dam, which is 350 ft. high, was the anticipated high mortality of seaward migrants in passing over the spillway (Chapman, 1940b). Model studies suggested that downstream migrants would be killed on the spillway face and in the energy-dissipating area at the base of the spillway. Since large numbers of injured and dead kokanee are found below Grand Coulee Dam each spring, the decision not to build passage facilities for adult salmon and trout appears to have been justified. It seems likely that sockeye smolts passing over the spillway or through the turbines at the proposed Moran Dam would also suffer severe mortalities. The mortalities measured at other dams show that the rate of mortality is dependent on the design and method of operation of spillways and turbines as well as on gross head. Available turbine and spillway mortality information is summarized in TABLE 7.

Various investigators have suggested that the main causes of spillway mortality are abrasion and turbulence. Pressure change and cavitation are believed to be contributing factors. Probably most of the injuries sustained by fish passing over the spillway of Baker Dam are caused below the point where the free-falling stream from the spillway gates impinges on the concrete spillway about 100 ft. below the crest of the dam . After impinging on the spillway face, the stream spreads out to a thin sheet of extremely turbulent and fast-flowing water. Since the concrete face is eroded and very rough, many injuries are caused by abrasion. It was also determined that the violently turbulent pool at the base of the spillway caused mortalities. Mortalities would be expected to increase at higher dams because the conditions that produce abrasion, pressure change, cavitation and turbulence would be accentuated.

Ski-jump Spillways

Expriments at the two dams on the Elwha River (Schoeneman and Junge, 1954) showed that a large proportion of the mortalities could be attributed to pressure changes and mechanical injuries. The relatively low mortality rates measured at the 180-ft. free-fall spillway at Glines Dam may be explained on the basis that pressure changes and mechanical injuries were virtually eliminated

TABLE 7—Measured mortality rates suffered by downstream-migrant salmon and trout in passage over spillways and through turbines.

Dam	Head (Ft.)	Species	Average Length (In.)	Spillway Mortality (Per cent)	Turbine Mortality (Per cent)
1. Puntledge (Puntledge River)	350	Steelhead	4.9	—	42
		Kamloops	2.7	—	28
		Kamloops	1.8	—	29
		Pink, chum, coho, chinook, Kamloops	1.4	—	33
2. Cleveland (Capilano River)	295	Coho	Smolts	57	—
		Steelhead	Smolts	69	—
3. Baker (Baker River)	250	Sockeye	3.75	64	34
		Coho	4.1	54	28
4. Glines (Elwha River)	194	Coho	4.25	8*	30
		Chinook	2.75	6*	33
5. Seton (Seton Creek)	142	Sockeye	3.4	—	9
6. Ruskin (Stave River)	130	Sockeye	3.4	—	10
7. Elwha (Elwha River)	100	Chinook	2.75	37	0
8. Big Cliff (N. Fork, Santiam River)	90	Chinook	4.7	2	11
9. McNary (Columbia River)	90	Chinook	2.1	2	11
10. Bonneville (Columbia River)	60	Chinook		15**	15**

Notes:

* The spillway at Glines Dam consists of a free fall or ski-jump where a small quantity of water drops into a large, deep pool.

** It was not possible to separate spillway and turbine mortalities in this experiment at Bonneville Dam.

References:

1. Can. Dept. Fish., 1958.
2. Vernon and Hourston, 1957.
3. Hamilton and Andrew, 1954.
4. Schoeneman and Junge, 1954.
5. Andrew and Geen, 1958.
6. Internat. Pacific Salmon Fish. Comm., unpubl.
7. Schoeneman and Junge, 1954.
8. Wash. Dept. Fish., unpubl.
9. Wash. Dept. Fish., 1957.
10. Corps of Engineers, 1948.

because most of the drop occurred as a free fall through air. Nevertheless, there was some mortality, possibly caused by impact and turbulence in the pool below the spillway, by inhibition of respiration, and by increased predation. Mortalities of 17 to 32 per cent were measured in dropping hatchery-reared coho yearlings 250 ft. over an experimental ski-jump spillway at Baker Dam (Regenthal, 1957). In the ski-jump spillway at Cleveland Dam on the Capilano River, the water drops 295 ft. but only about one third of this drop is a free fall through air. It is believed that the very high mortality of 57 to 69 per cent was caused by insufficient depth in the tailwater cushioning pool and abrasion on the spillway face and canyon walls (Vernon and Hourston, 1957).

Pressure Change

Pressure change has frequently been suggested as a major cause of mortality in turbines. Hogan (1941) has shown that fish subjected to a vacuum suffer distended eyes and hemorrhages. Injures such as ruptured or missing eyes, and various hemorrhages can be attributed, at least in part, to a sudden release of pressure. Observations have shown that all of these injuries can also be caused by impact, such as in throwing fish against a solid object.

Harvey and Pyper (MS.) have studied the effects of a wide range of pressures and vacuums on sockeye smolts. The studies were carried out at Cultus Lake in a cylidrical tank 3 ft. long and 1 ft. in diameter, equipped with plastic observation ports in each end. The range of this equipment was from 310 pounds per square inch (p.s.i.) above atmospheric pressure to 14 p.s.i. (95 per cent of an absolute vacuum) below atmospheric. Pressure could be applied at the rate of 150 p.s.i. per second and released at the rate of 10,320 p.s.i. per second. Rates of pressure increase, magnitude of pressure, rates of pressure decrease and magnitude of vacuum were recorded electronically. Control and pressurized fish were hold two weeks for observation following each test.

In the spring of 1958, 48 preliminary experiments were conducted on 980 smolts. Releases from high pressures of 310 p.s.i. resulted in 4 to 10 per cent mortality. Rate of application and release of pressure appeared to have no influence on mortality rate. In another test, repeated cycles of 10 releases from pressures of 50 p.s.i. resulted in a cumulative mortality of 23 per cent.

Studies in 1959, involving 143 tests in which 17,000 sockeye smolts were used, indicated a complex pattern of immediate and delayed mortality. Immediate mortality ranged from 0 to 48 per cent and was related to the water temperature and the gaseous saturation of the water. Very high mortality rates were observed when sockeye smolts were subjected to pressure change in warm water supersaturated with oxygen. The "immediate mortalities" were, in the main, the result of gas emboli in the vascular system, which caused death within two to three minutes. In addition, there was a low level of mortality resulting from severe hemorrhage. Immediate mortality increased with increasing positive pressure, increasing magnitude of vacuum and increasing water temperature above a base level. Delayed mortality during two weeks of holding was approximately 3 per cent greater in test fish than controls. These experiments were continued in 1960 to study the physiological effects of pressure and pressure change.

Some workers have suggested that pressure change is not an important factor in contributing to mortalities of young fish passing through turbines. This opinion, however, has been based on incomplete data. Whereas studies conducted several years ago suggested that young fish were able to withstand sudden pressure change without significant injury, more recent studies indicate that the whole problem is exceedingly complex. The adverse effects of pressure release on juvenile salmon and trout may be dependent on whether the fish are accommodated to the high pressure before release. Unpublished studies of the State of Washington Department of Fisheries suggested that a sudden release of pressure had more severe consequences if the fish were first equilibrated with or accommodated to a high-pressure environment. An adequate understanding of pressure accommodation has not been achieved, probably because the role and functioning of the swim bladder is not understood at the present time. The causes of formation of gas emboli in the circulatory system have not yet been determined. Current experiments may resolve many of these problems.

Cavitation

Cavitation is believed to be one of the causes of injury to fish passing downstream through turbines. The phenomenon of cavitation may be described as a violent implosion resulting from the sudden collapse of water vapor bubbles. Minute bubbles of water vapor are formed in localized areas in the stream of water flowing through a turbine when the water vaporizes as a result of velocity changes that reduce the pressure to the vapor limit. These bubbles collapse immediately upon entering a zone of higher pressure. The resulting impact of water produces an extremely high pressure that is transmitted radially outward, followed by a negative pressure wave. This phenomenon is frequently observed in turbines, particularly near the trailing edges of the vanes. One of the consequences of these violent cavitation implosions is removal of metal from the boundary surfaces, resulting in what is called "pitting".

Muir (1959) developed the hypothesis that mortality among young fish passing through turbines is caused mainly by exposure to cavitation. He reported experiments that suggested that fish are not injured by high pressure, sudden release of pressure, or exposure to partial vacuums. Exposure of coho fingerlings to cavitation in a test chamber produced extensive injuries, however. An immediate mortality of approximately 50 per cent and subsequent mortalities appeared to result from mechanical shock that occurred following the collapse of a pocket of water vapor.

Other factors may cause mortalities to juvenile salmon passing through turbines. Abrasion and impact on the turbine runner or on the surface of the draft tube may cause some injury. Mechanical injuries occur in turbines, as the various studies have shown, but the frequency of injuries attributable to abrasion and impact is not high. It seems likely that the mortalities result from a combination of several factors which singly may not be particularly injurious but which, in combination, produce significant mortalities.

Modifications of Spillway and Turbine Design to Reduce Mortality Rates

It may be possible in some instances to modify spillway and turbine design to reduce mortality rates of juvenile salmon. Preston and Rydell (1957) pointed out that in recent years the design of spillways and turbines at Columbia River dams has been influenced to some extent by considerations of salmon and trout conservation. It has been assumed that mortality rates would be minimized if spillways were designed with streamlined flow and with as little turbulence as practical in the bucket, or energy-dissipating area, at the base of the spillway. From an engineering point of view, rapid and efficient energy dissipation is desirable to avoid high velocities downstream that could cause scouring of the stream bed. Compromises have been considered and worked out by model studies to provide hydraulically efficient energy-dissipating areas and to minimize flow conditions such as back-roll and excessive turbulence that might be harmful to fish. Conditions likely to produce cavitation on spillway piers and baffles and on the face of spillways are avoided wherever possible. Rough concrete is considered harmful, not only because of possible abrasive action on fish but also because of the possibility of cavitation.

Turbine design has also received some attention in recent years. Preston and Rydell (1957) noted a trend towards use of Kaplan turbines instead of Francis wheels at Columbia River dams. The trend to limit heads on Columbia River dams to the range 90 to 110 ft. may also be beneficial for fish passage. These trends, however, appear to be a result of economic considerations rather than primarily for fisheries conservation. Kaplan turbines have been considered less harmful to fish that Francis turbines because of their larger waterway openings and slower speeds but this has not been tested.

Much interst has recently been shown concerning possible modifications of turbine design following publication of the hypothesis, presented by Muir (1959), that cavitation is a primary cause of turbine mortalities. It has been proposed that cavitation should be eliminated, or at least reduced to a very low level, by relatively simple design modifications and by lowering the runner elevation with respect to tailwater. Theoretically, cavitation could be eliminated in turbines by maintaining adequate positive pressures in the draft tubes.

The method of operation of turbines has also been shown to be an important factor affecting mortality rates. Mortalities were measured at the 90-ft.-high Big Cliff Dam under two turbine load conditions. The stated mortality of 11 per cent (Table 7) was measured at a normal overload (80 per cent wicket gate setting) but at part load (40 per cent wicket gate setting) the mortality increased to 21 per cent. Turbines are generally designed to give maximum efficiency at rated head and full load. Part or overload operation or altered flow to compensate for changes in head, generally cause less streamlining of flow and therefore may be expected to produce conditions more harmful for fish passage.

One of the spillway design modifications cited by Preston and Rydell and other workers is the recent development of ski-jump spillways. Experiments conducted at Glines Dam on the Elwha River in 1952 and 1953 (Schoeneman and Junge, 1954) suggested that mortality rates suffered by juvenile salmon in passage over spillways could be greatly reduced by dropping the water and fish through air from the spillway crest to a large energy-dissipating pool at the base of the spillway. After discovering that yearling coho suffered a mortality rate of only 8 per cent and 90-day-old chinook salmon fingerlings only 6 per cent in passage over the 194-ft. free-fall spillway at Glines Dam, the State of Washington Department of Fisheries conducted wind tunnel tests to determine the height of fall required for reaching terminal velocity. It was determined that small fish reach a terminal velocity of about 40 miles per hour during a free fall of 150 ft. Fish of various sizes were also dropped from helicopters from heights of 100, 200 and 300 ft. For fish less than 6 in. long, the mortality rate suffered in free fall was much lower than the mortality rates measured in passage over the 250-ft. spillway at Baker Dam. Fish larger than 6 in. long suffered a high mortality rate because they reached a higher terminal velocity and therefore hit the water with greater impact. A temporary ski-jump spillway built at Baker Dam reduced the mortality rate to about half that suffered by fish passing over the concrete spillway of the dam (Regenthal, 1957). Coho yearling had been shown to suffer mortality rate of 54 per cent in passage over the spillway of this 250-ft. dam whereas the mortality suffered in passage over the ski-jump spillway was 17 to 32 per cent. Dropping the fish through air eliminated abrasion, which was considered to be the primary cause of mortality in passage over the spillway. The observed mortality in passage over the ski-jump spillway was still very high, however. Injuries were probably caused by impact on the pool below the dam and by turbulence in this pool. A few fish were seen to fall short of the pool and strike the spillway face. One disadvantage of free-fall spillways is that wind action may cause the fish to strike solid objects such as the dam or canyon walls. As previously noted, the high mortality rate observed in passage over the free-fall spillway at Cleveland Dam was considered to have been caused by insufficient depth in the cushioning pool. No information is available as to the depth or volume required in the cushioning pool in relation to the quantity of spill or the height of fall to prevent mortality. In the free-fall experiments at Baker Dam the fish did not suffer the full effects of turbulence, energy dissipation and abrasion in the cushioning pool because the spillway was shut off soon after the test fish were released. Similarly, these factors did not contribute to the mortality in the experimental fish drops from helicopters.

A fish-protective method such as a free-fall spillway reduces but does not eliminate the mortality and stress imposed on fish. While such fish-protective methods may minimize the loss at dams, it does not follow that the problem of passing downstream-migrant salmon over dams has been solved The cumulative effect of several dams on downstream migrants may result in significant losses even if the spillway and turbine mortality rate at individual dams are low. On the Fraser River, the commercial fishery for sockeye salmon is regulated to allow approximately 20 per cent of each race to escape to the spawning grounds. Thus, for every 100 adults produced, 80 may be taken by the commercial fishery and 20 should be allowed to escape to maintain production at the same level. Any factor, such as a dam, that reduces the number of smolts reaching the ocean reduces the number of surviving adults by about the same proportion. A 15 per cent mortality imposed during the seaward-migrant stage would result in a return of only 85 adults for every 100 that would otherwise have been produced. Since 20 must be allowed to reach the spawning grounds, only 65 would be available for the commercial fishery. This loss would represent a reduction of 19 per cent in the commercial catch. For two dams, each killing 15 per cent of the seaward migrants, the reduction in the allowable commercial catch would be 35 per cent. The development of hydroelectric power at four possible sites on the Fraser River between Hope and Lyttton and six on the Thompson between Lytton and Kamloops Lake has been proposed. If these dams were built, and if only 15 per cent of the seaward-migrant sockeye were killed at each dam, the commercial fishery dependent on Fraser River runs spawning above Lytton would be reduced 60 per cent and the runs above Kamloops Lake, including the large Adams River run, would probably cease to have any important commercial value. Early experiments at the 60-ft. Bonneville Dam indicated a mortality rate of 15 per cent but recent experiments at McNary Dam, which has a head of 90 ft., indicate a mortality of only 11 per cent. Even if the mortality rate at proposed dams in the Fraser River watershed was only 10 per cent, one dam would reduce the population to such an extent that the commercial fishery would have to be cut by 12 per cent to allow an adequate escapement of adults, four dams would result in a theoretical reduction of 30 per cent and 10 dams would result in a reduction of 80 per cent. While it is possible that the average mortality rate might be less than 10 per cent per dam because the weaker fish would be killed at the first dam, it is also possible that the average mortality rate might be greater than 10 per cent because fish that survive the first dam might be weakened to such an extent that they would be unable to withstand the stresses imposed by succeeding dams.

ARTIFICIAL GUIDING STIMULI

Extensive studies are being made by various fisheries agencies and other groups in the United States, Canada, and other countries to find methods that might be effective in guiding seaward-migrant salmon and trout away from the hazards of spillways and turbines. If such methods could be found they would reduce and possibly eliminate mortalities that occur when migrants pass through turbines and over spillways. It must be reiterated, however, that such methods would not be a "solution" to the fish-power problem. As is shown in this report, there are many other problems, some of them of equal importance, which have not been solved and are not receiving the degree of attention that the downstream-migrant problem is receiving at the present time. Further, guiding devices at dams might introduce other adverse factors, such as land-locking of fish in reservoirs, that would cause serious fish losses.

The uniform and forthright downstream migrations of juvenile salmon suggest that the fish respond in a definite manner to external stimuli. There is no doubt that fish have highly sensitive receptor organs. It has been reasoned, therefore, that if natural stimuli cause fish to respond in a definite manner, it might be possible to use artificially introduced stimuli to guide downstream-migrant salmon. Stimuli of the natural environment such as light, sound, odors or visual cues, or artificial stimuli such as electricity might be effective in artificially guiding the seaward migrants at dams by attracting, leading, or repelling them. In spite of the fact that very little is known of stimuli associated with the seaward migrations of salmon and trout, a great deal of effort has been expended during the past 10 years or so in attempts to devise methods of using artificial stimuli to control or guide the movements of these fish. Their behavior has been studied under the influence of various stimuli in laboratory and field experiments. Various experimenters have discovered that the movments of young salmon can be controlled with a high degree of success in laboratory and small-scale field experiments but on a larger scale the same stimuli are much less effective.

Light and Shade

Observations of juvenile salmon and trout in their natural environment reveal that these fish are highly sensitive to variations in light intensity. Sockeye fry emerge from the gravel only during periods of low light intensity. On the other hand, upstream migration of sockeye fry to their rearing lake, such as at Chilko River, occurs during daylight. Pink salmon fry emerge from the gravel during darkness and move downstream with the current. If they do not reach deep water before the increasing morning light, they retreat into the gravel bed of the stream until the light intensity begins to decrease the next evening. Upon reaching deep water, they school and exhibit typical feeding behavior. The migration of sockeye smolts out of lakes is also associated with light intensity. Although there is much variation in the daily pattern of migration, the peaks of migration generally coincide with the marked changes in light intensity of the morning and evening hours. Experiments conducted in Chilko River suggest that sockeye smolts tend to stop migrating in rivers during daylight when the water is clear but in turbid rivers the migration continues during the day as well as at night. These observations indicate that light has a pronounced effect on the migratory behavior of juvenile salmon.

Results of experiments in which artificial light has been used in attempts to determine its attractive or repellent value in guiding downstream-migrant salmon have been quite variable, apparently depending on how the light is positioned. Andrew *et al.* (1955) reported that lights suspended above the water surface on one side of a 24- by 30-ft. test area did not have an appreciable effect on the movement of sockeye smolts. A submerged spotlight, however, was effective in attracting about 60 per cent of these fish. Observations suggested that, under certain conditions, downstream-migrant sockeye are attracted by artificial light during periods of darkness. It was proposed that this reaction might have been a result of the distinct schooling behavior of this species. When a few fish become visible in lighted areas, other fish may school with them. It was also suggested that when their passageway is brightly illuminated, the fish either evade the lighted area or orient with respect to the sides or bottom so that they are not readily carried downstream by the current.

Brett and Alderdice (1958) reported that when a narrow beam of light was directed, from above the water surface, across one half of a two-choice experimental area, little if any deflection was obtained. Fish that entered the lighted area tended to hold position in the stream temporarily. However, marked avoidance occurred when one half of the experimental area was totally illuminated. They point out that fish tend to hold position in an illuminated area and that a sampling trap located downstream from such an area would catch fewer fish than one located elsewhere.

Fields (1957) observed a deflecton of downstream-migrant salmon away from a narrow beam of bright light directed across one side of a two-choice test area. The young of all five species of Pacifis salmon, as well as steelhead and cutthroat trout, were also shown to exhibit negative phototaxis when held in aquaria. Small-scale laboratory experiments in clear water revealed that fewer fish entered the lighted area as the light intensity was increased. However the number fish found in the lighted area increased with the velocity of the water.

In a validation of the laboratory results under natural conditions with with wild migrants, a 40-ft.-long light barrier was used to span a small creek (Fields *et al.*, 1956). The barrier was positioned at an angle of 35° to the direction of stream flow. This clear-water stream was 28 ft. wide and varied from 8 to 20 in. deep under the light barrier. Data gathered during a 10-day period revealed that the proportion of fish captured in traps downstream from the lighted barrier was less than the proportion captured in these traps when the light was not used. The guiding effciency was considerably lower than in the previous laboratory experiments but it was still statistically significant. The practical significance may be questioned, however. In one test, the light barrier was placed so as to guide fish into a trap near the right bank that strained about 25 per cent of the stream flow and captured, under control conditions with the lights off, about 40 per cent of the migrating fish. When the lights were turned on, the proportions of fish captured in this trap during four successive hours of operation were 93, 82, 72, and 64 per cent respectively. The guiding efficiency was high for the first hour but declined so rapidly that the lights might have been ineffective after a few more hours of operation. Furthermore, the presence of this light barrier blocked the normal downstream migration past the experimental site. Whereas 309 fish moved downstream through the experimental area in the first hour after the lights were turned on, 481 in the second hour, 271 in the third and 127 in the fourth, there were 726 in the first hour after all the lights were turned off and 402 in the second hour. This blocking effect was evident even when 200-watt lamps were replaced with 7.5-watt lamps.

In a continuation of these studies in a larger stream (Fields *et al.*, 1958), it was determined that although bright lights had a repellent effect on juvenile salmon, they were ineffective in turbid water. These experimenters also noted a positive phototactic behavior previously observed by other experimenters. They observed that juvenile salmon are sometimes *attracted* by artificial light instead of repelled. It is not at all clear where repulsion ceases and attraction begins. The amount of light needed for attraction varies with the level of the surrounding illumination. A 7.5-watt bulb that attracted young salmon in the late evening was observed to repel them 30 minutes later at the onset of darkness.

It has been observed that fish moving downstream in bright sunlight seek cover along the shore or along shaded passageways. This reaction has been apparent in the forebays of dams and in experimental test areas and raceways. At night, the fish even seek the shadows cast by moonlight and artificial light under some conditions. Although it is unlikely that shade could be used to guide fish effectively in the deep turbid waters upstream from large dams, results of experiments at Cultus Lake (Andrew *et al.*, 1955) show that a shaded or protective passageway might be used as an aid in guiding fish during daylight hours at least. Brett and Alderdice (1958) recommended that by-passes should be covered and that this cover should be continuous with a similar cover along the deflector and the reservoir bank, providing a continuous, shaded passageway that would tend to lead the fish to a by-pass. The authors further suggested that low illumination under this cover would be beneficial at night.

On the basis of numerous experiments it seems very unlikely that artificial light would be effective as a primary means of guiding juvenile salmon in the forebay areas at dams. Varying turbidity of the water, the varying response of juvenile salmon to different light intensities, the questionable practical efficiency of artificial light at a guiding mechanism even in small-scale field experiments, and the fact that a significant proportion of juvenile salmon migrate downstream in large, fast rivers during the day are all major disadvantages that suggest that the use of artificial light as a guiding stimulus would not provide a solution to the problem of keeping downstream-migrant salmon away from hazardous areas at dams. However, there is every indication that these techniques would be of value in improving the efficiency of other, more positive guiding devices, if such could be developed. For instance, the tendency of juvenile salmon to be attracted to light has been used in experiments at Baker and Merwin Dams to increase the effectiveness of experimental fish by-passes in the forebays of these dams.

Rising Air Bubbles

Continuous streams of air bubbles emitted from closely spaced holes in a pipe have been used in attempts to deflect young downstream-migrant salmon. Brett and MacKinnon (1953) did not observe any significant deflection of chinook salmon underyearlings with a veil of air bubbles. In another experiment, Brett and Alderdice (1958) noted that sockeye yearlings avoided a veil of air bubbles across one half of a 10-ft. wide trough during daylight periods. The effectiveness decreased considerably at night. Andrew *et al.* (1955) reported the results of an experiment in which a veil of air bubbles was produced across one half of a 24-ft.-wide test area. Sockeye smolts were attracted to the veil of air bubbles during daylight but were repelled by it during darkness. The guiding effciency was increased during darkness when the wall of bubbles was illuminated by lights above the water surface. It appeared that during daylight the surface turbulence produced by rising bubbles afforded some protection for fish but that during darkness the surface turbulence and rising air bubbles repelled the fish. The myriad reflections from the moving bubbles and turbulent water surface may have repelled fish when the veil of bubbles was illuminated at night. Warner (1956) also investigated the efficiency of rising air bubbles as a method of deflecting young fish and found that a device, called an air-jet fish deflector, that made use of both rising air bubbles and noise was completely ineffective. Air discharging through orifices vibrated diaphragms over these orifices and produced a continuous loud noise.

The very low efficiencies and variable results obtained to date in experiments with air bubbles suggest that this method would not be of practical value in guiding downstream-migrant salmon at large dams.

Sound

Various investigations into the possible use of underwater sound as a method of guiding downstream-migrant salmon indicate that sound has no value as a guiding method. Burner and Moore (1953), using various frequencies and intensities of underwater vibrations in experiments with trout, noted initial fright reactions when the vibrations were first applied. However, fish soon became accustomed to the sound and no guiding was evident. Brett and Alderdice (1958) used a variable-frequency oscillator and a subsurface transducer in experiments with yearling sockeye salmon and found that the fish exhibited no response whatever to underwater vibrations from 1 to 10 kilocycles. Sounds of much lower pitch, produced by tapping an iron rod against the wooden bottom on the experimental area, resulted only in sudden darts by the fish. Moore and Newman (1956) concluded, on the basis of controlled laboratory experiments, that "sound waves were ineffective as an attracting or repelling force."

Odor

While many experiments have been conducted that demonstrate the sensitivity of salmon and trout to odors, no method has yet been developed that utilizes olfactory perception for guiding salmon away from hazardous areas at dams. Hasler (1954) stated: "In fishes, we are dealing with an acuity of olfaction which matches any attainment of terrestrial animals." Fish can be trained to associate odors with particular stimuli. Experiments have shown that salmon fry can discriminate between several different odors. Of many organic odors presented to untrained or "unconditioned" salmon, none were found that attracted them, many seemed not to be perceived, and the remainder were repellent. It has been shown that adult salmon are repelled for short periods of time by dilute aqueous extracts of mammalian skin but Brett and Alderdice (1958) found that neither this odor nor formalin had any appreciable effect as a deterrent or attractant for yearling sockeye salmon. In current research, attempts are being made to determine the age at which fish acquire sensitivity to odor, to determine the biochemical nature of olfactory tissue, and to use this information as a basis of predicting which odors fish might be trained to respond to. If young salmon could be conditioned to a particular odor during early stages of their fresh-water life and if they would retain this to the adult stage, the migration of adult salmon at dams might be expedited by introducing the odor into the passage facilities. In conjunction, a repellent odor might be used to deter adult salmon from expending unnecessary energy in fighting spillway and turbine discharges. These possibilities seem remote at this time, however. Similarly, in spite of their observed sensitivity to odor, there seems very little possibility that downstream-migrant salmon could be deflected away from hazardous areas at dams by the introduction of specific repellent odors into the water. The possibility of training large native populations of young salmon to be repelled by specific odors seems equally remote.

Dye

Brett and Alderdice *(ibid.)* used clouds of a dark blue dye (methylene blue) rising in bursts from the bottom of the test area in an effort to deflect sockeye smolts. Deflection away from the dye was observed during daylight but negligible guiding was obtained during darkness.

Visible Curtain of Vertical Elements

After observing that schools of downstream-migrant salmon did not readily converge to pass through a narrow vertical slot, Brett and Alderdice *(ibid.)* made significant progress towards a better understanding of the behavior of juvenile salmon by experimenting with the use of a curtain of closely spaced hanging chains or cables as a method of deflection. The first experiments, conducted in 1953, showed that sockeye smolts were deflected away from a curtain consisting of vertical strands of 3/16-in. brass "safety" chain suspended at up to 4-in. centers and extending from the water surface to the bottom of the test area. The effciency was lower at night than during the day. Subsequent experiments showed that the sight of the chain was the effective stimulus causing deflection and that the guiding efficiency could be improved by mechanically oscillating the chains. In discussing the results with this improved, mechanically oscillated barrier, the authors stated:

"Although these preliminary results were indicative of the potential possibilities in the method of deflection by vibrated chain, a number of inherent limitations characterized the unit. As the water velocity increased above 1.0 foot per second, its effectiveness was reduced. The constant 'pressure' of the water current caused the sockeye schools to move into direct contact with the chain and, despite being struck by moving links, they passed through the intervals between strands. The increased current also served to displace the free, bottom end of the chain at a progressively acute downstream angle, which further reduced deflection. Mechanically, it was not possible to fasten or weight the chain and still produce oscillations of large amplitude. At greater depths, these problems were likely to increase. Further application of this mechanical combination was not warranted.

"Two other major issues arose. Firstly, repeated experience along the deflector reduced its efficiency. Salmon often travelled laterally along the curtain but would not enter Pen 2 (the by-pass trap). This resulted in initial deflections which were climaxed not by capture in Pen 2, but instead by passage through the curtain as a consequence of persistent attempts to continue downstream. It was apparent that the lack of an attractive by-pass could have a very significant influence on the success of a deflector. Secondly, the influence of many other biotic factors brought repeated break-throughs when deflection seemed imminent. Voracious attacks of predators, casual passage of large fish, near-by spawning activities of suckers, and animated behaviour of fisherman or observer had adverse effects on successsful guiding. A deflection relation which was so sensitive to a wide variety of natural phenomena was not likely to stand the test of time. Unless modification could overcome this sensitivity then the present practices would prove fruitless."

In an effort to obviate some of the problems inherent in oscillation of the curtain barrier and to achieve more effective deflection, these workers experimented with a double curtain of ¼-in. cables hung vertically and traveling horizontally on an endless belt. The suspended cables moved continuously towards the by-pass in the upstream row and returned across the stream in the downstream row. The water depth was about 4 ft. Flood lights placed above the water surface at 6-ft. intervals illuminated all of the 58-ft.-long barrier in the clear, shallow water. The upstream face of each cable was painted white to increase light reflection. A maximum interval of 6 in. between cables and a minimum rate of horizontal travel of 8 in. per sec. were basic requirements for achieving deflection in excess of 75 per cent of sockeye salmon. Even in this relatively small test area, a significant proportion of the fish inevitably escaped through the barrier. The deflection of yearling coho was at a relatively low level compared with that for sockeye.

After three years of experimentation, an attempt was made in 1956 to combine a number of potential deflecting agents with the moving cable technique in a concerted effort to guide young salmon at the fry stage, to improve the deflection of coho yearlings and to check the deflection of sockeye smolts.

The experiments were conducted in a small creek about 50 ft. wide with a maximum depth of 3 or 4 ft. at the test site. The velocities ranged from 0 to 1 f.p.s. The deflector consisted of a double curtain of hanging cables. The cable size was reduced from ¼-in. to ⅛-in. galvanized wire rope and 2-oz. lead weights were added to the cable tips. Each cable was 43 in. long, sweeping the bottom. The two rows were spaced 3¼ in. apart. A continuous line of 60-watt lumiline bulbs shone directly onto the moving cables from above the water surface. To increase the effectiveness of the visual stimulus, a 3-ft.-wide flashboard was placed on the stream bottom below the cables. In a further attempt to increase the deflection efficiency, a direct-current electrical field was provided from the double row of hanging cables to a third row 12 in. downstream. The cables on this downstream row were stationary, 12 in. apart, and extended to within 2 in. of the bottom.

This deflection apparatus was completely ineffective as a method of guiding chum, pink and coho fry. Brett and Alderdice (1958) stated: "It appeared that the fry at this stage had a very fixed behavior pattern evolved to meet the problem of survival from predation. Their habit of emerging from the gravel soon after darkness overtakes the stream-bed, and of moving *en masse* rapidly and individually (not schooled) in a downstream pulse, was in contrast to the behavior responses among the older, larger sockeye and coho fingerlings. As a result none of the deflector features effective with yearlings proved to be of value for fry. The idea of scaling down the cable interval for smaller fish was consequently not appropriate. An entirely new approach would be necessary if the smaller fish were to be deflected.

"It is of importance to note the predation effect under the circumstances of increased vulnerability of fry, resulting from the use of light. A gradual accumulation of the two main predators, coho and sculpins, with an odd trout, began to occur soon after the fry migration commenced. Virtually none of these predators could be spotted during the day. However, once the deflector lights were turned on and fry began their nocturnal migration, a phalanx of competing coho formed an array above and below the cable area, with a large number of cautiously moving but quick-acting cottids at gravel level. . . . Although it is impossible to say how many of these fry would have been captured anyway, it is obvious that greatly increased vulnerability under illumination will result in an increase of predation. The fry are leaving the protective niche of the gravel-bed to face the fate of free-swimming life. The sudden illumination of the fish and the alarm responses to the deflector provide good reason to discard such approaches as potential means of guiding salmon fry."

It may be noted that increased predation resulting from the use of artificial illumination does not appear to have been given adequate consideration by proponents of the use of light alone as a guiding method.

The addition of an electrical field to the moving cable deflector increased the guiding efficiency by curtailing the tendency of fish to follow others through the deflector. Without the electrical field, "break-throughs were like a leak through a small hole in a dam which, if not plugged, grows to flood proportions." Addition of the electrical field frequently stopped minor break-throughs and curtailed the tendency to follow-the-leader through the barrier. In spite of the addition of the electrical field, the primary factor causing deflection of the yearling fish was the visual stimulus from the moving curtain. Approximately 95 per cent or more of the sockeye and coho yearlings were deflected with this small-scale barrier using an 8-in. spacing between cables and an 8 in. per sec. rate of travel.

Brett and Alderdice stated that the effectiveness of the technique of guiding yearling sockeye and coho with a moving curtain of vertical elements combined with an electrical field should be measured under conditions considered to be representative of the present or proposed power developments in British Columbia. They pointed out that this step is sufficiently large that no safe prognosis can be made as to the possible effectiveness of the method when appplied on a practical scale.

Electrical Screens

It is likely that more effort has been expended in attempts to use electricity to guide fish than in the development of any other possible means of guiding. Studies on the reaction of fish to electrical stimuli date back to at least 1863, when a patent was granted for a fishing device consisting of two parallel plates connected to a battery. Numerous experiments have been conducted in many countries in efforts to develop a method for using electricity to keep fish out of irrigation and power intakes and other hazardous areas. None of these attempts have proved particularly effective when tested on a practical scale.

The history of electric screens for downstream-migrant salmon and trout has been characterized by alternate periods of enthusiasm and disillusionment. The first patent for an electric screen in the United States was granted in 1917 and various private organizations have been active since that time in promoting the use of electricity for controlling the movements of fish. Demonstrations in laboratory tanks and in hatchery ponds have frequently been used to indicate "proof" of the effectiveness of electrical stimuli in controlling fish movement but practical applications have often been unsuccessful. In spite of large expenditures for research and development, and in spite of the fact that there are many reports of laboratory and small-scale field investigations of various types of electric screens, there are few reports describing the several practical-scale applications of electric screens that have been tried and subsequently rejected for one reason or another.

In early stages of the development of electric screens, attempts were made to use electricity as a method of *scaring* fish away from water diversions. Frequently, it was found that the intensity of stimulus required to repel fish was also sufficient to severely impair their swimming ability. Consequently, many fish were swept past the electric screen by the water velocity. Sometimes fish were immobilized by the electrical stimulus and if the water velocity was not high enough to sweep them past the electric screen they settled to the bottom in the electrified area and were killed.

Early experiments revealed that the voltage gradient required for eliciting a response was inversely related to fish length. That is, a voltage gradient that was high enough to scare small juvenile salmon and trout was too high for larger fish. Many of the larger fish were therefore killed. Whereas electric screens were installed in the 1920's in Washington, Oregon and California for preventing loss of seaward-migrant salmon at irrigation diversions, practically all of these were removed by about 1932 and replaced by mechanical screens. Some of these early electric screens were considered successful for a time, while others obviously failed to perform the function for which they were intended. During the early period in their history, electric fish screens fell into disrepute and were frequently labeled as destroyers rather than preservers of fish.

Experiments with electric screens have, however, been of some practical value because methods of using electricity as an aid in stream census work have been developed in recent years. Various types of electrical stimuli are used for catching fish in streams for obtaining samples of the resident population, for population estimates or for ridding streams of undesirable species. Portable generators are used to supply electric current to electrodes held in the stream. When the electrodes are energized with alternating current the fish are stunned or killed and can therefore be more easily captured. In recent years, direct current or interrupted direct current has been found to be more satisfactory in some respects because concealed fish are drawn from their hiding places towards the positive electrode and, in addition, they are not as severely injured with a direct current stimulus as with alternating current.

The most recent enthusiasm for electric screens in the United States and Canada developed after Groody *et al.* (1952) demonstrated that the Pacific sardine *(Sardinops caerulea)* could be led to the positive electrode in a trough containing sea water when unidirectional current pulses were used. When small animals are placed in a direct-current field they orient so that their heads face the anode or positive electrode. This reaction is terms "galvanotropism". A second reaction of actively swimming towards the anode is termed "galvanotaxis". Since 1930, various studies have been made to investigate the effectiveness of different electrical wave forms in producing galvanotaxis but, prior to 1952, little had been done to investigate the possibility that galvanotactic stimuli might be utilized in electric fish screens. Several investigations were initiated about this time to explore this possibility.

The use of electrical stimuli for attracting fish was investigated in connection with other studies related to the control of sea lamprey *(Petromyzon marinus)* populations in the Great Lakes. Mechanical weirs and traps had been tried as a method of blocking the upstream migrations of adult sea lampreys to spawning streams but the operation of these weirs was expensive and fraught with operating problems, especially during periods of flooding. In an effort to circumvent these difficulties, tests were performed to determine if the weirs could be replaced by alternating current electric fish screens. It was determined that "an effective and practical electro-mechanical sea lamprey weir and trap could be built and operated with greater efficiency and at appreciably less cost than the strictly mechanical type control devices" (Applegate *et al.,* 1952). However, food and game fishes were also blocked by the electric field. These fish were not "guided" along the fringe of the electrical field to a by-pass which was provided for their migration to spawning areas upstream. Using the findings of Groody *et al.* (1952) as a starting point, investigations proceeded in an effort to determine the most efficient electrical stimulus for producing galvanotaxis and to apply the findings so as to lead fish to by-passes at the alternating current sea lamprey fences.

Studies showed that the use of unidirectional current to attract or lead fish would not be entirely successful. The most satisfactory results were obtained with pulsated direct current of an essentially square wave shape at a duty cycle of 66 per cent and a frequency of three pulses per second. However, size selection alone restricted the usefulness of the leading device. For fish of a certain size, the desired galvanotactic response could be obtained only with voltage gradients that fell within a very narrow range. The determination of the actual limits of this range for each size class of trout was complicated by a large variability in response for test animals of similar length. A voltage gradient applied to stimulate the desired movement in large fish would not cause a similar movement in small fish. On the other hand, a voltage gradient that was sufficient to control small fish would narcotize, injure or even kill large fish in the electrical field. Some fish suffered a severe dislocation and separation of several vertebrae, others suffered severe internal hemorrhage and had a large quantity of blood present in the air bladder (McLain and Nielsen, 1953).

Another research program, initiated in 1952 as a result of the apparent lack of knowledge concerning the practical usefulness of the galvanotactic principle, was designed to investigate the feasibility of using electric screens energized with galvanotactic stimuli to guide sockeye smolts (Andrew *et al.,* 1955). Laboratory studies showed that sockeye smolts exhibit a galvanotactic response but attempts to attract these fish to a single positive electrode in a large creek were unsuccessful. When the voltage gradient was too low, the only response was an alarm reaction and when the gradient was too high the fish were quickly narcotized. Fish were immobilized and killed by the relatively high voltage gradients near the electrodes but they did not exhibit galvanotropism in the weak electrical field midway between the anode and cathode. Attraction of fish to a positive electrode, although possible in an insulated laboratory tank, could not be accomplished on a practical scale because the voltage gradient between the electrodes could not be made sufficiently uniform. It was concluded, therefore, that guiding downstream-migrant sockeye in major rivers by using galvanotropic stimuli to attract them over considerable distances would not be feasible.

However, to make the field more uniform and still take advantage of the galvanotropic response, an electric screen was devised consisting of two closely spaced rows of electrodes energized with unidirectional stimuli in such a manner that when fish migrated downstream past the upstream row of electrodes they would be attracted back upstream. A great number of combinations of electrode arrangements and electrical stimuli were tried and it was found that in small-scale field experiments the guiding efficiency approached perfection. One of the most efficient combinations consisted of ⅛-in.-diameter electrodes suspended vertically in two rows 24 in. apart with the electrode wires spaced at 12-in. centers in each row. Electrical stimuli that produced the greatest orientation to the positive electrode with the least impairment of swimming ability also produced the best guiding. Both direct current and interrupted direct current gave high guiding efficiencies.

In the largest experiments that were possible at this field test site, an electric screen was consructed across a 100-ft.-wide creek. The electrode rows were 4 ft. apart and 186 ft. long and extended across the stream at an angle of 45° to the general direction of stream flow. The water depth along the electrodes ranged from 1.9 to 3.6 ft. and the velocity averaged 0.35 f.p.s. with a maximum of 0.68 f.p.s. When these electrodes were energized with 60 volts direct current or 72 volts interrupted direct current at a duty cycle of 80 per cent and a pulse repetition rate of 4 cycles per second, over 95 per cent of the fish were guided to a trap that captured only 20 per cent of the fish when the electric screen was not operated.

On the basis of this significant success, the experiments were then extended to determine the effectiveness of an electric screen placed across the spillway and turbine intakes in the forebay of Baker Dam. The electric screen consisted of vertical electrodes in two parallel rows spaced 24 in. apart, extending from a point on one bank of the forebay to about the center of the dam, a distance of 252 ft. The electrodes extended to a depth of 50 ft. Many tests were conducted in efforts to utilize this electric screen to deflect fish away from the spillway and turbine intakes and to guide them to a surface by-pass at the dam. There was a slight but practically insignificant increase in the numbers of fish entering the by-pass when the electrodes were energized. The electric screen appeared to cause the fish to sound and enter the power intake, the top of which was submerged 85 ft. at minimum forebay level. During alternate power-on, power-off tests, it was observed that when the electrodes were energized there was a reduction in the proportion of fish passing over the surface spillway and a significant increase in the proportion passing through the tunnel. The number of fish entering the by-pass remained practically unchanged regardless of whether the electrodes were energized or not. Visual observations showed that fish that were stopped by the electric screen did not follow along the electrified area to enter the by-pass trap as they had done in the shallow water of the previous small-scale experiments.

This study revealed that the practical guiding effectiveness of artificial stimuli can not be determined solely on the basis of laboratory or small-scale field experiments. Many problems were encountered in the large-scale tests that could not have been anticipated on the basis of laboratory studies. Behavior differences were quite pronounced. In the small-scale experiments the fish followed along the upstream side of the electric screen to the by-pass trap but an entirely different reaction was observed in the large forebay of Baker Dam. Some fish retreated upstream after encountering the electric screen across their migration route and some sounded to great depths in the forebay. It seems possible that in the creek used for the preliminary tests the fish were accustomed to confinement and therefore were more easily guided into the by-pass.

It seems that electric screens, which introduce a stimulus that is entirely foreign in the natural environment of the fish, cause the fish to behave in an abnormal manner. Such behavior changes may adversely affect the survival of the fish. The alarm reaction that results from exposure to an electrical stimulus affects behavior in such a manner that fish are not readily led into a by-pass.

Extensive investigations of the possible value of electrical stimuli for guiding downstream-migrant salmon have been made by the United States Fish and Wildlife Service. This research program was initiated in 1952 with a study of the possible lethal effects of pulsated direct current (Collins *et al.*, 1954). Various experiments were also conducted in a 15- by 10-ft. section of a 30- by 24-ft. tank having a maximum water depth of 16 in. In these experiments, attempts have been made to evaluate different electrode arrangements and electrical stimuli that might be effective for use at large-scale installations. For instance, Trefethen (1955) described experiments in which the effectiveness of one type of narrow direct current field in diverting salmon fingerlings in flowing water was explored. The electrical conditions were held constant at a voltage gradient of 1 volt per centimeter, a frequency of 8 pulses per second and a pulse duration of 40 milliseconds, with a square wave form. It was determined that under the conditions of this experiment the maximum effectiveness occurred when the electric screen was placed at an angle of 40° to the direction of water flow, with a 24-in. spacing between the two electrode rows and with ½-in. electrodes spaced 12 in. apart in each row.

Raymond (1956) described experiments conducted in the same laboratory. He investigated a new principle in electrical guiding. Electrodes were placed at 30-in. centers in a single row. Only two of the five electrodes used in this electrode array were energized at any one time. The two electrodes farthest from the by-pass were energized first, then the next adjacent pair, and so on to the end of the array in a continuous sequence. Approximately 80 per cent of the test fish were guided into the desired zone when the most effective combinations of pulse frequencies and durations were used. Newman (1959) demonstrated that fish guiding was due to avoidance rather than galvanotaxis in a sequentially energized single-row electrode array similar to that described by Raymond. The relation of field polarity to fish guidance was tested under laboratory conditions by using a single-row electrode array sequentially energized so that: (1) positive polarity was always towards the upstream end of the row of electrodes, (2) positive polarity was always towards the downstream end, and (3) polarity alternated to cancel out polarity orientation. No difference in guiding effectiveness was noted.

Extensive tests are currently being conducted at small-scale field installations to evaluate these laboratory findings and to further explore the possibilities of various electrical guiding techniques. Even in small, slow-moving streams it has been found that a significant proportion of the fish are able to escape through electrical barriers. The possibility of using improved electrode arrangements in combination with artificial illumination is being explored. Through continued research, an economical method may be developed for preventing downstream-migrant salmon and trout from entering certain types of water diversions but optimism concerning possible effectiveness of such methods at proposed Fraser River dams is not warranted at the present time.

A serious disadvantage involved in the use of any artificial guiding stimulus is that downstream movement is impeded. It has been observed that the application of certain artificial stimuli causes fish to exhibit alarm. This apparent alarm results in a regrouping of fish schools, holding position in flowing water, sounding to greater depths in deep bodies of water, or retreating upstream. Some of these reactions were evident in the experiments described by Brett and Alderdice (1958), others have been described by Andrew *et al.* (1955). A most striking illustration of this problem was provided by the experiments in Hooknose Creek in which an attempt was made to guide salmon fry with illumination and a moving curtain of cables. Fry were not guided but held position in the stream above the deflector for some time. Sudden illumination and the consequent alarm response resulted in a greatly increased vulnerability to predation. At Baker Dam, sockeye and coho smolts not only sounded upon encountering the electric screen but also delayed in the forebay and retreated upstream.

Changes in behavior resulting from the application of artificial guiding stimuli produce serious problems that must be taken into account in any consideration of guiding techniques. Any delay in the seaward migration associated with the use of artificial guiding techniques may result in loss due to residualism. It has been pointed out that sockeye can remain in fresh water for one or more years past the normal migratory period. Loss of fish due to residualism might be as serious as the mortalities suffered by passage over spillways or through turbines. Further, increased predation may be expected as a result of residualism and congregation of downstream migrants above the guiding equipment. Because of this delay and residualism it is probably impossible to determine the true effciency of guiding methods and devices. In large-scale field experiments it is virtually impossible to accurately determine the number of actively migrating fish that attempt to pass through, around or under the guiding device. Further, alarm reactions and behavior changes are not conducive to efficient attraction to a by-pass. By-pass operation, which is discussed in a later section, is one of the most important aspects of the guiding problem. It is also important to note that behavior changes that cause delay will interfere with the operation of a guiding device and while the device might appear to be reasonably effective in diverting small numbers of fish it may fail when large numbers of fish are delayed upstream from it.

Possible Adverse Effects of Exposure to Electrical Stimuli

Even if electric screens were considered effective for guiding downstream-migrant salmon, their total effectiveness would remain in doubt until conclusive experiments had been performed to determine the effect of electrical stimuli on ultimate survival of the fish. Serious adverse effects of various types of electrical stimuli have been demonstrated by several experimenters. For instance, Hauck (1949) described injuries suffered by rainbow trout when a 60-cycle alternating-current fish shocker was used in an attempt to salvage these fish from an irrigation canal. A 500-watt generator was used, with the voltage adjusted to 80 to 90 volts so that it was just high enough to stun the fish momentarily. The reactions of rainbow trout to contact with the electrical field between the electrodes were varied. Increased respiratory action was evident in all fish. Paralysis of the swimming musculature was typical and ranged from complete paralysis to paralysis of the side nearer the electrode so that the fish swam in an arc around the source of current. Total paralysis caused the fish to float on their sides momentarily, after which they slowly sank to the bottom. Considerable mortality was noted among fish that were captured and held in ponds. Dissection revealed severe internal injuries, including fractured vertebrae, ruptured arteries and veins, hemorrhaging, death of tissues (a secondary effect), curvature of the spine, and extreme dilation of blood vessels in various parts of the body, including the brain.

Similar severe injuries among large fish have been reported by other experimenters (Holmes, 1948). Numerous experimenters have reported fingerlings being killed by electrical exposure but no conclusive evidence appears to be available as to the physiological causes of death. Collins *et al.* (1954) subjected groups of chinook salmon finderlings to pulsated direct current and concluded that the total voltage to which the fish were subjected (fish length x voltage gradient) was the effective factor in mortality. The rate of mortality increased with fish length, voltage gradient, and pulse frequency. The mortality also increased with the duration of exposure and increasing water temperature.

Verhoeven *et al.* (1957), in studying the effects of electric shock on juvenile salmon, concluded that the fish were not injured and their rate of mortality was not increased unless the shocks were so severe that the fish failed to resume breathing almost immediately after the current was turned off and also failed to regain equilibrium within about 20 minutes.

Aserinsky *et al.* (1954) exposed coho fingerlings to electrical stimuli for one minute to investigate factors in pulsated direct current that cause galvanotaxis and side effects in young salmon. Twenty combinations of voltage gradient, pulse frequency and pulse duration were studied. The experiments indicated that orientation to a positive electrode and loss of equilibrium were both dependent on the direct current component of the stimulus. Increasing the pulse frequency increased inhibitation of respiration. The authors observed that the onset of orientation preceded the onset of loss of equilibrium but the difference in voltage gradient between the onset of the two reactions, particularly when fish length was taken into consideration, provided very little factor of safety.

Aserinsky (1954) showed that exposure to electrical stimuli temporarily reduced the ability of coho fingerlings to adapt to a sodium chloride solution. He considered that electroshock may be a profoundly serious threat to the survival of aquatic organisms. The latter are continually dependent for survival on their ability to prevent hydration while in fresh water or dehydration while in sea water. Consequently, any disturbance of osmoregulation could lead to radical changes in body chemistry and possible death. Whereas electricity may cause the greatest harm to terrestrial organisms during the period of actual shocking, the damaging effects to fish may occur after electroshock if the fish have thereby become more permeable to an ever-threatening environment. Aserinsky cited evidence that the mineral content of fish was altered following electrical exposure. In addition to noting the adverse effect of reduced osmoregulatory capacity, he postulated that electroshock could interfere with the fishes migratory behavior by changing the internal ionic concentrations, which may be closely related to migration.

Nakatani (1955) showed that exposure to direct current, either pulsated or continuous, increased the inorganic phosphate content of the blood of young coho salmon by about 20 per cent. This increase was thought to be due to vigorous muscular activity and inhibition of respiration rather than to purely electrical events. Electroshock also caused a significant reduction in the volume of blood fluids, as measured by hematocrit values.

While these physiological consequences of electroshock appear to indicate that electrical stimuli cannot be used without adverse effect, changes may also occur with respect to sensory perception and behavior that could affect the survival of downstream-migrant salmon. Fields *et al.* (1954) showed that young coho and sockeye salmon exhibit a significantly reduced avoidance to light after being exposed to electric shock. The light avoiding behavior of all shocked fish was altered immediately after shocking but only the largest fish exposed to the heaviest shock were significantly affected 24 hours later. During the period from 1 to 60 days postshock there was no decreased efficiency in the avoiding response to light that could be attributed to the electric shock. It is entirely possible, however, that the observed changes in sensory perception could make juvenile salmon temporarily more susceptible to predation.

In conjunction with the Salmon Commission's studies at Cultus Lake, an experiment was conducted to measure the effect of electrical exposure on ultimate survival of downstream-migrant sockeye. This test was not conclusive, however, because the fish were exposed under controlled conditions and had to be handled rather severely. In this test, sockeye smolts that had migrated out of Cultus Lake were captured in the outlet stream, exposed to pulsated direct current, marked by fin clipping, and released into the stream with an appropriate control group. The fish were subjected to two 30-second electric shocks separated by a 30-second rest period. The stimulus was interrupted direct current at a nominal voltage gradient of 1.5 volts per inch, 4 pulses per second, with an 80 per cent duty cycle. The effect of this shock on growth, survival and reproductive ability was determined by recovery of the surviving adults in the Fraser River commercial fishery and at a weir at the outlet of Cultus Lake. Out of a total of 111,264 fish marked, the mortalities prior to release were 1.38 per cent for the exposed group and 0.88 per cent for the control group. From an adult recovery of 544 of the exposed and control fish, it was concluded that the electrical exposure had little or no effect on subsequent growth or survival. Eggs from the fish that had been subjected to electroshock appeared to be as viable as eggs from the unshocked fish.

Experiments conducted to date have not revealed adverse effects of electroshock that would preclude the use of electrical techniques for guiding downstream-migrant salmon. However, these experiments have been conducted under controlled conditions. Since studies have revealed behavior changes and latent effects that could affect survival of the fish, more experiments are required before electrical stimuli can be safely used for guiding major populations of downstream-migrant salmon.

MECHANICAL FISH SCREENS

Mechanical barriers, in the form of fixed or moving grillages or wire screens, have been used for many years with varying success to keep young salmon and trout out of small diversion flows for power, irrigation and water supply projects. The success of such screens depends on the type of screen employed, the water velocities, the location of the screen with respect to the ability of the fish to escape from it, the size of stream, area to be screened, and the size and location of adequate by-passes. There are several problems involved in the use of screen barriers, of which high initial and operating costs, plastering of fish on the screen, and carry-over of fish appear to be the most important. Where the approach velocities are low enough and the screens are protected from clogging, either fixed or traveling belt screens can be employed with some degree of success. However, because of the fine-mesh screen necessary to exclude salmon fry and the problems of keeping the screens clean, as well as the cost of providing the required screen area and alignment to satisfy the velocity criterion, such screens have not been used as a means of guiding migrants in the forebays of large dams. Descriptions of the different types of mechanical fish screens and their applications and limitations are given by Lindgren and Spencer (1939) and Leitritz (1952).

The earliest type of fish screen was installed on small irrigation ditches and consisted of a vertical sheet of wire screen with no provision for cleaning of debris. These screens proved unsuccessful as they soon clogged with leaves and other debris. More recently, automatic cleaning methods have been used in conjunction with fixed screens. In commercial models, a rake on an endless belt brings debris to a surface flushing trough. This arrangement is satisfactory for removing large debris but the fine-mesh screen required for stopping salmon fry and yearlings can still become clogged with twigs, leaves, moss and algae. Further, holes can develop in the screen below the water surface and may not be detected for long periods of time.

A novel application of fixed vertical screens was employed for diverting downstream-migrant salmon at a hydroelectric installation on the Nisqually River in Washington. It was found that a significant economy could be effected with the use of plane vertical screens rather than a commercial moving belt screen. An attempt was made to overcome the cleaning and inspection problems by periodically lifting the screens vertically above the water surface where they could be inspected and automatically cleaned with high-pressure jets of water. The plant discharge of 1000 c.f.s. passes through a screened intake structure consisting of eight bays, each 13.5 ft. deep by 12.25 ft. wide. The debris problem and the problem of fish being plastered on the screen were minimized by placing the screens in a line at an angle of 55° to the direction of water flow so that the debris and fish would tend to be swept along the screens by the water flow. Each screen bay is provided with two panels that slide into slots in the piers between bays. To clean one screen, the alternate panel is set in position and the other panel lifted out. A serious operating problem was encountered when the screens and guides froze during the winter operating periods. As far as is known, however, downstream-migrant salmon move along the screen without delay and continue their migration down the Nisqually River. However, the problems encountered in screening this shallow and relatively small water diversion cannot be considered typical of the screening problems that would be created if major dams were constructed on the Fraser River.

Another early type of stationary fish screen was the "bar" type, consisting of a rack of sloping bars spaced close enough to prevent passage of fish. This screen had the advantage that it could be cleaned manually more readily than the stationary wire screen. However, it was found that the bars obstructed a large proportion of the stream flow and also that fish could escape through the long vertical openings between the bars more readily than through wire screen openings. On some of the early bar screen installations an automatic cleaning mechanism was employed, consisting of a horizontal bar or rake carried up the upstream face of the sloping rack and down the downstream face. The rake was carried on an endless chain driven by a paddle wheel. After several years of operation, this type of screen was discarded because it was found that many fish escaped between the bars and through the seal at the bottom where the cleaning rake passed under the screen.

The most common type of fish screen in operation today consists of a rotating cylinder (or "drum") of wire screen set across the channel so that the axis of the cylinder is horizontal and perpendicular to the direction of water flow. This screen, when properly designed, operates efficiently for small diversions. Small floating debris is carried by the rotating drum and deposited into the canal downstream from the screen. Unfortunately, however, small fish can also be carried over the screen. For small irrigation ditches, screens of this type have been built as small as 2 ft. in diameter and 3 ft. long, to strain 1 c.f.s. or less. For larger diversions, several large-diameter drums are used, such as on the White River in Washington where eight screens are provided, each 14 ft. in diameter by 12 ft. long.

A limitation of this type of screen is that it cannot be used to screen deep intakes. It has been found that fish frequently escape at the bottom or sides of the drum where a seal is provided to make contact between the rotating drum and the canal. Fish may also escape when heavy debris dents the wire screen, thus leaving a gap between the bottom seal and the rotating drum. The previously mentioned problem of carry-over of fish on drum screens is particularly serious when the water velocity is too high, when the water rises too close to the top of the drum or when the by-pass is not adequate to quickly attract fish away from the screening area.

Moving belt screens have been used as fish screens in recent years. They were developed for water supply intakes and standard designs are manufactured commercially. They consist of an endless belt of wire screen panels that are carried vertically upward on the upstream side and down again on the downstream side. Debris is usually washed off the screen above the water surface with high-pressure water jets. The high initial cost, the problem of fish plastering on the screen, the carry-over of fish, and the possible loss of fish through the seals at the sides and bottom are the main disadvantages of moving belt screens.

Fisheries agencies have experimented with many different designs of mechanical fish screens. A recent innovation consisted of a sheet of perforated plate sloped at an angle of about 30° to the bottom of the channel. This screen was cleaned by a wiper blade that pulled debris upward and over the top of the screen (Wales *et al.*, 1950). This "perforated plate screen" was considered for some time to be an improvement over drum screens but it is not used at the present time because the cleaning device did not prove satisfactory. New designs are continually being evolved and tested in efforts to develop more satisfactory and economical methods of screening water diversions.

Apart from mechanical design and operational aspects, the velocity criterion is one of the most important considerations in the design of fish screens. The approach velocity must be low enough to permit fish to maintain a position upstream from the screened area and to swim across the screen to reach a by-pass channel. Fish may be injured by coming in contact with the wire screen even though the water velocity is substantially lower than the maximum swimming speed of the fish. Seaward-migrant fingerlings appear to be passively carried downstream by the water velocity during darkness. Since they do not exhibit strong swimming tendencies at this time, they frequently come in contact with the wire screens at water diversions and are sometimes carried over the top of rotating screens. It is therefore necessary to limit the maximum velocity of approach at mechanical fish screens to a fraction of the maximum swimming speed. Experience has indicated that for screens that are automatically cleaned the maximum velocity of approach should not exceed 1.5 f.p.s. and that sufficient screen area should be provided so that under usual conditions the average velocity of approach will not exceed 1.0 f.p.s. This requirement is specified for screens designed to deflect yearling salmon. For newly emerged fry, approach velocities as low as 0.1 f.p.s. have sometimes been required but an allowable average velocity of 0.4 f.p.s. is probably satisfactory for properly cleaned mechanical screens.

Some indication of the swimming speeds of young salmon has been obtained in various studies. Experiments conducted at Baker Dam in 1950 (Hamilton and Andrew, 1954) showed that yearling sockeye and coho salmon could not swim against a velocity of 4.5 f.p.s., could maintain their position for short periods of time in velocities of 2.3 f.p.s., and could easily swim upstream in velocities of 1.4 f.p.s. These fish ranged from about 3 to 5 in. in length. Laboratory studies of the swimming ability of fingerlings were made when it was found that many young fish were being killed by mechanical screens at a cooling water intake (Kerr, 1953). In a velocity of 1 f.p.s., approximately 10 per cent of chinook salmon fingerlings ranging in length from 1.25 to 1.89 in. were plastered on a screen after a 10-minute period. In a velocity of 1.5 f.p.s. approximately 85 per cent of the fish were plastered in the same period of time. The following are some of the conclusions drawn by this author: "The swimming ability of juvenile striped bass and king salmon increases with size. For example, bass one inch long can stem a current of about one foot per second for 10 minutes; while bass four inches long can stem about two feet per second for ten minutes. However, fish of one age group will vary an inch or more in length and in many instances the smaller fish of one age group were still swimming when the larger fish were impinged on the screen. Little difference was observed between the swimming ability of comparable yearling salmon and bass, which varied from 1 ft./sec. for the fish approximately 1 inch long to over 2.75 ft./sec. for bass in the 5 to 7 inch group. . . . . A maximum average design approach velocity of 1.5 ft./sec. seems reasonable when all factors are considered."

In view of the fact that a large proportion of the fish were only 1.0 in. long and that about 85 per cent of these were impinged on the screen after an exposure of only 10 minutes, it appears difficult to justify the choice of 1.5 f.p.s. as a design velocity. However, many complicating factors had to be taken into consideration at this particular installation.

It has previously been pointed out that the ability of fish to perform is related to water temperature. Brett *et al.* (1958) have shown that the maximum sustained swimming speeds occur at 15°C (59°F) for yearling sockeye and 20°C (68°F) for coho (FIGURE 10). The cruising speed was defined as: "the swimming speed which a fish can maintain consistenly for a minimum period of one hour under strong stimulus without gross variation in performance." After acclimation to the optimum temperature of 59°F, the following cruising speeds were attained by sockeye: 1.07 f.p.s. for a mean length of 7.10 cm. and 1.52 f.p.s. for a mean length of 13.92 cm. Coho acclimated to 68°F attained approximately the same speeds: 1.00 f.p.s. for a mean length of 5.60 cm. and 1.35 f.p.s. for a mean length of 9.04 cm. The cruising speeds for sockeye increased approximately 0.07 f.p.s. for

1 cm. increase in fish length and for coho the increase was 0.09 f.p.s. At temperatures other than the optimum, there was a marked reduction in cruising speed for both sockeye and coho. For instance, at 43°F, which is close to the minimum temperature encountered during the seaward migration, the cruising speed of underyearling sockeye was reduced to 73 per cent of that attained at the optimum performance temperature.

These workers concluded: ". . . . it is apparent that if approach velocities above dams exceed 1.0 ft. per sec. (30 cm./sec.) a real problem for safeguarding under-yearlings is presented. Their capacity to stem such a current for more than an hour is limited to a relatively small temperature range, 12.5 - 17.5°C. for sockeye, and 18.5 - 21.5°C. for coho . . . Approach velocities above dams which exceed 1.0 ft. per sec. will cause increased difficulty in guiding young salmon into safe by-passes if more than 20 to 30 minutes elapse during which the fish are forced to stem the current. Fatigue from exceeding the cruising speed is likely to occur."

In view of this information it is not surprising that many seaward migrants are carried over rotary drum screens. The sustained swimming ability of juvenile salmon appears to have been over-estimated in many instances. Not only have screens been installed in velocities higher than the cruising speed of the fish they were designed to protect, but also the by-pass facilities have frequently been so inadequate that it would not be unreasonable to expect that several hours might elapse before fish entered them.

Chapman (1935) showed that small salmon and trout are frequently plastered upon and carried over rotary drum screens and that this carry-over is related to fish size, water velocity, screen mesh size, and adequacy of the by-pass. It was found that chum and coho salmon and steelhead trout will escape through a revolving screen that is covered with screening having a mesh opening equal to or greater than the width of the fish at the posterior head region and the depth of the fish at the insertion of the pectoral fins. In these tests, chum and steelhead fingerlings having a length of 1.75 in. (4.4 cm.) and under were not carried over the top of a revolving screen when the approach velocity was less than 0.4 f.p.s., but at velocities of 0.8 f.p.s. the percentage carry-over was very high. For fish 2.0 in. (5.1 cm.) long, a velocity of 1.2 f.p.s. was considered satisfactory. For chum salmon 1.3 to 1.56 in. (3.3 to 3.96 cm.) long, Chapman reported the following data on approach velocity and the percentage of fish carried over a revolving drum screen:

Water Velocity (f.p.s.)	Percentage of Fish Carried Over	No. of Fish in Test	No. of Tests	Duration of Tests (hours)
0.40	4	100	15	71
0.59	70.5	51	1	1
1.10	84	50	1	0.5

He also reported that coho 5 cm. long and greater were able to maintain their position in a velocity of 1.18 f.p.s.

Sockeye fry migrating up Chilko River to reach Chilko Lake have been observed to progress upstream at an average rate of 0.26 f.p.s. against an average shoreline velocity of about 0.54 f.p.s., which suggests that their maximum sustained swimming speed is about 0.80 f.p.s. For a distance of 1.0 ft., the maximum swimming speed was estimated to be 1.4 f.p.s. For a distance of 4 ft., in velocities ranging from 0 to 0.85 f.p.s., these fish moved upstream at a rate of 0.13 to 0.39 f.p.s. From these tests, the maximum swimming speed over a 4-ft. distance was found to be 0.98 f.p.s. These fish were approximately 2.8 cm. in length. It may be concluded that their sustained cruising speed would be about 0.8 f.p.s. and that they could escape from localized velocities up to 1.4 f.p.s., such as might occur immediately upstream from a screened opening, provided adequate resting areas were immediately available.

Experiments conducted by the Canada Department of Fisheries at small fish screens on the Nicola River indicate that chinook, coho and steelhead fry are able to avoid the screens when the approach velocity is 0.4 f.p.s. or less. Nearly all are killed on the screens when the approach velocity reaches 1.0 f.p.s.

In considering the feasibility of mechanical screens for protecting downstream-migrant salmon at possible dams on the Fraser River, the velocity requirement is of prime importance. On the basis of the previously mentioned experiments, it may be concluded that the maximum approach velocities upstream from mechanical screens should be limited to 0.40 f.p.s. for fry and 1.0 f.p.s. for yearlings. Therefore, the forebay velocities at proposed dams on the Thompson River below Kamloops Lake and on the Fraser River below Seton Creek would have to be limited to less than 0.40 f.p.s. for protection of seaward-migrant pink salmon fry. Sockeye yearlings would require velocities of less than 1.0 f.p.s. for their protection on the main stem of the Fraser River and on those tributaries that drain sockeye-rearing lakes.

Quite apart from the cost and physical problems involved in construction and maintenance of mechanical screens in the forebays of proposed Fraser River dams, the anticipated high approach velocities at these dams would likely preclude the use of mechanical screens. The very restricted cross-sectional area available at the various dam sites would mean high forebay velocities, which have been calculated to be 30 times greater than the allowable maximum for mechanical screens intended to protect pink salmon fry. There is the possibility that the allowable velocity for mechanical screens could be increased if the screens were set at an angle to the direction of stream flow so as to direct the fish more quickly to adequate by-passes. It is quite unlikely, however, that mechanical fish screens could provide a practical method for preventing pink salmon fry and sockeye smolts from entering the spillways and turbines of the large dams that have been proposed for construction on the Fraser and Thompson Rivers.

FLOATING SCREEN BARRIERS

An experiment was conducted in 1956 at Baker Dam in the State of Washington to compare the efficiency of an electric screen with that of a webbing barrier for deflecting downstream-migrant salmon away from the spillway and turbine outlets of this dam (Andrew *et al.*, 1956a). The webbing barrier, like the electric screen, was suspended from floats. However, the webbing barrier, which was 240 ft. long, extended to a depth of only 15 ft. whereas the electric screen extended to 50 ft. Both were installed in the same location in the forebay, where the average velocity during comparable tests was only 0.15 f.p.s. A by-pass trap was located at the dam at the downstream end of the deflectors.

It was known from previous experiments (Rees, 1957) that the majority of sockeye and coho yearlings migrated downstream in the top 15 ft. of the reservoir. It was estimated that 82 per cent of the sockeye and 90 per cent of the coho migrated downstream in the top 15 ft. of the forebay of Baker Dam. Very few yearlings were normally present at depths greater than 30 ft. However, a large proportion of the fish were deflected downward by the electric screen and eventually entered the turbine intake, the top of which was 85 ft. below the surface of the reservoir. Consequently, the proportion of the run that entered the by-pass during periods of operation of the electric screen was only slightly higher than the proportion that entered when the electric screen was not operated. However, during the preliminary experiments of 1956, when the 15-ft.-deep webbing barrier was installed, the proportion of the coho run that entered the by-pass increased from 19 per cent to 68 per cent. Further, the proportion entering the deeply submerged tunnel to the powerhouse did not increase when the webbing barrier was installed.

This comparison clearly demonstrated the superiority of a physical barrier over the type of electric screen that was used in this instance. Presumably the webbing barrier provided a fixed, physical lead that guided fish much more effectively than did the electrical barrier.

This experiment was continued in 1957 to obtain more extensive information on the reaction of sockeye yearlings and to test the effect of a deeper barrier. A floating webbing barrier 400 ft. long and 30 ft. deep was installed in the forebay of Baker Dam in an attempt to prevent sockeye, coho and chinook salmon seaward migrants from passing over the spillway and through the turbines and to direct them to a surface by-pass or "skimmer" trap at the dam. Although the by-pass used in this experiment appeared to be considerably more effective than others used in several previous experiments at this location, fish were observed to congregate and apparently delay in the forebay upstream from the barrier. Some fish sounded under the barrier and passed over the spillway or through the tunnel. While it was not possible to determine the proportion of the run that remained in the reservoir and was lost as a result of predation and residualism, over 90 per cent of the coho yearlings that migrated past the dam were deflected into the surface by-pass by means of the webbing barrier in some of the tests. This deflection system, however, was almost completely ineffective for protecting sockeye yearlings.

An important difference in the behavior of sockeye and coho migrants was observed. In all the tests, the success of guiding sockeye was considerably less than for coho. The guiding and trapping efficiency for sockeye increased when the population in the forebay consisted largely of coho. Sockeye showed a greater tendency to sound under the barrier than did coho and they also appeared more reluctant to enter the by-pass. In tests at Mud Mountain Dam on the White River in Washington, chinook salmon fingerlings were noted to be more reluctant to sound than coho yearlings (Regenthal and Rees, 1957). These observations of behavior differences are significant as they emphasize that experimental results require careful and cautious interpretation. Results obtained with one species or race of salmon do not necessarily apply for all species and races.

A 120-ft-deep, floating steel- and plastic-mesh barrier has been constructed across a 2800-ft. width of the Snake River upstream from the 395-ft.-high Brownlee Dam to deflect downstream-migrant salmon and steelhead into three floating traps (Engineering News-Record, 1958). The barrier is constructed in three layers. A plastic mesh with ⅛-in. openings is backed by a wire screen with 6-in. square openings, which in turn is backed by steel cables spaced 20 ft. apart. The net is anchored only at the banks and is suspended from floating pontoons. It is intended that the fish will enter three skimmer traps at the water surface, be sorted according to three sizes to reduce predation, and then pumped through a rubber pipeline to tank trucks that will haul the fish 15 miles downstream.

The physical problems involved in this scheme are so great that is it not likely to come into general use as a screening method. The efficiency of the fish-collecting system at Brownlee Dam has not yet been accurately determined but the number of fish captured in the by-pass traps in 1959 was much lower than anticipated. Inspections made by the fisheries agencies have revealed that it will be difficult if not impossible to keep the screen operative. Divers have found holes in the plastic mesh through which many fish could escape. The physical problems of keeping the barrier fish tight, free of debris, and completely functional have apparently not been overcome.

Apart from the physical problems, there are also many biological problems involved. For instance, when the ⅛-in. plastic meshes become partially or fully obstructed with algae and suspended materials, the flow will largely be diverted under the net. The effect of such a flow change on the behavior of the fish cannot be predicted on the basis of available information. It has been reported, however, that chinook and coho fingerlings have sounded to at least 160 ft. to migrate from the reservoir above Mud Mountain Dam (Regenthal and Rees, 1957). This and other problems require extensive investigation.

LOUVER BARRIERS

A new concept in the deflection of downstream migrants was developed in connection with the diversion of up to 5000 c.f.s. from the Sacramento-San Joaquin Delta near Tracy, California (Bates and Vinsonhaler, 1957). In an attempt to find a satisfactory method of preventing the loss of young fish, primarily chinook salmon, striped bass, American shad, and white catfish *(Ictalurus catus)*, several possibilities were investigated. On the basis of information available from previous studies, the possibility of screening with sound waves, electricity, or air bubbles was rejected. Revolving drum screens were considered unsatisfactory because of cost, the depth required and the fluctuation in water level. A multiple eddy trap and a system involving a vertical screen and a curtain wall similar to that at the Contra Costa steam plan (Kerr, 1953) were also rejected. Belt-type traveling screens were originally considered to be the only screens that offered any possibility of functioning in the Tracy intake canal. However, because they had never been used in a similar situation and because they were costly, both initially (estimated at $4,500,000) and in operation and maintenance, there was some reluctance to invest in them. It was therefore decided to try traveling screens and other types of screens and also to explore new possibilities at a pilot structure.

A perforated plate screen tested at this pilot installation was unsatisfactory as it clogged in a short time. The reciprocating wiper blades moving over the upstream side of this sloping screen were not adequate for removing debris. Fine debris such as moss was squeezed by the wiper blades into the perforations. These and other stationary panel screens were very difficult to clean and they were therefore replaced by self-cleaning moving belt screens.

The by-pass system used in conjunction with the moving belt screens was entirely inadequate. It consisted of a number of small ports located along the upstream face of the screens with pipes leading from these to pumps. Few fish entered these ports in relation to the number that were plastered on the screens. Alterations weer therefore made in the traveling screens so that fish that became plastered on them could be collected. While a large number of fish was collected in this manner, the mortality rate, particularly among the shad, was very high.

In conjunction with these tests at the prototype installation, an investigation was conducted to study the efficiency of louvers in diverting fish. It soon became apparent that louvers and similar devices offered promise for guiding fish out of a channel and into the safety of a by-pass without delaying their downstream migration and with a minimum of exhaustion or shock from physical contact with a screen. Consequently, this screening technique was adopted.

The louver system, as illustrated in FIGURE 28, consists of a fence-like series of vertical steel slats. As detailed in FIGURE 29, each louver slat is set at right angles to the direction of stream flow. The louver array is placed diagonally across the stream so that the fish tend to be swept along the array to a narrow by-pass slot at the downstream end. It was found particularly important that the pattern of flow toward the louvers be uniform and as free of turbulence as possible. This was considered essential to allow fish to maintain their orientation with respect to the direction of flow as they approach the louver array. Unless flow straightening vanes are used, the flow on the downstream side of the louvers is initially directed at right angles to the direction of flow in the channel. This direction change is objectionable in that it causes non-uniform velocities.

The investigators found that a by-pass slot width of 2.5 in. was satisfactory; young salmon and striped bass exhibited no apparent hesitation in passing through this narrow slot. However, trout appeared to be more reluctant to enter this narrow opening and the investigators felt that by-pass slot widths up to 18 in. might be necessary for these fish. A width of 6 in. was selected for the final installation at Tracy. A gradual acceleration of the flow at the by-pass entrance was found desirable to reduce delay or accumulation of fish upstream from the by-pass.

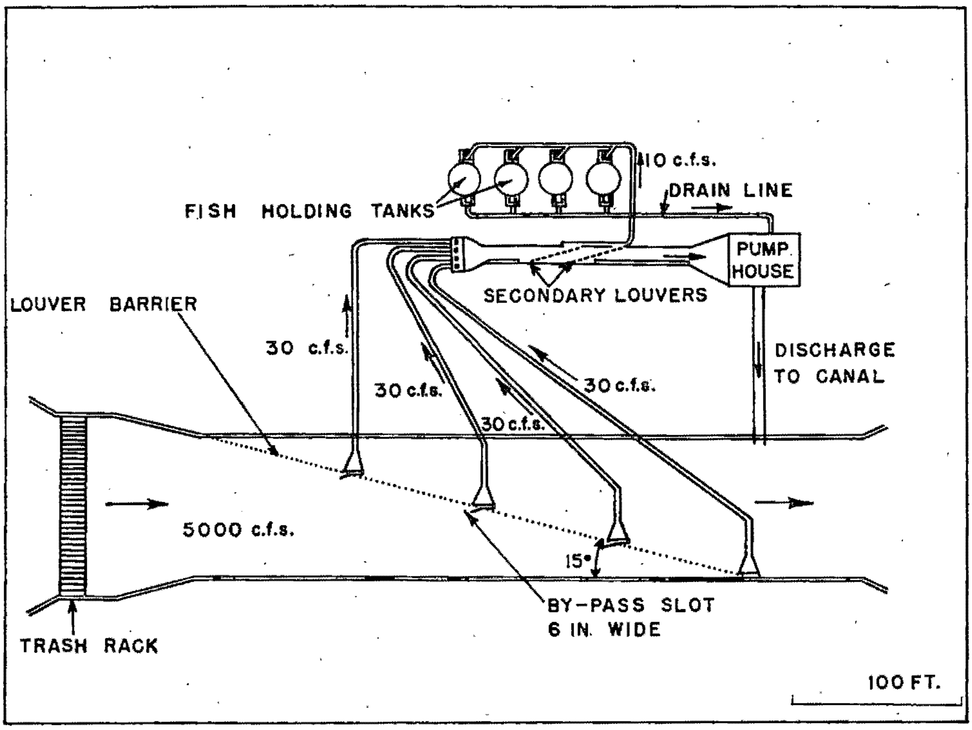


FIGURE 28—Louver barrier at the Tracy pumping plant. (From Anon., 1957.)

The prototype louver facility at Tracy consists of a barrier 320 ft. long and 25 ft. deep made of vertical louver slats 2 in. wide by 3/16 in. thick spaced at 1-in. centres. Spacings of 2 in. or more were considered equally effective in preliminary testing but since the prototype installation was unique, the more conservative spacing was used. At the maximum design velocity of 4 f.p.s., the head loss across the structure is approximately 0.4 ft. Four by-passes are provided, spaced about 75 ft. apart along the louver array. Each is 6 in. wide and extends from the bottom to the water surface. A maximum flow of 120 c.f.s. can be diverted through the by-passes. In conjunction with the primary louver structure, there are two more sets of louvers for further concentrating the by-passed fish before they are placed in holding tanks to await truck transport to an area away from the influence of the canal intake. The total cost of these fish-protective facilities was about $2,000,000.

Debris is one of the most serious problems involved in the operation of louver barriers. At Tracy, most of the debris is intercepted at a trash rack immediately upstream from the louvers. The openings between the rack bars are 2⅛ in. Small debris collecting on the rack is removed by a mechanical rake and large debris is hauled by means of a cableway to the end of the trash rack where a ramp is provided for its removal. The louver array is divided into panels and a gantry crane is provided on the louver structure to lift the panels out of the water so that fine debris can be washed off with water from a high-pressure

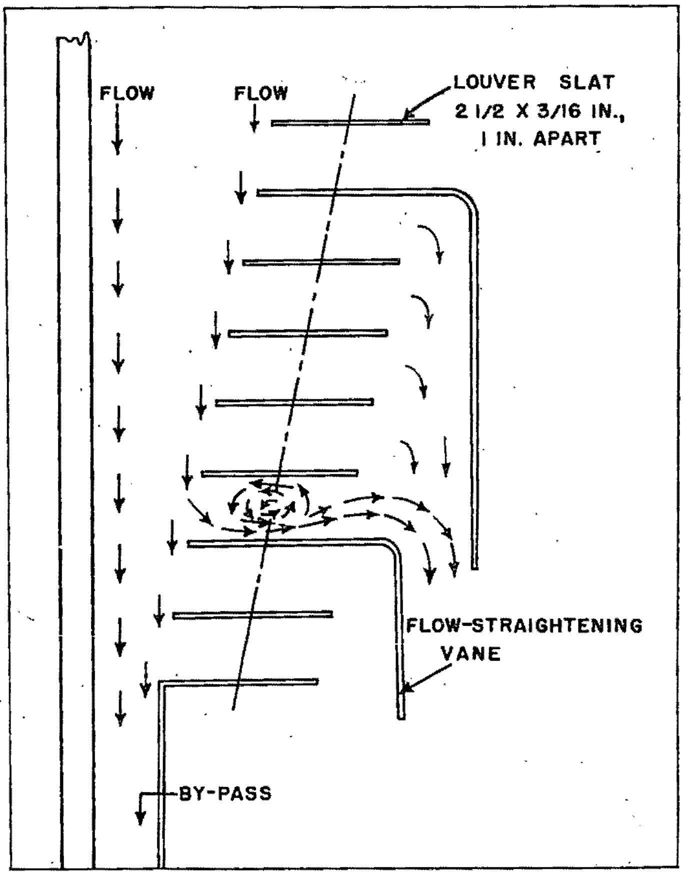


FIGURE 29—Detail of louver slats used at the Tracy pumping plant. (From Anon., 1957.)

hose. The debris encountered at this installation consists mainly of logs, branches and pond weeds. Leaves are seldom found on the structure, a situation not encountered at most diversions.

The operation of a recently constructed louver installation on the Rogue River in Oregon appears to be seriously affected by debris, which in this case consists largely of leaves. Cleaning the debris off the louvers is a major operation because it must be done by hand raking. A photograph and a layout drawing of the installation are shown in FIGURE 30. This installation was constructed at a powerhouse intake to prevent the loss of steelhead fingerlings. It is located in a canal about 85 ft. wide by 12 ft. deep discharging up to 3600 c.f.s. The louvers are vertical steel bars 9 ft. long, 5/16 in. by 2½ in. in cross section, with the flat face of the bars perpendicular to the stream flow. The clear space between adjacent bars is 2 in. The louver panels are arranged in the form of three "V's", with an 18-in.-wide by-pass at the apex at the downstream end of each "V".

Experiments at Tracy indicated that it was necessary to have the by-pass approach velocities slightly higher than the velocities upstream from the louvers. However, this requirement is not fulfilled at the Rogue River structure. Many fish apparently escape through this louver barrier.

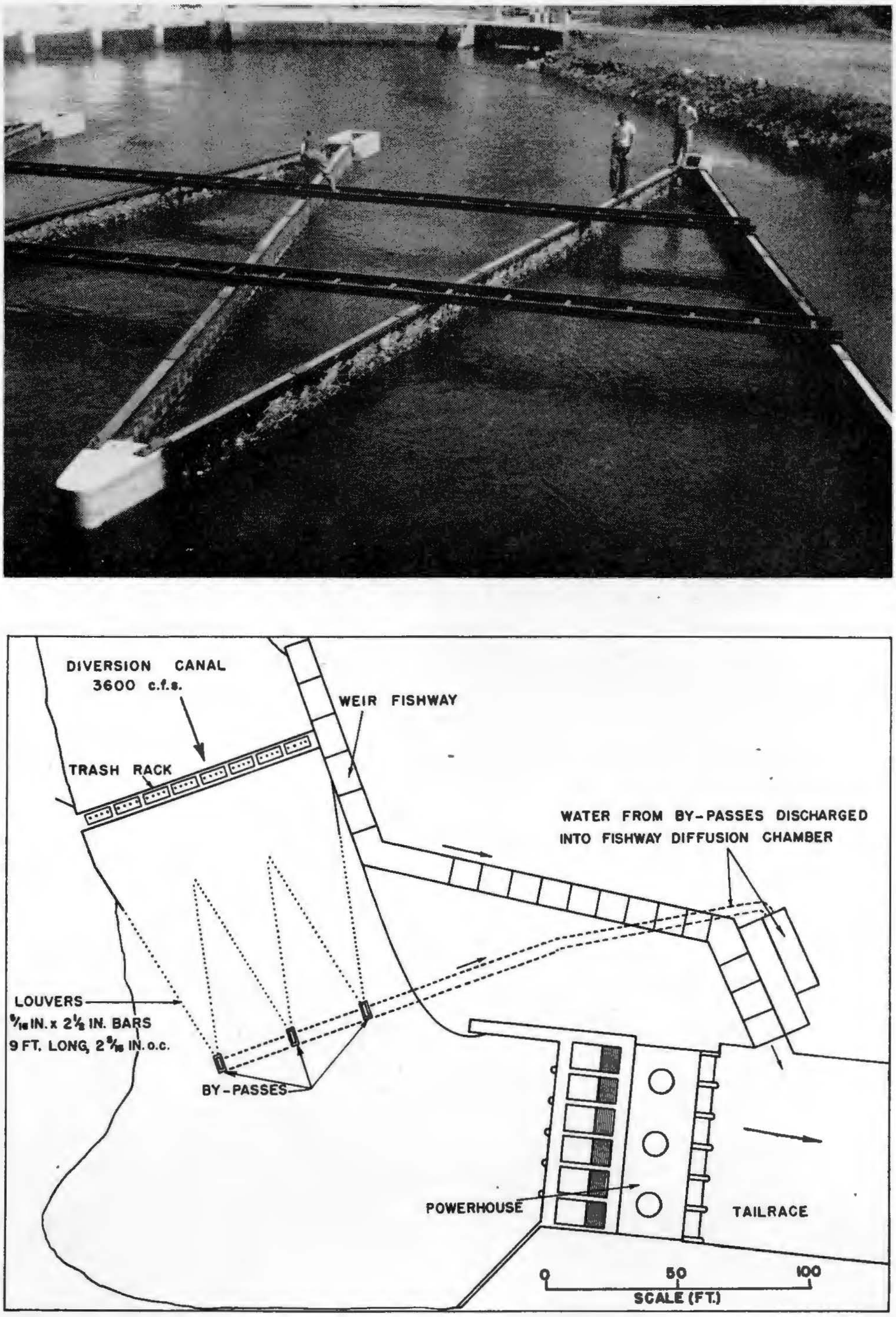


FIGURE 30—A louver installation on the Rogue River in Oregon for diverting downstream migrants.

Experiments conducted by the Canada Department of Fisheries on the Puntledge River in British Columbia indicated that, under the experimental conditions at this installation, the deflection efficiency increased with the size of fish (Can. Dept. Fish., 1958). A barrier consisting of vertical louver bars set at a spacing of 2 in. with an approach velocity of 3 f.p.s. deflected 60 to 75 per cent of chinook salmon fry and 80 to 85 per cent of sockeye and steelhead smolts. A full-scale installation of a louver barrier was recommended for construction at a hydroelectric installation on the Puntledge River to salvage a large proportion of the salmon and trout populations that at the present time suffer a mortality rate of 30 to 40 per cent in passage through the turbine. A double row of louvers was recommended at this 1000-c.f.s. diversion in an attempt to improve deflection efficiency.

The over-all efficiencies of the louver barriers installed at the Tracy diversion and on the Rogue River have not yet been measured. While these facilities may protect a large proportion of the downstream migrants, many problems would be involved in extension of the louver barrier technique for protection of downstream-migrant sockeye and pink salmon at the major dams that have been proposed for construction on the main stem of the Fraser River. Apart from the enormous cost of such facilities on the scale that would be required at main-stem dams, the physical and biological problems appear so complex that it is unlikely that louver barriers could be used effectively to protect downstream migrants at such dams. Their effectiveness in diverting recently emerged pink fry has not been investigated. Also, the effect of population pressure on the effectiveness of louver barriers has not been studied. Louvers and other deflecting methods may fail when a large number of fish reach the barrier in a very short period of time. The total number of fish intercepted annually at Tracy or on the Rogue River is relatively small compared with the millions of fish that would be expected in the downstream migration in the Fraser River. Although no evidence appears to be available on this subject, it might be anticipated that pressure of numbers would cause a greater proportion to escape between the louver bars. These and other problems require extensive investigation, which must be based on costly large-scale experiments.

While there can be no doubt that louver barriers can be very useful for screening downstream migrants at relatively small water diversions, the dangers involved in extrapolating results from small-scale experiments have previously been emphasized. Application at proposed Fraser River dams would involve many problems. At the proposed Moran Dam, for instance, the peak expected spillway flow has been estimated at 270,000 c.f.s. and the maximum turbine discharge would be approximately 85,000 c.f.s. While it might be physically possible to provide a louver barrier to strain these large discharges, the depth and area of the barrier would be so much larger than the largest louver barrier constructed to date (5000 c.f.s.) that prediction of the deflection efficiency would be totally unjustified. Keeping such a structure operative during the spring months when large quantities of debris are carried in the water would be a major problem. Further, the cost of such facilities at large dams would be tremendous.

DEEPLY SUBMERGED TURBINE AND SPILLWAY OUTLETS

One method that is becoming increasingly popular for protecting downstream migrants at dams consists of placing turbine intakes at considerable depth below the crest of the dam to minimize the number of migrants that will exit via this route. In conjunction, a by-pass is provided as a relatively safe route for the fish from the forebay surface to tailwater. This method has recently been recommended at several proposed dams because of the unknown value of artificial guiding devices, mechanical screens and louvers at such installations.

Observations at Baker Dam showed that only a small proportion of the downstream-migrant sockeye and coho salmon migrated through the 85-ft.-deep turbine intake when a surface spill was available, but that significant numbers did sound to this depth when there was no surface exit (Hamilton and Andrew, 1954). Subsequent experiments at this location confirmed that few fish migrated through the submerged outlet when water was spilled at the surface. However, these experiments showed that artificial surface by-passes were not completely effective in eliminating the migration through the tunnel (Andrew *et al.*, 1955 and 1956a). Rees (1957) showed that very few sockeye and coho normally migrated downstream in depths greater than 30 ft. Tests indicated a preference by both species for the surface layer (0 to 15 ft.) when both the spillway and tunnel exits were available. The numbers of fish in the deeper layers (15 to 90 ft.) increased when only the tunnel exit was available.

Schoeneman and Junge (1954) reported that at Glines Dam hatchery-reared chinook salmon readily sounded to a depth of 65 ft. to enter the submerged tunnel when no surface exit was available. Few hatchery-reared coho yearlings sounded under the same conditions. Both species preferred the surface outlets when they were available, although the depth of tunnel submergence was not great enough to prevent migration through this exit.

Experiments at Mud Mountain Dam on the White River in Washington have also added some information concerning the preference of downstream-migrant salmonids for surface exits from reservoirs. This dam was built for flood control and has no provision for surface spills. Migrants moving seaward from the stream above this dam must either remain in the reservoir or sound to a variable depth depending on the amount of storage. Under normal operation, all discharge is directed through a 9-ft. tunnel at the base of the dam.

In 1957, the migration of chinook and coho salmon was studied in relation to changes in the depth of submergence of the outlet tunnel (Regenthal and Rees, 1957). From the experimental results it was calculated that in a 100-day migration period all of the coho migrants would sound to depths of 118 ft. or less but if the reservoir surface was 160 ft. above the top of the tunnel only 8 per cent of the run would move downstream out of the reservoir. Similarly, more than 95 per cent of the run of chinook salmon would sound to a depth of 118 ft. during a 100-day migration period but less than 8 per cent would sound to a depth of 160 ft. In general, the chinook salmon exhibited less tendency to sound than did the coho. Within the range of submergence depths investigated, all fish delayed for some period of time before sounding to the tunnel.

It appears that outlet submergence is a partially effective method for preventing downstream migrants from entering hazardous areas at dams but several complications arise in attempting to apply this technique at installations having larger discharges than those tested. At Baker, the tunnel flow was 2200 c.f.s., at Glines 1500 c.f.s. and at Mud Mountain approximately 2000 c.f.s. However, dams on the Fraser River would have to pass much larger discharges. The peak flood discharge for a dam at Moran Canyon has been estimated at 270,000 c.f.s. If an attempt was made to protect seaward migrants at such dams by means of outlet submergence, a great deal of additional information would have to be obtained to determine the submergence depth required. It seems likely that the extent to which fish will sound in seeking an exit from a reservoir depends upon the zone of influence of the approach velocities to the exit. Outlets having larger discharges than those investigated would attract water from a greater area of the forebay and would probably have to be placed at greater depths. Sockeye smolts have been subjected experimentally to pressures equivalent to 720 ft. of depth (310 p.s.i.) with no apparent ill effects. While it is apparent that smolts can withstand great pressures, it is not known whether their behavior patterns would permit migration to such depths.

Very little information is available concerning flow patterns towards subsurface outlets at dams. Measurements have been made of gross velocities at several dams but the measuring devices available at the present time do not record the very low velocities that seaward-migrant salmonids may be able to detect and follow. Consequently, studies of the fundamentals of flow to submerged outlets are currently being undertaken by means of models using the electrical analogue technique. A recently completed model study undertaken at Oregon State College in connection with the hydraulic design of fish-protective facilities at Pelton Dam utilized a novel technique involving the use of hydrocarbon globules for determining direction of flow in the forebay of the dam.

An important step towards a solution to the problem of determining the minimum permissible submergence of outlets at dams would be achieved if factors influencing the migration paths of juvenile salmon in reservoirs could be delineated. Dendy (1948) stated that in three storage reservoirs in the Tennessee Valley the depth distribution of fish was related to thermal stratification when adequate oxygen was available. In the forebay of Bonneville Dam, where velocities and turbulence are relatively high because of the large discharge and shallow river depth, downstream migrants have been observed to be distributed over the entire 60 ft. of depth (Burner, 1949). As already noted, most of the migration at Baker Dam is in the top 15 ft. of the reservoir, with only a few fish found below 30 ft. of depth. At full load, full resevoir, and with no spill, the average approach velocity in the forebay at Baker Dam is about 0.06 f.p.s. At Bonneville Dam, with a discharge of 300,000 c.f.s., the average velocity at a section just upstream from Bradford Island would be more than 3 f.p.s. Well-defined thermal stratification also develops in the reservoir above Baker Dam during the period of downstream migration whereas there is no evidence of thermal stratification in the Bonneville reservoir at this time. Investigations of such distributional differences in relation to observed differences in the environment are continuing in an effort to obtain an understanding of the distribution of downstream migrants in reservoirs. Eventually it may be possible to predict the behavior of downstream migrants under a given set of reservoir conditions but available information is far from adequate for that purpose at the present time.

In considering the feasibility of submerged outlets as a fish-protective method, it immediately becomes apparent that where large discharges must be provided for, such as on the Fraser River, the method could not be used unless the dam was high enough to provide sufficient depth of submergence. At such high dams, a large difference between the water temperature at the surface and at the submerged outlets would be expected. The river below the dam would therefore be colder than surface layers of the reservoir.

At existing dams the problem of subjecting downstream migrants to a significant temperature change as they pass from the reservoir to the river below the dam has seldom arisen because the fish follow and are transported by the main flow of water either over the spillway, if this exit is available, or through the turbines. But if means could be developed for guiding and collecting the downstream migrants in surface layers of the reservoir and transporting them for release below the dam, a temperature problem could arise. The stress produced by sudden temperature changes of the order that might occur could be expected to have some adverse effects on the downstream migrants.

During much of the period of downstream migration at the proposed Moran Dam the surface by-passes and the turbine discharge would be the only outflows. Since the turbine outlets would draw water from a considerable depth in the reservoir there would be a difference in temperature between the colder turbine water and the warmer surface water spilled through the by-pass. The magnitude of this difference would depend on the depth of submergence of the turbine intakes and on climatic conditions. Little difference would be expected at the start of the downstream migrations but the surface layers could be more than 20°F warmer than tailwater at the end of the migrations. FIGURE 9 presents the results of estimates of tailwater river temperature compared with reservoir surface temperature and existing river temperature assuming turbine intakes submerged 230 ft. below the dam crest and spill outlets submerged an additional 60 ft. Thus, migrants passing over the dam in the relatively small by-pass flow would be subjected to a sudden decrease in water temperature when they entered tailwater. TABLE 8 presents the probable differences in temperature that would occur throughout the period of downstream migration. It has previously been shown that the migration of sockeye smolts would be considerably delayed in passage through long, low-velocity reservoirs. On the assumption that these fish would be capable of migrating through such reservoirs, previous calculations suggested a delay of about 40 days in the proposed Moran reservoir. Since the peak of migration from upstream rearing lakes occurs about May 1, the peak of migration at Moran Dam might therefore not occur until about June 15 and many fish would still be migrating through the reservoir during July.

TABLE 8—Estimated reservoir surface and tailwater temperatures at the proposed Moran Dam during the period of downstream salmon migration.

	RESERVOIR SURFACE	TAILWATER		DIFFERENCE	
	°F	Average Year °F	Low-water Year °F	Average Year °F	Low-water Year °F
May 1	44	40	39	4	5
June 1	54	42	40	12	14
July 1	65	44	43	21	22
July 31	70	52	46	18	24

It has been shown (Brett, 1952) that sudden temperature reductions can cause a mortality among young salmon. The severity of the mortality depends on the thermal history, the temperature change, and the duration of exposure. FIGURE 31 shows the relationships between these variables that resulted in a 50 per cent mortality.

As Brett (1958) pointed out, an indiscriminate stress, such as temperature, that kills even 10 per cent of the fish is approaching the catastrophic level for the whole population. It is evident that if deeply submerged turbine outlets are used exclusively, mortalities to downstream migrants could occur in the tailrace. It would be necessary, therefore, to provide a means of regulating the temperature of the water drawn to the turbines so that there would be as little difference between tailwater and reservoir surface temperatures as possible. This requirement would necessitate locating the turbine intakes in a manner that would ensure withdrawal of a large proportion of water of the same temperature as the water in surface by-passes. In many cases this requirement might preclude the use of deeply submerged turbine and spillway outlets as a means of preventing downstream migrants from using these hazardous exits.

It has previously been indicated that the use of submerged outlets at a high dam would change temperatures in the river downstream to such an extent that adult salmon could also be seriously affected. As shown in FIGURE 9, water temperatures below the proposed Moran Dam could be as much as 15°F colder than normal river temperatures during the period of upstream migration of adults. Gibson and Fry (1954) showed that for lake trout *(Salvelinus namaycush)* the metabolic rate decreased to 55 per cent of the maximum when the water temperature was reduced to the extent indicated at the proposed Moran Dam. Such a reduced metabolic rate might result in a significantly longer migration time in the river up to the dam, which would add to the total delay caused by the dam and reservoir. Even if the delayed fish succeeded in reaching their spawning grounds, their reproductive ability might be greatly reduced because environmental conditions might not be favorable for spawning. The new temperature regime resulting from the use of submerged outlets at the dam could also affect spawning of pink salmon below the dam in the main stem of the Fraser River near Hope.

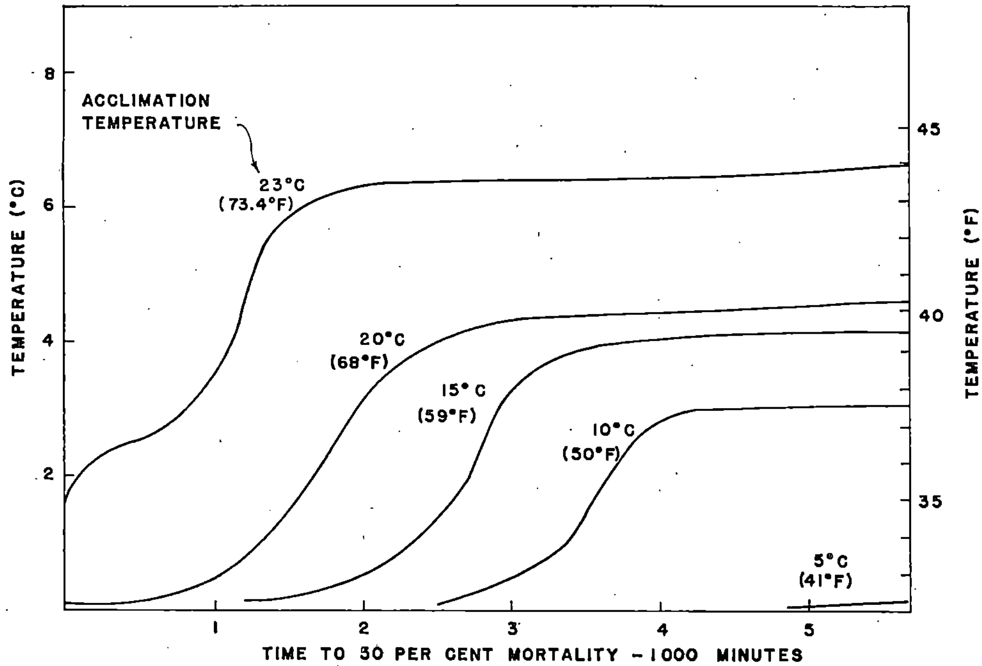


FIGURE 31—Median resistance times to low temperatures among 6-month-old sockeye salmon acclimated to temperatures indicated. (From Brett, 1952.)

On the basis of the available evidence, therefore, it appears essential to maintain the temperature of the Fraser River downstream from such a dam within the usual range of temperatures encountered in the existing river. To satisfy this criterion, it would be necessary that the turbine and spill outlets be capable of withdrawing water from various levels to obtain the desired temperatures in the combined discharge. This requirement would necessitate withdrawal of turbine and/or spill discharge from a wide range of reservoir levels with great flexibility of control.

Use of outlet submergence as a method of protecting downstream migrants has many limitations. The method is of no value at low dams and the preceding analysis shows that it would be of limited value at a very high dam on the Fraser River. Furthermore, adequate design criteria are not available to permit application of this method of fish protection with any assurance of success even at dams of intermediate height.

FOREBAY COLLECTING DEVICES FOR DOWNSTREAM MIGRANTS

Any possible method of diverting seaward-migrant salmon and trout away from hazardous areas at dams is largely dependent for its success on the adequacy of by-passes for collecting the fish above the dam. A number of experiments have been conducted in recent years to investigate the requirements of effective by-passes. Although some of the prototype installations constructed to date have apparently not been particularly effective, significant advancements towards an understanding of the requirements of by-passes are being made.

Some indication of the requirements of a successful by-pass can be obtained by considering the behavior of seaward migrants under natural conditions. At a lake outlet, where the velocity is gradually accelerating, there appears to be little delay in entering the outlet stream. At the outlet of Cultus Lake, on the other hand, some delay has been observed at a point of abrupt acceleration of flow.

The distribution of smolts in a reservoir is, of course, a major consideration in by-pass design. In many instances smolts are found primarily in the surface layers. As previously noted, investigations have demonstrated that fish exhibit a preference for the surface layers in the forebay of Baker Dam. At Bonneville Dam, however, fish have been observed to be distributed over the full 60-ft. depth of the forebay (Burner, 1949). These observed differences in distribution may be associated with differences in temperature. Thermal stratification is very definite in the reservoir behind Baker Dam. Approximate isothermal conditions are more general in the Bonneville reservoir. Such conditions are probably associated with a more uniform vertical distribution of downstream migrants in the Bonneville reservoir. The ineffectiveness of small surface by-passes in such a situation is suggested by the insignificant numbers of fish captured in the four by-passes at Bonneville Dam. These were provided for capturing downstream migrants attracted towards screened water intakes. These by-passes are not effective in attracting fish away from the spillway and turbine intakes. According to Anas and Gauley (1956) they are presently being used for the primary purpose of obtaining small samples of downstream-migrant populations for biological studies.

Further, in considering the requirements of surface by-passes, the effect of subsurface outlets must be considered. Regenthal and Rees (1957) noted that at Mud Mountain Dam there was an inverse relationship between the number of fish migrating out of the submerged exit and the depth of submergence. A similar relationship was noted at Baker Dam (Andrew *et al.,* 1955). These authors also noted a decrease in the proportion of migrants sounding to the tunnel as the surface spill was increased. Results of observations made in 1955 are shown in TABLE 9. The spillway gates at Baker Dam are 9.5 ft. wide by 13 ft. deep and discharge about 1700 c.f.s. each. The tunnel discharge is 2200 c.f.s.

TABLE 9—Percentage of downstream migrants using submerged tunnel at Baker Dam during periods of continuous turbine and spillway operation.

	SPILL CONDITION		
	One Gate	Two Gates	Three Gates
Native sockeye	6.2	4.0	2.4
Native coho	1.7	1.4	4.0
Hatchery chinooks	9.0	2.0	—

These observations indicate the need for considering the effect of submerged outlets in attraction of downstream migrants. Whereas an 85-ft. deep tunnel discharging 2200 c.f.s. may not attract more than 5 or 10 per cent of the fish when an adequate surface exit from the reservoir is available, a tunnel at the same depth but discharging twice as much water might attract a much higher proportion of the downstream migrants. Little is known concerning the discharge required in surface by-passes to attract fish from the reservoir and to prevent them from entering subsurface outlets.

Various studies have been conducted in attempts to design and evaluate by-passes. Experiments at Baker Dam with a 24-c.f.s. by-pass were not successful in collecting migrants, possibly because of the rapid acceleration of water at the by-pass entrance (Andrew *et al.*, 1955). Further experiments (Andrew *et al.*, 1956a) with a 265-c.f.s. by-pass with more gradual acceleration of approach velocities still did not attract the majority of fish except when aided by a long webbing barrier that diverted migrants to it. Even with this large by-pass, the migrants appeared reluctant to enter it.

Experiments were continued at this site in 1957 with an improved by-pass and although considerably more success was achieved in collection of yearling coho salmon, it proved ineffective for collection of sockeye smolts. These tests involved the use of a webbing barrier, 400 ft. long and 30 ft. deep, which was intended to deflect sockeye, coho and chinook salmon to a "skimmer" by-pass and to prevent them from passing over the spillway or through the turbines. As previously stated, the webbing barrier was not completely effective because many fish sounded under it. However, experiments and observations at the by-pass itself yielded much information concerning the problems involved in forebay collection devices.

The by-pass consisted of an overflow weir and an inclined-screen trap with an approach channel or "funnel" upstream from it to provide a more gradual acceleration of velocities towards the weir. A diagrammatic sketch of this by-pass is shown in FIGURE 32. The funnel was 32 ft. long and tapered from a 16-ft-square entrance to a width of 8 ft. and a depth of 12 ft. at the weir. The weir, which was 7.5 ft. long, was operated at heads ranging from 12 to 30 in.

It was apparent that the funnel or transition section at the entrance to the skimmer trap had certain distinct advantages. In the experiments at this site in 1955 a similar by-pass was used without the funnel. The entrance to the by-pass was located at the upstream face of the dam at the water surface. During daylight, schools of several thousand fish swam within 3 ft. of the entrance and often remained in this area for some time. The fish closest to the trap entrance frequently moved to within 6 in. of the weir but immediately swam upstream again. During darkness, when a submerged spotlight was directed upstream from the centre of the by-pass opening, large schools of fish congregated in the beam and swam back and forth in the illuminated area with the result that each time a school ventured close to the weir a few members of the school were caught by the high velocity and drawn into the trap. The majority still retreated upstream, however, just as they had done during daylight. The observed behavior of the fish indicated that the sudden increase in velocity at the trap entrance tended to cause alarm. Hence, the funnel, which provided a transition between

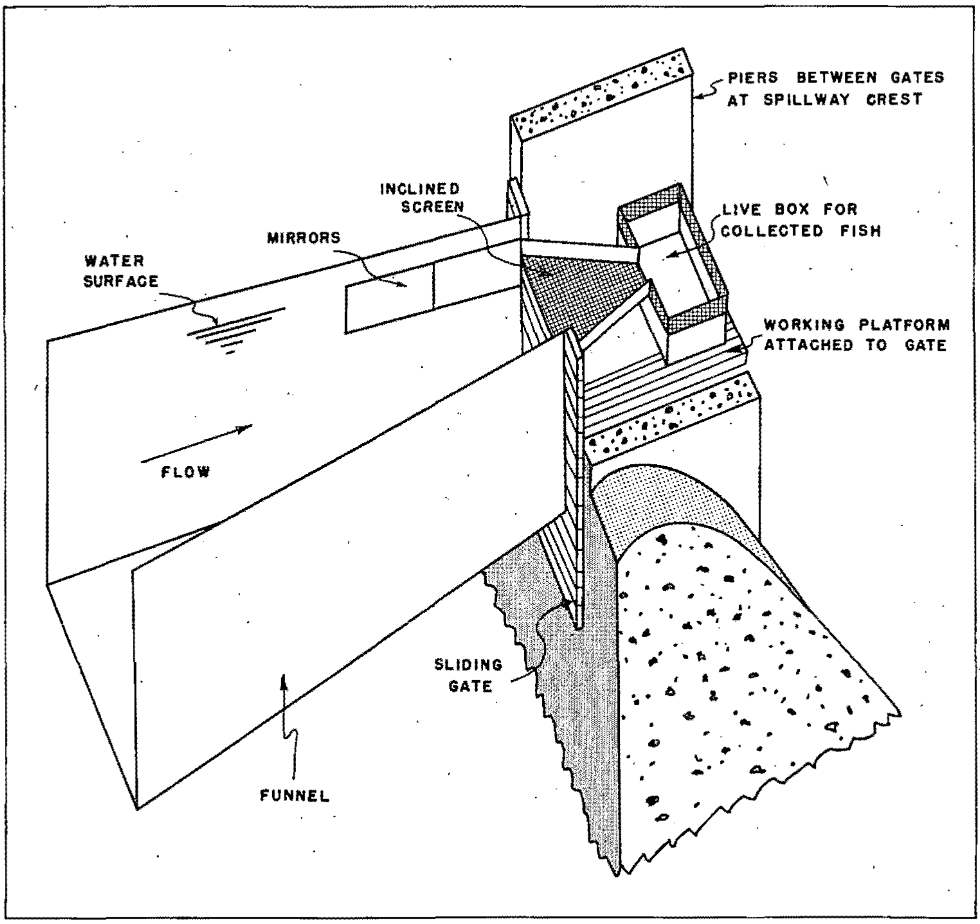


FIGURE 32—"Skimmer" by-pass for downstream migrants, tested at Baker Dam in 1957.

the low forebay velocity and the high trapping velocity, was provided in subsequent experiments. A second advantage was that the funnel provided an accumulating or holding area for the fish. Without the funnel, fish that retreated from the high velocity at the trap entrance often swam so far out into the forebay that they were beyond the sphere of influence of the trap. However, after the funnel was installed, it was noted that fish that appeared reluctant to enter the trap on their first pass usually remained in the funnel and made other passes towards the trap entrance. Part of the school usually entered the trap on the first pass and all or nearly all of the remaining members of the school usually entered on the second or third pass.

Subsurface lights at the upstream end of the funnel increased the percentage of fish captured in the by-pass. Single lights of 7.5, 150 and 300 watts appeared to be equally effective. A subsurface light at the weir crest and a light over the collecting compartment downstream from the weir also tended in increase the number of fish caught in the by-pass but lights that illuminated the walls of the funnel appeared to reduce the trapping efficiency.

Fish did not readily enter the trap during daylight and it appeared that extensive modifications would be required to make the system functional at all times of the day. Covering the whole funnel with tarpaulins to eliminate direct sunlight decreased the efficiency of the trap.

The effect of different flows was also investigated. A head of 24 in. on the weir of the skimmer trap, or a flow of 70 c.f.s., was much more effective than a head of 12 in. (25 c.f.s.). A 30-in. head, which gave a flow of 100 c.f.s., did not appear to be much more effective than a head of 24 in.

This by-pass was more effective than those used in previous experiments at Baker Dam but it was still quite inadequate, even for collecting fish from this small 350-ft.-wide forebay. While some success was achieved in capturing coho, many of these fish and most of the sockeye smolts passed over the spillway or through the tunnel in spite of the fact that they had to sound under a 30-ft.-deep barrier to do so.

Another experiment in which the fundamental requirements of by-passes were investigated was conducted on the Lakelse River (Brett and Alderdice, 1958). The by-pass was considered one of the most important factors affecting the success of methods of deflecting or guiding sockeye and coho smolts. Various alterations were made to increase the by-pass efficiency and these were based in part on the principle that stream orientation is mainly by vision. In addition it was proposed to create a gradual increase in the velocity of the incoming water. Such changes were aimed at sweeping the fish into and through the by-pass without providing them with visual or turbulence cues that might stimulate strong upstream swimming responses.

The by-pass, discharging 24 c.f.s., was about 8.5 ft. wide at the entrance. The walls and floor were covered with smooth plywood painted brown. The walls converged near the entrance to the trapping portion of the by-pass. Both sides of the approach channel were lined with mirrors. Water velocity gradually increased from 0.8 f.p.s. at the entrance to 4.4 f.p.s. at the narrowest point. The water depth at the entrance was about 22 in. and the stream depth 5 ft. upstream was about 30 in. compared to the maximum stream depth of about 48 in.

Brett and Alderdice stated that this by-pass was far from perfect, although a decided improvement over a previous by-pass that had been tried. They maintained that: "The combination of shallow by-pass water and the relatively rapid decrease in depth at the approach, together with the changed light-reflecting qualities of fresh gravel at the entrance, appeared to act as deterrents to efficient operation." Some indication of the problems involved in providing adequate by-passes at large dams is obtained when it is realized that these apparently slight changes can seriously affect by-pass efficiency.

As a result of their experiments and observations, Brett and Alderdice made the following recommendations concerning by-pass design for sockeye and coho smolts: The fish should be by-passed through a flume characterized by streamlined flow, with the water accelerated uniformly at not more than 0.1 f.p.s. per ft.

All visual and turbulence cues should be reduced as much as possible. Alternately, false cues, such as from cross-reflecting mirrors, should be introduced. The final trapping velocity should be 5 f.p.s. The opening to the by-pass should be three to four times the width of the mass of moving fish (not less than 10 ft.) with a depth equivalent to that of the river bottom or 5 ft. below the level at which the lowest 5 per cent of the fish are swimming. The by-pass flume should be covered and this cover should extend upstream to create a protective shadow for the fish to follow. Low illumination should be provided under this cover at night. Some of these recommendations would be difficult, if not impossible, to achieve if millions of downstream migrants had to be by-passed at large dams on the Fraser River. However, the concepts developed in modern by-pass research may be considered as desirable guides to follow in future research.

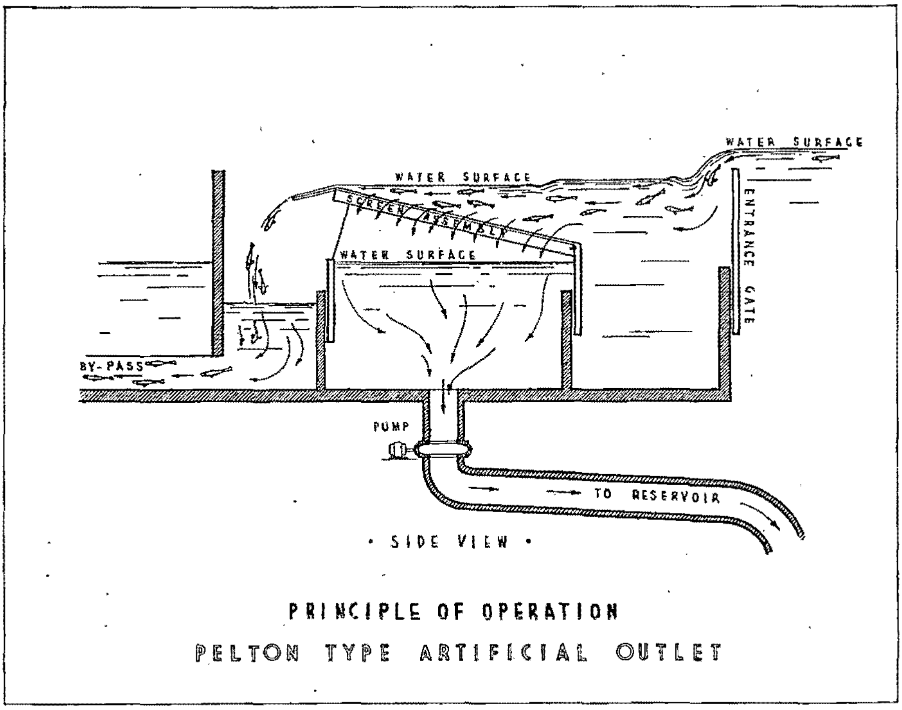
Research on by-pass design in the 200-ft.-deep forebay at Merwin Dam on the Lewis River in Washington demonstrated that a surface by-pass entrance was more effective than subsurface entrances extending to a depth of 20 ft. The by-pass consisted of a skimmer trap essentially the same as that tried at Baker Dam except that the fish entrance could be moved vertically while maintaining the weir and inclined screen at a fixed elevation. Apparently this by-pass, even with a surface entrance, was not effective as only a small proportion of fish released into the reservoir were captured even though many fish were seen in the forebay of the dam. Modifications, including the use of lights and gradual acceleration of flow, did not improve the effectiveness of the by-pass to the point that it could be considered satisfactory for practical use in providing an exit for seaward migrants. Surface spilling seldom occurs at this dam and the turbine intakes are located at a depth of 180 ft. The progeny of the adult salmon transported over the dam tend to be trapped in the reservoir and it is therefore essential that an effective surface by-pass be developed. In spite of several years of experiments, few fish have been captured in the by-pass in relation to the number apparently present in the forebay area. Hydraulic studies of a similar type of surface by-pass or "skimmer trap" were made in connection with fish facilities for the proposed Mayfield Dam on the Cowlitz River in Washington (Richey, 1957).

The skimmer principle was also utilized at Pelton Dam on the Deschutes River in Oregon (Eicher, 1958a). The turbine outlets at this dam are deeply submerged and spilling of water over the crest of the dam will seldom occur. The surface by-pass has a pumped flow of 200 c.f.s. to attract the fish. Approximately 98 per cent of the flow is passed through an inclined screen trap and returned to the reservoir. The artificial outlet structure consists of a concrete box approximately 70 ft. high, 35 ft. wide and 50 ft. long. The flow of 200 c.f.s. leaves the reservoir either through or over an adjustable gate and enters a 15-ft.-square entrance pool. At the downstream end of this pool the water flows over a weir onto the inclined screen. Water is pumped from below the inclined screen to the forebay through a 7-ft.-diameter pipe that extends to sufficient depth to prevent the exit velocity from affecting velocities at the surface of the forebay. Approximately 4 c.f.s. is discharged over the end of the inclined screen to carry fish into a 30-in.-diameter pipe leading to a fishway. After passing through the fishway, which is three miles long, the fish are discharged to the river. A schematic drawing of this type of by-pass is shown in FIGURE 33.

A surface by-pass that involves fewer engineering problems was recently constructed at the North Fork Dam on the Clackamas River in Oregon (Eicher, 1960), This by-pass is similar to that at Pelton Dam in that a flow of 200 c.f.s. is pumped from the forebay and the fish are screened out of this attraction flow before entering the transportation facilities to tailwater. However, instead of using an inclined-plane trap for this purpose, as at Pelton Dam, the by-pass at the North Fork project utilizes vertical, moving-belt mechanical screens (FIGURE 33). Using the principle that has been found highly effective in louver barriers, the mechanical screens are set on an acute angle to the direction of water flow so as to lead the fish to the by-pass, which is a vertical slot 12 in. wide the full height of the mechanical screens. Eicher maintained that this type of by-pass is not only less costly to build but is much easier and cheaper to maintain and operate. Both the North Fork and Pelton by-passes have operated satisfactorily and have captured large numbers of fish. While these by-passes are apparently efficient in collecting downstream migrants from the forebays of these dams, no evaluation of the total numbers captured in comparison with the total number in the reservoir has been made. Landlocking in the reservoir may be a problem.

Experiments with floating by-pass traps have been conducted by the State of Washington Department of Fisheries at three locations: Mud Mountain Dam, Lake Washington, and Baker Dam. The device is being tested at Baker Dam to obtain some indication of its effectiveness in capturing sockeye and coho smolts. This type of by-pass consists of a floating structure moored in an area of the forebay known to be on the migration path of a large proportion of the fish. The by-pass at Baker Dam is 68 ft. long and 36 ft. wide with a fish-collection channel 10 ft. wide and 8 ft. deep down the center of the barge. This channel is open at one end only. Three electrically operated pumps are mounted on the barge for pumping water from the closed end of this channel to produce a flow from the forebay into the open end. Fish are screened out of the collection channel by means of louvers and screens before the water enters the pumps. The louvers are arranged horizontally across the channel so as to provide a sloping ramp that forces the fish towards the water surface. After passing the louver section, the fish enter a screened section and are diverted into live boxes. The total flow is about 85 c.f.s., which produces an average velocity of about 1 f.p.s. at the entrance to the collection channel.

The method of determining the effectiveness of this floating by-pass structure consisted of comparing the total number of smolts captured at Baker Dam during one season's migration with the number that might be expected if average fresh-water survival had occurred. No attempt was made to enumerate fish passing over the spillway or through the turbines. In spite of the fact that spilling frequently occurred in 1959, significant numbers of fish were captured.



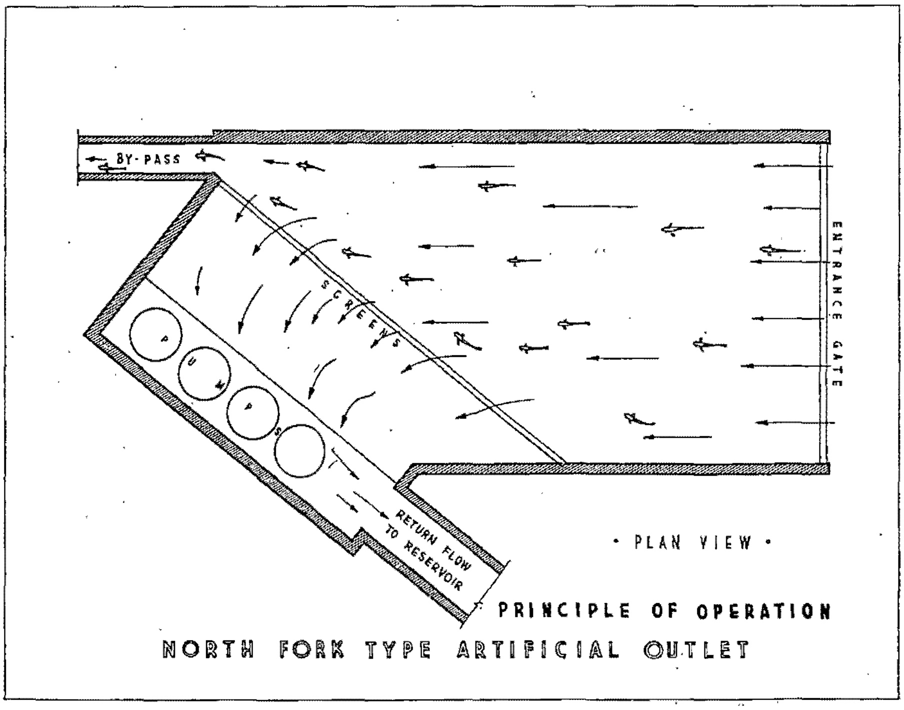


FIGURE 33—Schematic diagrams of by-passes used in the forebays of Pelton and North Fork Dams for collection of downstream migrants. (From Eicher, 1960, with courtesy of *Electric Light and Power*.)

A similar type of by-pass, shown in FIGURE 34, is being used in conjunction with the previously described 2800-ft.-long by 120-ft.-deep floating barrier at Brownlee Dam on the Snake River. Fewer downstream migrants have been captured in the three by-passes provided than were expected on the basis of the spawning population. Delay and possible residualism in the reservoir appears to be a problem at this location as at other dams where downstream migrants are trapped.

An important consideration in the design of by-pass systems that involve trapping and holding of the fish was provided for in the design of the by-pass system at Brownlee Dam. On numerous occasions it has been observed that cannibalism occurs when large downstream migrants, particularly coho, are retained in the same compartment as smaller migrants. Recognizing this fact, the designers of the facilities at Brownlee Dam have attempted to separate different size groups prior to holding and transporting them. After entering the by-pass, fish pass through two sets of screens that sort them into three sizes. They then enter holding tanks located on the by-pass structure. These tanks are linked by an 8-in.-diameter pipeline and a pump-and-lock system to tanks at a truck-loading station on the right bank of the river. Each size group is transported separately through the pipeline to the loading station.

The floating by-pass system was designed primarily to solve the problem of collecting fish from the surface layers of reservoirs where there is a large flucuation in forebay elevation. At Pelton Dam, the fluctuation does not exceed 7 ft. and it was therefore possible to construct the by-pass system as an integral part of the dam. However, such a small fluctuation is exceptional. At the dam proposed for construction in Moran Canyon on the Fraser River, the expected fluctuation would be approximately 200 ft. The structural problems involved in providing a 200-ft. vertical slot in the dam through which downstream migrants could be passed from a surface by-pass can readily be appreciated. While it might be possible to provide a series of ports through the dam, many problems would be involved. The additional handling necessitated by pumping or physically lifting fish from a surface by-pass to trucks, flumes or other transportation devices located at an elevation higher than the crest of the dam could only have an adverse effect on the fish. Moreover, such a system would introduce considerably more mechanization, which is always subject to failure or improper operation due to human error.

Another problem in connection with by-pass design is whether the fish after being delayed in passing through long reservoirs would exhibit the same behavior as undelayed fish. It has not been demonstrated that seaward migrants will pass through long reservoirs, nor has it been demonstrated that they would exhibit the same behavior responses following extensive fresh-water delay. Thus, if seaward migrants can successfully pass through long reservoirs, their by-pass requirements might be quite different from those for undelayed fish. For instance, at the proposed Moran Dam, which would have a 170-mile-long reservoir, it would not be unreasonable to expect fish to avoid the warm surface layers. A surface by-pass might therefore be of no value.

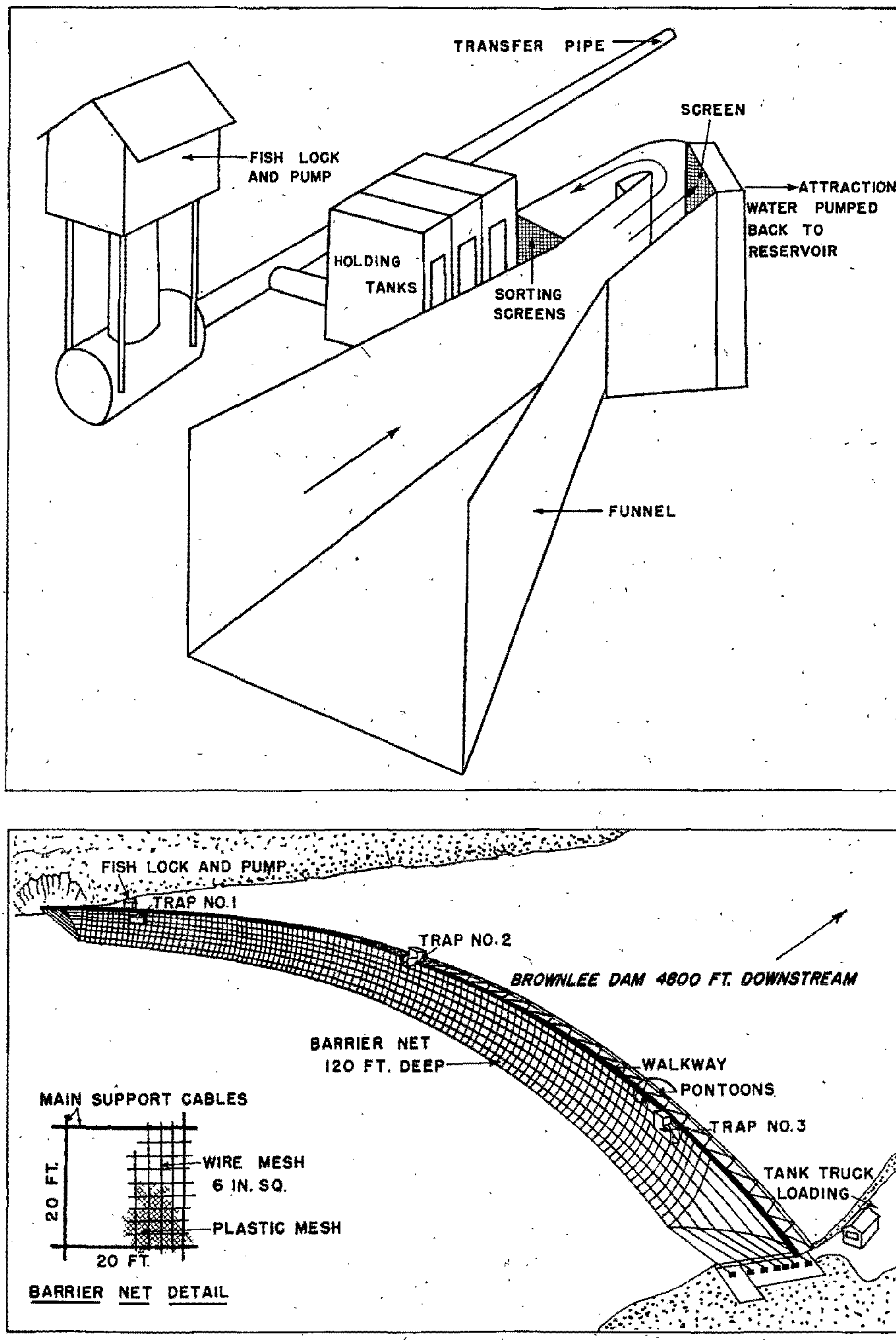


FIGURE 34—Floating net and by-pass traps for capturing downstream migrants at Brownlee Dam on the Snake River. (From Engineering News—Rec., 1958.)

Present knowledge of the behavior of seaward migrants in relation to methods of collecting them in the forebays of large dams is so inadequate that it would be impossible to determine the required size, shape, number and distribution of by-passes at any large dam. Current research on the requirements of a successful by-pass is progressing at an accelerated pace but recent studies do not provide cause for optimism concerning the design of adequate by-passes capable of handling the enormous numbers of sockeye smolts and pink fry that would be affected by the large dams proposed for construction on the Fraser River.

It seems apparent from current research that a prime requisite of by-passes is a large discharge. The magnitude of flows for the several by-passes that would be required at a large dam on the Fraser River cannot be determined at this time. To attract migrants from a reservoir from which large, subsurface spillway and turbine discharges are drawn, the total by-pass flow might have to be about equal to the turbine discharge. Some means would probably be required, therefore, to recover a large proportion of the by-pass flow either by recirculation or by diversion to the turbines. Apart from the mechanical problems involved and the high cost of such a system, there is no assurance that the fish would not be injured. Screens or louvers for this purpose would present a serious operational problem of cleaning. The over-all effectiveness of such systems, particularly where large forebay fluctuations may be expected, is very much in doubt.

Since large discharges are probably required for attracting migrants and for preventing them from sounding to submerged turbine and spillway outlets, it seems unlikely that by-passes using small flows will ever be successful at large dams except possibly when used in conjunction with efficient and practical devices for guiding migrants to them. The results of current research do not provide any basis for concluding that any form of by-pass or guiding device developed to date could be recommended for application at large dams, such as those proposed for construction on the Fraser River.

METHODS OF TRANSPORTING DOWNSTREAM MIGRANTS OVER DAMS

The problem of transporting large populations of downstream-migrant salmon over dams from forebay to tailwater has received very little study because neither guiding methods nor forebay collection devices have yet been perfected. Therefore, only general observations can be made concerning the feasibility of possible transportation methods such as tanks, barges, flumes, pipes, locks, and free drops.

Assuming that fish could be collected in surface by-passes at dams, the immediate problem of introducing these fish into the necessary transportation devices would have to be faced. The problem is complicated by the fact that wide fluctuations in forebay level are common. As previously mentioned, the expected fluctuation at the proposed Moran Dam would be about 200 ft. The facilities built at Brownlee Dam provide a pumping and locking system for transporting fish a horizontal distance of nearly 3000 ft. from floating by-pass traps to a tank-truck loading station located above high-water level.

By providing a continuous series of ports through a dam, from maximum to minimum forebay elevation, pumping of fish could be eliminated but other problems would be created. Such a system would probably present a structural problem in design of high dams and it would certainly involve a complicated and unprecedented system of valves or gates to regulate the flow through the openings to correspond to by-pass inflow and to maintain suitable water levels for the fish after they entered the by-pass. The submergence of any opening in use and the velocity through it would also have to be limited to prevent harmful pressure changes and cavitation. While it would be possible to design a system that would function hydraulically, it would be a much more difficult task to assess the effectiveness of any design in providing safe and suitable passage for the migrants. Such factors as turbulence, abrasion, local pressure change and vacuums must be considered in evaluating a particular design. At the present time it is not possible to assign any permissible maximum numerical values against which to judge a particular design.

Although the problem of getting fish from a by-pass, which must be capable of vertical movement, into a transportation device has not been solved, a few observations can be made concerning the possible effectiveness of various transportation methods.

Transportation in Tanks

Tank trucks are frequently used for transporting relatively small numbers of fish and it might be presumed that this method or a modification of it could be extended to solve the problems of passing large numbers of downstream-migrant salmon over dams and/or around reservoirs. However, the capacity of trucking or other hauling systems is very limited. Common practice in transporting fish by truck involves limiting the load to about one pound of fish for each gallon of water (Norris *et al.,* 1960). It is relatively easy to meet this loading limitation at hatcheries because the number and weight of fish are known in advance and the rate of hauling is not controlled by a variable factor such as rate of migration. The problem is much more complicated in nature, where fish of widely varying size migrate downstream at a very irregular rate. In a single hour in 1958, over 3,500,000 sockeye smolts migrated from Chilko Lake into Chilko River. Considering other races as well, it would not be unreasonable to expect a peak hourly migration of 10,000,000 sockeye smolts down the Fraser River. The length of Fraser River sockeye smolts generally varies from 60 to 110 mm., corresponding to 230 to 35 fish per pound respectively (Clutter and Whitesel, 1956). The average is approximately 75 mm. or 110 fish per pound. Assuming that the fish were of average weight, the passage of 10,000,000 fish would require loading, transporting and unloading facilities for 90,000 gallons of water per hour. Additional transporting facilities would have to be available in the event the fish were larger than average. It is apparent that the physical problems involved in transporting such large numbers of sockeye smolts would not be easily solved.

In addition to the physical problems, transportation of fish involves serious biological problems. Some of the known problems have previously been discussed, in connection with transportation of adult salmon over dams. It was shown that the possibility of mechanical injury and physiological stress resulting from excitability of the fish is a serious disadvantage of all mechanical methods of transport. Black (1956) pointed out that mortality of fish during and after transportation is a common experience of the fish culturist. Often death is caused by oxygen deficiency, adverse temperature or to combinations of these and other factors. Black cited evidence to show that the delayed planting mortality, which has been reported by several investigators, may be caused primarily by physiological disturbances resulting from severe muscular activity in the transportation tank. It seems that holding, handling and mechanical transportation of fish should be avoided if at all possible. There is much evidence to suggest that mechanical transportation of downstream-migrant sockeye at Fraser River dams—whether in truck-mounted or track-mounted tanks—might be impossible without affecting the survival of the fish.

Transportation by Barges

Barge transportation may also be considered as a possible method of getting young salmon through reservoirs and over dams. Barges have been used experimentally for transporting hatchery-reared salmon on the Columbia River, where it was possible to pass the barges through navigation locks at Bonneville Dam. Additional handling problems would be involved if this transportation method was attempted in river systems where navigation locks were not provided at each dam. The Columbia River barging experiments were important, however, in that they suggest an important problem involved in artificial transportation of downstream-migrant salmon through reservoirs. It must also be borne in mind that artificial transportation of naturally reared downstream migrants through a reservoir would necessitate collection of the fish at the upstream end of the reservoir, which would probably be extremely difficult.

The purpose of the experimental program instituted by the State of Washington Department of Fisheries on the Columbia River in 1955 was to determine the effectiveness of barge transportation for reducing seaward-migrant mortalities caused by predation and passage over spillways and through turbines. Ellis (1956) stated: "Losses of young migrant salmon through the direct effects of hydroelectric dams and natural predation have become especially critical on the Columbia River watershed with the ascendency of power and other water-use developments. These dams also have created, particularly in recent years, conditions ideal for fish that prey on migratory salmon."

For four consecutive years, groups of approximately 200,000 90-day-old hatchery-reared chinooks were released at various points in the Klickitat and Columbia Rivers. One group was released at the hatchery on the Klickitat

River, a tributary of the Columbia River about 200 miles from the ocean. Three groups were transported downstream by tank truck. One was released at the junction of the Klickitat and Columbia Rivers, one was released in the Elokomin River, which is near the mouth of the Columbia River, and one was released in the Columbia River near its mouth. The fifth group was transported 40 miles by tank truck to the Columbia River and released into a screened barge measuring 55 ft. by 21 ft. with a draft of 5 ft. This barge was towed 165 miles downstream to a point near the mouth of the Columbia River. The journey required 51 hours, with the tug and barge maintaining a speed of three to four knots. Without being removed from the barge, the fish passed through the navigation lock at the 60-ft.-high Bonneville Dam.

Based on three years of returns of marked adults, it appears that long-distance transportation, whether by truck or barge, seriously reduces the survival and homing of chinook salmon. Apparently fish barged downstream have less homing instinct and/or survival than those trucked downstream (Wash. Dept. Fish., 1959). The proportion of each group returning to the hatchery was much smaller for fish released at the mouth of the Columbia River than for fish released directly from the hatchery. This increased straying among the groups transported downstream by truck or barge suggests that if fish are to return to a particular hatchery or stream they must be liberated in that stream. Any means of long-distance river or reservoir transportation to eliminate predation and spillway and turbine losses therefore appears of questionable value.

Transportation through Pipes

It might be possible to use long pipelines for transporting downstream migrants to eliminate some of the objectionable features involved in tank or barge transport. If, as seems unlikely at present, fish could be collected at the upper end of a reservoir, they might be transported quickly around the reservoir and dam through a pipeline. Shorter systems might be used to transport fish from a forebay collecting device to tailwater. However, problems of pressure change, cavitation and abrasion would have to be fully evaluated. Some means of energy dissipation might be required to prevent high velocities that could lead to cavitation and abrasion of fish on the pipe wall. Energy-dissipating methods would introduce turbulence, and possibly pressure change and abrasion that might be harmful. The possibility of a reduced homing instinct also requires investigation.

A fish-transporting pipe that was designed to combine passage over a dam around a reservoir has been described by Eicher (1958b) for the North Fork hydroelectric project on the Clackamas River in Oregon. In describing the proposed fish-protective facilities, Eicher explained that two dams already existing on the Clackamas River downstream from the North Fork site were built prior to 1912 with no provisions for safe passage of downstream-migrant fish. It was desirable, therefore, to collect fish at the North Fork Dam and transport them to the tailwater of River Mill Dam, the lowest dam in the system, seven miles downstream. Facilities have been provided to collect the fish at the upper dam and divert them into a fishway that extends from the forebay of this dam to the tailwater of Cazadero Dam two miles downstream. Near the downstream end of this fishway the migrants are diverted into a five-mile-long pipeline that transports them to a point below River Mill Dam. This pipe is of smooth, low-pressure transite, 20 in. in diameter. Grade is such that head is largely balanced by friction loss. Negative pressures are avoided. The fish are transported at from 4 to 6 f.p.s., utilizing a flow of approximately 12 c.f.s. Introduction into the river below River Mill Dam is by means of a free fall from the end of an upwardly inclined pipe some 30 ft. above the water surface.

The pressure problem in passage through pipes merits some consideration. Effects of pressure and pressure change on salmonids have been discussed in previous sections of this report. Under certain conditions, pressure change apparently does not cause an appreciable mortality among sockeye smolts. However, the thermal history of the fish and the gaseous saturation of the water seem to influence the mortality rate of fish subjected to pressure change. Harvey and Pyper (MS.) found that sockeye smolts subjected to pressure change in warm water supersaturated with oxygen suffered a much higher mortality rate than those tested in colder water.

These observations are of great importance in considerations of the possible effectiveness of pipes as a method of transporting fish over dams from surface by-passes to tailwater. The by-passes must be located at the water surface to be effective in catching fish. Reservoirs that have deeply submerged turbine outlets to avoid attraction of seaward migrants are subject to considerable warming in the surface layers. Adverse temperatures in reservoirs may place a severe limitation on the permissible pressure changes and vacuums in pipes leading from by-passes to tailwater.

Since adequate design criteria have not yet been determined, the possible application of pipes as a means of transporting seaward-migrant salmon and trout over high dams, either in a single drop or in stages, would have to be fully investigated experimentally before any rational decision could be made as to the probable success of the method.

Transportation through Open Channels

Open channels such as fishways, canals, flumes or chutes provide a possible means of transporting fish from the forebay to tailwater or, if fish could be collected, from the upper end of a reservoir to tailwater below the dam. Passage through open channels might be expected to minimize stresses caused by environmental changes.

Some experiments to study fish passage through steep flumes have been conducted at Alder Dam on the Nisqually River in Washington (Schoeneman, 1959). Tests were conducted using a semi-circular section of 24-in. galvanized sheet-metal pipe 406 ft. long. From an entrance pool at the upstream end, the flume was inclined downward at an angle of 22.5° for a length of 350 ft. A curved transition section was used at the downstream end so that the discharge jet could be projected either horizontally or upwards at an angle of 15° to the horizontal. The total vertical height was 140 ft., 26 ft. of which was a free fall from the exit of the flume into a deep cushioning pool. Discharges of 5, 10 and 15 c.f.s. were tested. The velocities in the flume reached a maximum of 36 f.p.s. for 5 c.f.s., 44 f.p.s. for 10 c.f.s. and 49 f.p.s. for 15 c.f.s. The minimum velocity, which occurred near the bottom of the flume, was 75 to 80 per cent of the maximum velocity.

Mortality rates for passage of coho smolts through the flume were determined in 11 tests, all of the test fish being recaptured in a large net in the cushioning pool. The mortality rates ranged from 0 to 5 per cent but Schoeneman considered that this mortality was largely due to the method of recovering the fish after each test. Although there was no measurable difference in mortality between the horizontal and elevated flume exit positions, it appeared from visual observations that the elevated position was superior because the falling water was dispersed to a greater extent.

An important observation was that "many fish exhibited confusion and shock in the holding area" immediately after passing through the flume. The test fish were not subjected to predation or to other stresses of the natural environment. The experiments must be considered inconclusive in that it was not possible to determine the total effect of the stress imposed by passage through the flume. Schoeneman concluded that "this method of transporting downstream migrant fish from a collecting device to tailwater does not create a level of damage to fish serious enough to cause death; however, as the tests could not involve assessment of possible predation on fish stunned or confused by their being catapulted into tailwater, a full appraisal of all factors involved in delivering migrants to tailwater has not been possible."

The results of this experiment cannot be extrapolated to much larger flows and heads and steeper slopes. Additional information would be required on the effect of these variables to assess the suitability of flumes or chutes as a means of transporting migrants at higher dams or where larger flows were required. Experimental evidence obtained from investigations concerning the mortality of migrants passing over spillways indicates that limitations on head, slope, roughness and tailwater pool size and depth could be expected beyond which there would be significant mortalities.

A further complication involved in the use of open channels at dams where large forebay fluctuations can be expected is that joining the by-pass to such open channels would be particularly difficult. In all probability, closed pressure conduits would have to be used to provide the necassary connection, with the upstream end of the flume located at an elevation below minimum forebay level. This would introduce additional hazards for the fish.

The possibility of using open channels to transport fish past a reservoir has not been investigated. While this possibility might have some merit, the problems of collecting migrants at the upper end of a reservoir would preclude its use at this time.

Passage through Fish Locks

Another method that has been considered for passing downstream migrants at dams is the use of gravity or pressure locks. Fish locks, used as downstream passage facilities, would have to be integrated with some forebay collecting device. Both pressure and gravity fish locks might be adapted for this purpose although gravity locks would appear to present fewer problems. Pressure locks would require design modifications to permit use as a gravity lock or a brail would have to be used to force fish down the locks.

Gravity locks could be operated in a manner to provide transportation to tailwater for downstream migrants. The water level in the lock chamber could be maintained at an elevation slightly lower than the forebay level and the discharge from the lock could then be taken from the downstream end and either passed through a turbine or directly to tailwater. At appropriate intervals the inflow could be directed to another lock and the water in the lock chamber drained down so that the fish could be released to tailwater without significant pressure change. Mechanical fish screens, with all their attendant hazards, would have to be employed to prevent fish from being drawn into the turbine or from being released to tailwater while the lock was still under pressure. An advantage of this scheme is that it simplifies the problem of providing by-pass outlets through dams having wide forebay fluctuations but it involves so many biological and operating problems that, as far as can be determined, it is not used at the present time.

The Borland fish lock, commonly used at low dams in Britain, serves as an open channel through which downstream migrants may pass from forebay to tailwater (Engineering Digest, 1956). This device, as described in the section concerning passage of adult salmon over dams, involves the use of a sloping shaft through the dam. Water drawn from the forebay flows through the shaft, which may be baffled to avoid excessive velocities, and attracts upstream migrants at the downstream end. When a number of salmon and sea trout accumulate in the lower end of the shaft, a gate is closed behind them and the shaft is filled to forebay level, allowing the fish to escape. During the attraction and filling phases of the cycle, water is drawn from the forebay over a weir having a head of about 12 in. Downstream migrants can therefore use this route as an exit from the reservoir. No information appears to be available as to the effect of passage through the lock shaft on the ultimate survival of the fish. It would appear that passage down the sloping shaft of this device would involve the same type of problems as passage over a spillway.

Transportation by Free Fall

The studies of Schoeneman and Junge (1954) and Regenthal (1957) on mortalities caused by dropping small fish freely through air to a cushioning pool have been discussed previously. Work at dams on the Elwha and Baker Rivers in Washington suggested that juvenile salmon suffered less mortality in passing over ski-jump than contained-flow spillways. Fish up to 6 in. long were also dropped from helicopters as far as 300 ft. with little mortality.

Mortalities of 17 to 32 per cent were measured at Baker Dam for a total drop of slightly less than 250 ft. However, the spillway discharge was stopped soon after the fish were released, possibly reducing the severity of turbulence and abrasion in the cushioning pool. Possible mortalities resulting from the delayed effects of any stress and injury were not measured. Further, the full effects of predation on stunned fish were not measured since the test fish were recaptured a short distance below the spillway.

Winds are known to adversely affect the success of free-fall passage of fish over dams. Downstream migrants may be blown onto the face of the dam or the canyon falls, thus increasing the mortality.

It seems likely that the free-fall principle provides a means of reducing but not eliminating spillway mortalities. Whether this technique would have any biological advantages over flumes or pipes for passing downstream migrants from by-pass collection systems to tailwater is questionable. The advantage of the ski-jump technique is that abrasion on a spillway face is eliminated. No information has yet been obtained as to the size of the cushioning pool required for specific heights or discharges. As previously mentioned, the high mortality of 70 per cent in the ski-jump spillway at Cleveland Dam on the Capilano River was considered to be caused by the effects of excessive turbulence and abrasion in the relatively shallow pool at the base of the dam. Helicopter drops of fingerling salmon do not provide a real assessment of the possibility of transporting downstream migrants by free-fall because they do not take into consideration the effect of turbulence and abrasion in the stilling pool, the limitation in size of the stilling pool into which the fish must be directed, or the effect of predation on stunned and injured fish. Extensive research would be necessary to determine the feasibility and limitations of the free-fall technique.

PREDATION ON DOWNSTREAM MIGRANTS RELEASED BELOW DAMS

Predation on downstream migrants released below dams must be considered in determining the feasibility of passage facilities. Under natural conditions, opportunities for predation on smolts are minimized because the migration occurs over a relatively short time, the fish are distributed throughout the river, and fast, turbulent rivers such as the Fraser apparently do not provide a good environment for an abundance of predatory species. Dam construction not only creates river conditions that are often more favorable for predatory fish but also lengthens the migration time of smolts. Smolts may be concentrated at collection and by-pass systems as well as in the tailrace, thereby probably subjecting them to greater predation. Predators apparently accumulate below dams, possibly feeding on stunned, injured and dead fish from the spillway and turbine discharges. Concentrations of predators have also been observed at the entrances to experimental by-passes. Thompson (1959) noted predation of squawfish *(Ptychocheilus oregonense)* in the Columbia River on newly released hatchery-reared fish, which provided a localized prey population.

Losses of downstream migrants resulting from predation at dams have not been measured. However, any injury or impairment of the fishes' swimming ability caused by passage over a dam undoubtedly makes fish more susceptible to predation. No information is available on predator abundance in the Fraser River but their numbers might increase substantially if dams were constructed. Ellis (1956) considered that dam construction on the Columbia River has created an improved environment for predatory fish. At Bonneville Dam, for example, scrap fish accounted for over 29 per cent of all fish counted through the fishways in 1953 (Corps of Engineers, 1956b). Attempts to develop an electrical trapping device for continuously removing squawfish from areas of the Columbia River where hatchery-reared salmon fingerlings are released have been reported by Maxfield *et al.* (1959). They stated: "Since the fingerling salmon are released in dense concentrations, thus bcoming easy prey for predatory fish, the success of the salmon-rearing program is greatly affected by the predators. Biologists and hatchery personnel have often observed at times of release of fingerling salmon that the squawfish *(Ptychocheilus oregonensis* Richardson*)*, is the most destructive of these predators." Attempts to use electricity in controlling predator populations have not progressed beyond the laboratory stage. Both dynamite and gill nets have been used with apparently negligible success.

Possibly facilities for passing juvenile salmon over dams should be sufficiently versatile so that the fish might be dispersed over a great distance rather than localized by continual releases at a particular locality.

Effects of Changed Flow Regime on Downstream Migrants

The discharge regime of the Fraser River would be greatly altered by an integrated hydroelectric and flood control program. For most economical power development, the spring run-off would have to be stored for use in the winter low-flow period. Flow changes might have profound effects on survival of downstream migrants as the normal flood discharges would not be as effective in transporting fish down the river and into the estuary. The significance of this changed flow regime on downstream migrants cannot be predicted at the present time. Reduced velocities in the reservoirs and in the river downstream might add significantly to the time required for smolts to migrate from their lake rearing areas to the ocean. The delay attributable to reduced discharge, however, might be relatively unimportant compared with delays caused by reservoirs. Very little is known of the effects of delay in fresh water on the ability of juvenile salmon to make the transition to sea water. In a previous discussion of this subject, it was suggested that fresh-water delay could reduce the survival of sockeye smolts.

Reduced flood discharges of the Fraser River would not only delay the arrival of downstream migrants in the estuary but might also significantly alter oceanographic conditions in Georgia Strait during an important stage in the fishes' life cycle. In studying factors affecting the abundance of Fraser River pink salmon, Vernon (1958) examined climatically influenced features of the environment in fresh water and the area of early marine residence. The summer sea water temperature in Georgia Strait during the year of fry migration was closely and inversely correlated with abundance of returning adults. Salinity during the same period in Georgia Strait tended to be directly correlated with subsequent abundance of adults. Preliminary studies also suggest that the marine survival of sockeye is in some way affected by the discharge of the Fraser River at the time of smolt migration. High spring discharges appear to result in high survival from the smolt to the adult stage. While the underlying cause or causes have not been delineated, it would appear that the discharge of the Fraser River is an important factor determining the survival of juvenile salmon.

Fraser River discharge is known to have profound effects on the temperature, salinity, and other oceanographic features of Georgia Strait. Waldichuk (1957) showed that the Fraser River discharge was the major cause of salinity variation in this area. Tully and Dodimead (1957) also found that the discharge of the Fraser River had an important effect on the properties of water in Georgia Strait. The temperature, salinity, pH, and concentrations of dissolved oxygen, dissolved nitrates, nitrites, inorganic phosphates and silicates were studied. Conditions in Georgia Strait might be significantly changed by a major reduction in the flood discharge of the Fraser River and by increased discharges during the winter months.

Reduced discharge patterns during downstream migration might create other important changes. For instance, migrants might also be subjected to increased predation if river discharge was reduced during the period of seaward migration. The fish would be in the river for longer periods and there would be some clarification of the water as a result of the decreased velocities, both of which could contribute to increased predation loss.

It cannot be stressed too strongly that there is a great deal more involved in the fish-power problem than the fairly obvious problem of providing safe passage for migratory fish at dams. The possible effects on downstream-migrant salmon of changing the flow regime of the river is but one example of the little-understood problems that could be extremely important.

Conclusions Concerning Effects of Dams on Migrations of Juvenile Salmon

Dams constructed on the migration routes of Fraser River sockeye and pink salmon would threaten the survival of downstream migrants not only because of direct mortalities incurred in passage over the dams but also because environmental conditions on the migration routes and possibly in Georgia Strait would be significantly changed. Even if adequate means were developed to pass migrating young salmon safely over dams, the pronounced environmental changes that would result from integrated hydroelectric and flood control development of the Fraser River system could cause a significant decrease in production.

Those races of sockeye that migrate upstream as newly emerged fry to reach their rearing lake could be seriously affected by dams constructed on their migration routes. No method has been devised for passing these small fish upstream over dams. Further, any marked environmental changes could alter the behavior of fry, which might affect their upstream migration.

Migration of sockeye smolts from their rearing lakes may also be affected by dams. When a lake is used as a reservoir for hydroelectric or flood control purposes, storage of water and use of subsurface discharge outlets may alter the physical and chemical characteristics to such an extent as to impede smolt migration. Even more complex alterations of the physical and chemical structure of a lake may result when water is diverted into it from a foreign river system or when part of the water is diverted from it through an artificial outlet not located at the natural outlet. Available evidence suggests that temperature, discharge and other changes produced by hydroelectric and flood control developments on sockeye rearing lakes would adversely affect the downstream migration of sockeye smolts.

There are many indications that the production of sockeye and pink salmon would be reduced if the juveniles of these species had to pass through long, slow-moving reservoirs on their seaward migration. The temperature regime in reservoirs is so different from that in natural rivers that the behavior of young fish might be altered and their tendency to migrate seaward thus affected. Thermal stratification has been suggested as an undesirable feature of reservoirs in that downstream migrants may not pass through warm surface layers to reach a surface exit. One of the obvious environmental changes in reservoirs is the marked reduction in water velocity. Reduced velocities might result in delaying of juvenile salmon beyond the normal migratory period. The disposition for seaward migration may diminish following prolonged fresh-water delay. Landlocking of sockeye populations in reservoirs could be extensive. Even if the downstream migrants did succeed in reaching the ocean, their ability to make the transition to sea water might be adversely affected because of prolonged fresh-water delay.

Passage over spillways and through turbines generally causes a loss of downstream-migrant salmonids, the loss being particularly severe at high dams. Fish surviving passage over a dam may be debilitated to the extent that they may not be able to withstand normal stresses of the fresh-water environment or the stress imposed in making the transition to sea water. Ski-jump spillways and certain modifications of spillway and turbine design have been suggested as possible means of alleviating severe losses of young salmon at dams but these possibilities have not yet been adequately explored.

Much research is currently being conducted in efforts to devise methods of guiding young salmon away from hazardous areas and by-passing them around dams. Several recent experiments have shown that various artificial stimuli may be used to guide fish under laboratory conditions but the possibilities of practical application of artificial guiding methods under the difficult conditions at proposed Fraser River dams appear, at best, to be very limited. Mechanical fish screens, commonly used for preventing young salmonids from entering small water diversions, also appear to be impractical for proposed Fraser River dams. Although the high cost of mechanical screens is a major obstacle to their use at large dams, there are other, equally important, disadvantages. Some of these disadvantages might be overcome by using a combination of the principles involved in the most promising guiding techniques in conjunction with mechanical screens. Both hanging chain barriers and louver barriers have proved partially effective when tested on a relatively small scale. However, in view of the large discharge, high forebay velocities and other physical problems, there seems little likelihood that guiding or screening methods would be practical at proposed Fraser River dams.

Young salmon tend to migrate in the surface layers of deep, low-velocity reservoirs. This fact might be used in certain situations as a means of eliminating turbine and spillway mortality by placing these outlets at great depths and attracting the downstream migrants to surface by-passes. This possible method of protecting downstream migrants has not been adequately explored. Further, submerged outlets would be undesirable in many situations because temperatures in the river downstream would be greatly altered.

Several studies have been conducted to investigate possible methods of collecting downstream migrants in the forebays of dams and transporting them safely to tailwater. Large discharges appear essential for attracting downstream migrants in forebays of dams but smaller flows might be effective if means could be developed for guiding young fish. Although information concerning the requirements of by-passes is being accumulated at a rapid rate, results of current research do not provide any basis for concluding that principles of by-pass design have been sufficiently developed to permit design of effective by-passes at proposed Fraser River dams. Because of the lack of an effective method of collecting downstream migrants at dams, few experiments have been conducted to investigate methods of transporting young fish over dams. Although transportation in tanks is generally considered satisfactory for small numbers of fish, this method would probably be unsatisfactory for handling the large numbers of fish that would have to be passed at Fraser River dams. Other possible methods, such as pipes, flumes, fish locks and free fall, have not been adequately studied.

Increased predation on downstream migrants is quite probably an unavoidable consequence of dam construction. Reduced velocities above dams generally create a more favorable environment for predators. In addition, downstream migrants are probably more available to predators as the fish are released, possibly in a stunned condition, in localized areas below the dams.

The inevitable changes in flow regime resulting from hydroelectric and flood control developments could affect the survival of downstream migrants. Since the flood discharge of the Fraser River would be reduced, the time required for sockeye smolts to migrate from their lake rearing areas to the ocean would be increased. Such delay might affect the ability of seaward migrants to make the transition to sea water. Further, there is some evidence to suggest that the changed flow regime would alter oceanographic conditions in the estuary in such a manner as to adversely affect survival of the downstream migrants.

In general, it may be stated that survival of downstream migrants would be greatly reduced if a number of dams were constructed on the migration routes of the Fraser River. While current research programs may reval certain techniques for alleviating some of the adverse effects, much more extensive research is required before all of the possible adverse effects can be evaluated.

ALTERNATIVES TO NATURAL PRODUCTION

Various alternatives to natural production, chiefly culture in hatcheries, have often been proposed as possible methods of solving many types of fisheries problems. Use of artificial spawning areas, preservation of refuge areas, transplantation of affected populations, predator control and artificial enrichment of natural rearing waters have also been proposed. All have one thing in common in that, on the surface, they seem feasible and simple. However, the biology of the Pacific salmon is so complex and little-understood that efforts to use artificial methods to augment or replace natural production have proved successful only with certain species and certain races. Even with races known to be tolerant to artificial propagation, cultural practices may be unsuccessful when the natural environment is substantially altered.

Much research effort is needed to get beyond the trial-and-error stage in the use of these various alternatives. The importance of further research is being realized in connection with conservation of Columbia River fisheries. Leffler (1959) reported that 20 hatcheries have been rebuilt or newly constructed in attempts to rehabilitate salmon populations in the lower Columbia River. He reported, however, that after reviewing the Columbia program, a committee recommended that expenditures for enlargment of hatching facilities be terminated pending determination of the effectiveness of the hatchery program and until the more serious fish diseases are brought under control. It was recommended that greater emphasis be placed on research, particularly in regard to hatchery diets and diseases.

The following pages indicate some of the known problems associated with alternatives to natural production of salmonids, with special reference to Fraser River sockeye and pink salmon. While this review is by no means exhaustive, it does indicate the highly complex problems and the preliminary state of present knowledge.

Transplantation of Affected Populations

Integrated hydroelectric and storage development on the Fraser River would not involve dam construction downstream from the town of Hope, which is approximately 100 miles above the mouth. It has been implied that this lower area should be used for salmon production and that upriver populations should be transferred to downstream areas.

While there are many biological and physical problems involved in the transplantation of salmon populations, the proposal to transplant upriver populations to downriver areas is not feasible because unused or underpopulated spawning and rearing areas simply do not exist in the downriver area. If a stream or lake is not extensively utilized at present as a salmon spawning or rearing area, the existence of some factor or factors limiting salmon production in that area is suggested. Obvious factors such as adverse temperatures, adverse water quality, or lack of adequate spawning or rearing areas are usually involved in such cases. For the same reasons, there have always been barren areas above Hell's Gate. The only major areas that appear capable of substantially greater production in the Fraser River system are those in which salmon populations were decimated by effects of the Hell's Gate obstruction. These underpopulated areas are located above the locations of some or all of the proposed dams. Suitable sockeye and pink salmon producing areas below Hell's Gate already have well-established populations capable, under proper management, of supporting maximum populations. It is evident, therefore, that transplantation of upriver populations to downriver areas would not provide a solution to the fish-power problems that would result from dam construction in the upriver area.

Of paramount importance in any consideration of the transplantation principle is the fact that the genetic constitution of salmon populations places severe restrictions on the suitability of donor stocks for specific planting areas. Even if unused areas capable of supporting salmon populations were available, inherited characteristics, including time of migration and its relation to the environmental cycle, make upriver sockeye populations unsuitable as donor stocks for downriver spawning areas. Similarly, even in the upriver area, it is difficult to find suitable donor stocks for specific recipient areas. Much experience has been obtained on the Fraser River system in transplantation experiments designed to re-establish sockeye populations that were decimated by the effects of the Hell's Gate obstruction. Most of these experiments have failed, often because of the inability of donor stocks to reproduce effectively in the new environment.

Another important consideration in the transplantation principle is that transplanted stocks must be capable of withstanding the same commercial fishing intensity as other stocks that migrate through the fishery at the same time. There have been several instances where transplanted sockeye stocks have persisted for several cycles but have not sustained and are apparently incapable of sustaining a commercial fishery. Examples of such populations are the sockeye runs established by transplantation in Issaquah Creek and

Cedar River in the State of Washington. It has been found very difficult to re-establish depleted Fraser River sockeye populations because of the overlap in migrational timing of the various races. Since all races of Fraser River sockeye, with the exception of the Early Stuart, overlap other races in the timing of their migration through the commercial fishery, it is impossible to adjust the rate of fishing mortality for one race without disturbing the rate of fishing mortality of other races.

In a discussion of possible methods of rectifying an apparently serious decline of the Pitt and Birkenhead sockeye runs, it has been pointed out (Internat. Pacific Salmon Fish. Comm., 1960) that any regulatory adjustment of the commercial fishery to provide additional escapement of these two runs would be economically unsound. The report also states: "The continued decline in these two races of sockeye raises a serious problem because of the apparent genetic complexity of each of the two races. If either of the two populations were to approach extermination it is highly doubtful if any other races of Fraser River sockeye could adjust to the fresh-water environment represented by the Pitt and Birkenhead watersheds." Since transplanted populations do not appear to reproduce at as high a rate as long-established populations and since selective protection in the commercial fishery is generally not possible, it is usually difficult or impossible to create self-sustaining and commercially significant populations by means of transplantation.

Experiments have led to the formulation of certain basic concepts considered essential for successful transplantation of sockeye populations. These requirements have been summarized as follows (Internat. Pacific Salmon Fish. Comm., 1957): The migration distance from the ocean to the recipient stream must be the same as the migration distance to the donor stream. The temperature cycle in the reproductive area, including the spawning ground and the lake rearing area, must be the same in the donor and recipient streams.

Data collected by the Commission show that early spawning sockeye cannot be successfully transplanted to environments timed for late spawning, nor can sockeye migrating short distances to spawning grounds be transplanted to areas requiring a long migration. The same considerations may also be essential in transplanting Fraser River stocks of pink salmon. Ward (1959) has shown the existence of "early" and "late" runs of pink salmon. Transplants of upriver pink salmon populations, which are "early" runs, to reproductive environments typical of "late" runs might have little chance of success.

Several experiments have demonstrated that transplanted populations retain the migration timing of the donor stock. For instance, Rich and Holmes (1929) reported experiments in which eggs from Columbia River chinook salmon were incubated in hatcheries and the progeny released in other parts of the Columbia River watershed. Some of the releases were complete failures, with no returns detected in either the donor or rcipient streams. Returns of marked individuals were obtained in many cases but there was considerable straying of the adults to streams other than those planted. Most significant, however, was the fact that the transplanted fish that did return to the Columbia River generally spawned at the same time of year as the donor stocks rather than adjusting their timing to suit the environmental cycle of the receiving stream. Progeny of early-run chinook salmon planted in streams that supported native runs of late-run chinooks returned to the stream as early-run fish. Transplants of late-run fish to other late-run streams returned at the normal time. While the published literature on the subject of transplantation is not extensive, the unpublished results of many experiments confirm that transplanted populations retain the migration timing of the donor stock. Even if unused spawning and rearing areas were available in the lower Fraser River area, transplantation of upriver runs to downriver areas having different environmental conditions than the upriver areas would not be effective in establishing new runs.

Other experiments have also demonstrated the importance of duplicating the distance from the ocean to the donor and recipient streams. Early attempts to establish sockeye populations in depleted areas of the upper Fraser River watershed by transplanting populations from downriver areas were completely unsuccessful. Foerster (1946) stated that over 10,000,000 sockeye eggs were transferred from lower Fraser River streams to Eagle River, which is tributary to Shuswap Lake. These transfers, made between 1922 and 1926, were for the purpose of restocking a once-productive sockeye spawning area. Neither these transfers nor the transfer of 16,000,000 sockeye from Cultus Lake to Eagle River in 1929 were effective in establishing a self-sustaining sockeye population in Eagle River.

Foerster's report gives results of other experiments designed to determine the effectiveness of the transplantation method of rehabilitating upriver sockeye populations. Fingerlings reared in Eagle River water from eggs taken at Cultus Lake, tributary to the lower Fraser River, and at Adams River, tributary to Shuswap Lake, were marked and released. Only 12 adults of Cultus Lake origin were taken in the commercial fishery and not one was seen in Eagle River. Production from eggs obtained from Adams River, which is tributary to the same lake as Eagle River, was somewhat better but the returns to the spawning grounds in Eagle River consisted of only 10 adults from a total release of 559,400 fingerlings. The conclusion was reached that transplantation definitely failed to restore the sockeye runs to the depleted Eagle River area, there being either no returns (Cultus Lake eggs) or very small returns (Adams River eggs). Foerster stated: "It may be concluded, therefore, that mere transfer of eggs from one area to another will not necessarily result in an increase in the spawning stock returning to the new area. It was at first thought that the use of lower Fraser River stock to restore the runs to the upper river where decidedly longer up-river migrations are required might be unwise and unsound because of the possible inability of the lower river 'races' to meet the long and gruelling ascent of the river to the newer areas. It seems evident now, from the experiments with Adams River eggs, that use of upper Fraser River stock that has shown the ability to make the ascent of the river to the

Shuswap area is also not effective. Other factors must be involved and these should be elucidated before further transplantings are made, if restocking is to be successful."

It can be seen that transplantation of upriver runs to downriver areas would not be practical or successful in compensating for the loss of upriver spawning and rearing areas. Not only are there no unused areas available below Hope for transplanted populations but also it would be impossible to duplicate in the downriver area the environmental conditions and migration distances of the upriver runs. It is also evident that successful transplantation even from one upriver area to another is difficult to achieve. The transplantation experiments cited below illustrate some of the problems involved in establishing salmon populations in barren but potentially productive areas.

TRANSPLANTING ADULTS, FINGERLINGS, FRY AND EGGS

In some cases, adult salmon blocked by dams have been transferred to streams below the dams. Chapman (1940b) reported attempts to transfer adult salmon and steelhead captured at Rock Island Dam on the Columbia River to the Wenatchee River, which enters the Columbia between Rock Island and Grand Coulee Dams. Most of these fish were destined for spawning and rearing areas that had been made unavailable to them by construction of Grand Coulee Dam. After being transported by tank trucks and released in the Wenatchee River, which was racked at its lower end, the fish did not migrate to upstream spawning areas. After the weir was removed, some of the fish that had been tagged before release in the Wenatchee River were recaptured in other Columbia River tributaries. The salvage operations designed to preserve the salmon and steelhead populations that originated upstream from Grand Coulee Dam were partially effective, however. Some species and races were apparently capable of reproducing in tributaries downstream from Grand Coulee Dam.

In 1957, the feasibility of establishing a sockeye population in a barren area above a falls on Horsefly River was studied. A tank truck was used to haul 1000 sockeye from a spawning area in Horsefly River immediately below the falls to the stream upstream from the falls. However, tagging demonstrated that all of these fish moved downstream again and did not spawn in the large potential spawning area above the falls. The degree of ripeness of transplanted fish influences the success of such transplants. Fish close to maturity may be retained in new areas and spawn successfully provided the environmental conditions are satisfactory. Experiments at the Quesnel Field Station have shown that adult sockeye transported by truck or airplane will spawn satisfactorily when *forced* to remain on an artificial spawning area.

Parker and Hanson (1944) also reported successful spawning of transported adult salmon. Sacramento River chinook salmon that were prevented from migrating to their native spawning areas after construction of Shasta

Dam in California were transferred to Deer Creek, tributary to the Sacramento River. Spawning was apparently successful but a self-perpetuating run has not been established.

Transplants of fry and fingerlings have not been successful in establishing or rehabilitating salmon populations in the Fraser River system. Seventy-nine transplants of young sockeye undertaken between 1902 and 1936 failed in each instance to provide beneficial results. In all recent transplantation experiments on the Fraser River, donor stocks have been sought that spawned in areas located about the same distance from the sea as the areas contemplated for restocking. It was required that the water temperature cycle during the period of spawning and incubation in both the donor and recipient areas be approximately the same. In spite of these rigid requirements, transplants of sockeye fingerlings involving a total of 1,096,000 fish, failed to establish a single stock of spawners in barren spawning areas (Internat. Pacific Salmon Fish. Comm., 1957).

Pink salmon fry have also been transplanted from one river system to another. Since certain pink salmon streams support populations of spawners only every other year, attempts have been made over a period of many years to establish "off-year" populations in these streams. Pritchard (1938) described early transplantation experiments with pink salmon to establish a run in McClinton Creek, on an island off the British Columbia coast. In 1931 and 1935, eggs were incubated in a temporary hatchery built on a small tributary to McClinton Creek. Approximately 1,151,000 unmarked and 232,000 marked fry were liberated in the two years. The total return of adults to McClinton Creek consisted of only seven fish. Pritchard reported that transfers of pink salmon eggs from Alaska to State of Washington streams were also unsuccessful.

Transplants of eyed eggs have apparently been more successful. Approximately 300,000 eyed sockeye eggs and 193,000 fingerlings, both obtained from lower Adams River in 1950, were planted in Portage Creek in the Seton-Anderson system. Only a few pairs of spawners used Portage Creek in 1950 but in 1954 the escapement was estimated to be 3505 adults. Growth of the spawning population to 4803 fish in 1958 would suggest that a self-maintaining population is now established in this area. The donor stream and Portage Creek have approximately the same reproductive environment with respect to water temperature and are located about the same distance from the ocean.

A small run of sockeye has been established in Upper Adams River as a result of eyed-egg transplants from Seymour River, which is tributary to Shuswap Lake. Approximately 667,000 eyed Seymour River eggs were planted in Upper Adams River in 1950, 495,000 in 1954 and 780,000 in 1955. On the basis of live counts, it was estimated that 205 adult sockeye returned to the spawning area in 1954. An accurate count of the 1958 escapment could not be obtained because of adverse water conditions but this run was probably somewhat larger than that in 1954. When the proper donor stock is used, egg transplants may be effective in establishing runs in barren areas.

Eyed-egg transplants have also been used in attempts to establish runs of pink salmon. An experiment was undertaken in 1954 to study the possibility of establishing "off-year" runs of pink salmon in the previously described controlled-flow spawning channel in Jones Creek near Hope, B.C. Eggs were transferred from Lakelse River on the Skeena system and planted in Jones Creek channel after eyeing. From a total of 1921 females and 900 males trapped at a weir on Lakelse River, Neave and Wickett (1955) reported the following survival rates for the egg to free-swimming fry stage:

	Number	Per Cent
Eggs stripped and fertilized at Lakelse........	2,976,000	100
Eyed eggs shipped from Lakelse..................	2,738,000	92
Live eggs planted at Jones Creek................	2,606,000	87
Eggs hatched in Jones Creek.....................	2,140,000	72
Fry migrating from controlled channel..........	1,100,000	37

The percentages are based on the number of eggs originally taken from the parent fish. The fry output represents about 42 per cent of the live eggs planted. Summarizing this phase of the study, the authors stated:

"Fry output recorded from naturally spawning pink salmon in British Columbia streams has varied from about 1% to 23%. While the migrating fry in these instances were subjected to predation over somewhat greater distances than at Jones Creek before being counted, the relative success of the experiment up to the present stage seems obvious.

"Thus far, the experiment has produced the first known large output of pink salmon fry in the Fraser River system in a barren year. The number of migrants is equivalent to that which is known to have produced many thousands of returning adults under natural conditions in other localities."

Return of adults from this transplant was described in a later report (Wickett, 1958a) as relatively low, being 0.3 per cent of the outgoing fry as compared with a production rate of 0.9 per cent for the native population. Approximately 2800 pink salmon spawned in the creek in 1956 but because of unsatisfactory conditions—floods and silting—survival from the egg to fry stage was only 10 per cent. There were numerous reports of adult pink salmon in the Fraser River in 1958 when the progeny of these fry should have returned to spawn but the total spawning population in Jones Creek consisted of only 50 to 60 fish. Discharge of the creek was low and temperatures were high at this time. While the return from the fry to adult stage was three times as high for native as for transplanted stock, the successful return of off-year pinks suggests that further research might lead to establishment of commercial-sized populations of pink salmon in barren areas provided suitable donor stocks are selected and provided environmental conditions in the receiving stream are suitable for spawning and incubation.

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TRANSPLANTATION AS COMPENSATION FOR LOSS OF NATIVE SPAWNING AND REARING AREAS

The transplantation technique offers no hope for solution of fish-power problems that would result from extensive dam construction in the Fraser River system. Downriver areas that would not be obstructed by dams are already utilized for salmon production. It must be emphasized that numerous attempts have been made over a period of many years to re-establish sockeye populations in once-productive areas of the Fraser River system by this means without a great deal of success. Many of the transplants have failed completely while others have succeeded only in establishing small runs. With only one or two possible exceptions, sockeye runs that have been initiated by transplantation in the Fraser River system have not yet proved capable of reproducing at a rate equal to other natural-producing runs that migrate through the commercial fishery at the same time. Until it can be shown that transplanted runs are capable of competitive rates of production, the transfer of seed stock from one area to another cannot be considered an effective method of establishing self-sustaining populations.

Transplantation must be considered as an experimental technique which involves many problems and which has not yet been entirely successful even on an experimental basis. If the transplantation technique can be developed to the stage where it is an effective means of establishing sockeye and pink salmon populations in barren areas of the Fraser River system, this technique will be utilized to the fullest extent to increase the value of the Fraser River fisheries resource independent of any relationship with dam construction.

Hatchery Culture

Of all the methods of artificially culturing salmon, none has been as popular as the hatchery. Its apparent simplicity, combined with a desire to reduce the high fresh-water mortality rates observed in nature, has contributed to the popularity of hatchery culture. While hatcheries have been visualized as the solution to many fisheries problems, serious unexplained limitations are evident even after several decades of hatchery operation. In certain situations, hatcheries can undoubtedly fulfill an important role in fisheries conservation. Indeed, much success has apparently been achieved in some cases. Many unresolved problems have arisen, however, so that hatchery operations have failed to attain practical levels of production in the case of certain species and certain races. Where the fish involved were more tolerant to environmental changes, as in the case of coho and certain races of chinooks, hatcheries appear to have been effective in increasing total fish production. Further, hatcheries have maintained and even increased some salmon populations where natural spawning and rearing areas were limited. Little success has been recorded in fresh-water propagation of pinks, chums and spring chinooks, however, indicating that the different species have pronounced differences in their tolerance to the artificial environment of hatchery culture. In contrast to those instances where high rates of return have been achieved, there are other instances where hatcheries have failed as replacements for natural production. Further, capital and operating costs of salmon hatcheries often appear so high in proportion to the number of returning adults that the question arises, in some cases, as to whether they are of sound economic value except when a relatively high recreational and aesthetic value is placed on the product. Substantial improvements in the benefits to be derived from hatcheries might be obtained if intensive research was conducted to isolate and eliminate the inherent weaknesses of artificial propagation.

In recent years, hatchery culture has been proposed as a solution to Fraser River fish-power problems (Gwyther, 1958). It has been suggested that hatcheries should be constructed in the lower river area to compensate for loss of spawning and rearing areas that would be made inaccessible by dam construction in upriver areas. This proposal would involve holding the adults to maturity, spawning and incubating the eggs, and rearing the young to the seaward-migrant stage. Sockeye would have to be reared for approximately one year. Without presenting details concerning techniques of hatchery culture, it is the intention in this report to present an over-all evaluation of the possible effectiveness and problems of the cultural practices implicit in this proposal.

HOLDING ADULTS TO MATURITY

One of the first problems encountered in artificial culture of salmon is that of holding adults in good condition until sexually mature. This problem is particularly important in a large river system such as the Fraser where some sockeye migrate over 725 miles from the ocean to reach their spawning grounds. For instance, peak of passage at New Westminster of sockeye destined for Stellako River often occurs in early August, but peak of spawning does not occur until about September 25. If these fish were retained for hatchery operations in the lower Fraser River area they would have to be held for at least 50 days. Chilko River sockeye would have to be retained for about the same length of time and early-run sockeye destined for streams in the Stuart system would have to be held for about 30 days. Estimates of the average periods from time of passage at New Westminster to time of spawning for major races of sockeye are shown in Table 10. It is apparent that use of existing populations as a source of eggs for hatchery operations in the lower Fraser River area would involve retention of adults for lengthy periods. Further, fish would have to be held during summer months when suitable water supplies of moderate temperatures are difficult if not impossible to obtain. The physical and biological problems involved in capturing, holding and artificially spawning millions of upriver sockeye for hatchery operations in the downriver area would be so difficult to overcome that the entire proposal seems unworthy of serious consideration, at least at the present state of knowledge.

Retention of pink salmon, which migrate late in the season and spawn soon after arrival on their spawning grounds, would probably be less difficult. Ward (1959) showed that, in 1957, pink salmon passed through the Fraser

River gill-net fishery from August 31 to at least October 9, with the duration of passage of each major "race" extending over a period of 20 to 40 days. The mean date of passage through the lower Fraser River of the Seton, Thompson and main-stem Fraser races occurred about 20 days before the peak of spawning. Pinks destined for spawning areas in tributaries of the Fraser below Hope migrated through the lower part of the Fraser River about 20

TABLE 10—Approximate periods from peak time of passage at New Westminster to peak time of spawning for major races of Fraser River sockeye in 1954.

SPAWNING STREAM	PERIOD[1] OF PASSAGE AT NEW WESTMINSTER		PERIOD[2] OF PEAK SPAWNING	TIME LAPSE (Days from peak to peak)
	Peak Day	Duration of Run		
Early Stuart Streams	July 5	June 18 - July 22	Aug. 3 - 11	31
Bowron River	July 19	July 9 - Aug. 5	Aug. 25 - Sept. 5[3]	42
Pitt River	July 19	July 5 - Aug. 5	Sept. 10 - 15	55
Nadina River	July 26	July 14 - Aug. 5	Aug. 26 - Sept. 14	41
Horsefly River[4]	July 25	July 17 - Aug. 2	Aug. 27 - 29	34
Harrison River	Sept. 13	Aug. 16 - Sept. 17	Nov. 7 - 10	56
Seymour River	Aug. 2	July 16 - Aug. 26	Sept. 1 - 4	31
Chilko River	Aug. 2	July 1 - Sept. 2	Sept. 23 - 25	53
Stellako River	Aug. 2	July 14 - Sept. 6	Sept. 25 - 27	55
Raft River	Aug. 3	July 23 - Aug. 12	Aug. 24 - Sept. 2	25
Late Stuart Streams	Aug. 3	July 20 - Aug. 19	Sept. 13 - 16	42
Birkenhead River	Aug. 16	Aug. 4 - Sept. 30	Sept. 25 - 27	41
Weaver Creek	Sept. 13	Aug. 27 - Sept. 30	Oct. 20 - 21	37
Cultus Lake	Sept. 25	Aug. 27 - Oct. 7	Nov. 18 - 21	56
Adams River	Sept. 21	Sept. 13 - Oct. 7	Oct. 10 - 20	24
Little River			Oct. 10 - 20	24
South Thompson River			Oct. 15 - 20	27

[1] Period of passage determined by analysis of scale pattern of commercial catches above Pattullo Bridge.
[2] Period of peak spawning as recorded in Internat. Pacific Salmon Fish. Comm., (1955).
[3] Spawning period for 1952 because no observations made in 1954.
[4] All dates given are for the 1953 run because of small escapement in 1954.

to 30 days before spawning. Assuming that the rate of maturation during retention is the same as under natural stream conditions, the retention period for Fraser River pink salmon would probably not be longer than one month for hatchery-culture operations in the lower Fraser River area.

Very few attempts at holding adult sockeye or pink salmon for long periods of time have been reported. Foerster (1938), in comparing relative efficiencies of natural and artificial propagation of sockeye salmon, took into consideration the loss of eggs resulting from retention and handling of adults during hatchery culture. Sockeye were held in Sweltzer Creek, the outlet stream of Cultus Lake. Some early-arriving sockeye were held for roughly a month but the majority were held for only one or two weeks. The loss of eggs occasioned by retention and handling of adults varied from 13.4 to 33.9 per cent in five years of tests, the average loss being 22.8 per cent. During retention, the fish continually fought the hatchery weir in an effort to break through. This activity undoubtedly caused some of the mortality. Discussing results of the experiment in 1926, Foerster (1929b) stated: "In artificial propagation, however, it is necessary to retain the fish until they are in proper condition for spawning. All fish of the 1926 run, therefore, had to be held below the weir and a considerable loss occurred. This loss was accentuated slightly owing to the fact that the entire run was retained, whereas in a normal year of hatchery operation, the early and fresher fish are allowed to pass on to the lake, and also to the fact that the increased handling of fish consequent upon the presence of both ripe and unripe individuals may have proven detrimental. The losses were not, however, wholly caused by this necessary retention. Difficulty was experienced throughout the season in obtaining fully-ripe males and it often happened that a male which appeared to be in good condition would give up very little milt. These latter were first thrown back but it became apparent that they did not survive the handling and were picked up dead. It had been expected that they would continue to develop and might be used later when in better condition. This would account of a fair proportion of the losses among the males. Females partly spawned and thrown back to develop showed a similar tendency to succumb or if they did chance to survive, the eggs were often found to be water-hardened and useless."

In comparing natural and artificial propagation of coho and chinook salmon and steelhead trout, Briggs (1953) quoted several sources in an attempt to arrive at an average figure for the loss of eggs during retention of adults for hatchery culture. He attributed significant egg losses during this period to (1) mortalities of adults during retention, (2) futile spawning attempts in the retention area, (3) killing of "green" fish in which the sex products were too immature for use, and (4) failure to remove all eggs from the body cavity during egg-taking operations. He stated that under ordinary conditions the loss of eggs from the above causes greatly exceeds that which takes place during incubation in the hatchery. Briggs pointed out that the extent of the "holding" mortality varies widely with both the length of the retention period and the size of the holding ponds. When the holding ponds are located near the natural spawning area and the retention period is relatively short, significant losses can occur but more extensive losses often occur when the first are held in a downriver area far-removed from their natural spawning grounds. Average egg losses attributable to artificial retention were estimated by Briggs to be about 30 per cent for coho and chinook salmon and 40 per cent for steelhead.

There can be no doubt that loss of eggs resulting from retention and handling of sexually immature adults is a serious factor limiting the success of some hatchery operations. The loss is accentuated when the retention period is long and when environmental conditions are not ideal. It has previously been shown that sockeye spawning under natural conditions generally deposit ever 95 per cent of the total number of eggs available. Substantial losses occur when temperature conditions are temporarily adverse. It appears, however, that the artificial conditions necessitated by retention and handling of fish for hatchery operations cause a significant mortality of fish and, consequently, a significant loss of eggs.

A survey of published data suggests that temperature is a critical factor controlling the success or failure of holding salmon to maturity. Chapman (1940b) mentioned a steady, large mortality of spring chinooks in the Lewis River where water temperature in the holding ponds often exceeded 60°F. However, when holding ponds were established in Cougar Creek, where temperatures did not exceed 50°F, more success was achieved. An experimental holding pond built at Rock Island Dam on the main Columbia was also tested. Of 169 chinooks, sockeye and steelhead placed in the pond, 39 per cent died before spawning. Hanson *et al.* (1940) reported a holding mortality of 18 to 44 per cent in Battle Creek, a tributary of the Sacramento system. A total mortality among chinooks held in Sacramento River water was recorded where water temperatures ranged from 62° to 73°F. On the other hand, Parker and Hanson (1944) regarded Deer Creek in California as a satisfactory holding area for chinooks transferred from the Sacramento River even though temperatures were apparently high.

A successful attempt at holding sockeye for long periods has been reported by the Washington Department of Fisheries (1958). Fish were released into a deep, floating pen in Baker Lake, which is the natural maturing area for this race. It is important to note that the net was large and deep enough that the fish were not retained in an unnatural environment and that they were able to choose suitable water temperatures. The Fisheries Research Board of Canada has also been successful in holding coho and sockeye in a large pen in Great Central Lake. Chinook and sockeye salmon have successfully been held to maturity at several Pacific Coast installations. Many adult salmon are also being held at the many hatcheries in the States of Washington and Oregon but mortality during retention is still a serious problem, especially where fish must be held for more than a week or two.

Since the problem of holding adult salmon is a critical factor in hatchery culture, some research has recently been conducted in an effort to decrease the maturation period of salmon. Burrows *et al.* (1952) injected pituitary material in an attempt to accelerate maturation and Palmer *et al.* (1954) injected fish and mammalian gonadotrophins for the same purpose. Combs and Burrows (1959) also reported on the effects of injected gonadotrophins on maturation and spawning. In most cases, mortality of the injected fish was increased and the fertility of the eggs reduced. Injection of pituitary material and mammalian gonadotrophin had no appreciable effect in inducing more rapid maturation. Injections of fish pituitary extract were responsible for a slight advance in maturation time of female salmon and in some cases a considerable advance in male maturation. However, the small degree of success in inducing more rapid maturation and the undesirable side effects preclude use of these techniques at this time.

The use of controlled light has been employed successfully on a small scale to modify the rate of maturation of salmon. Combs *et al.* (1959) conducted experiments with sockeye salmon. Spawning was delayed by lengthening the daily period of light exposure but was hastened by use of shorter-than-normal photoperiods. Accelerated maturation appeared to favor higher female survival but egg mortalities were significantly increased. These authors considered the use of shorter-than-normal photoperiods to be a practical method of reducing adult salmon mortalities during a lengthy holding period.

Although adequate criteria are not available to permit the design of collecting, holding and spawn-taking facilities for upriver runs of sockeye and pink salmon, rough calculations can be made to give some indication of the numbers of fish that would be involved and the physical magnitude of the facilities that would be required. As previously stated, the escapement of Adams River sockeye salmon in 1954 amounted to more than 2,000,000 fish, of which approximately 1,250,000 entered the Fraser River in one day. Other major runs to the Chilko, Stuart and Quesnel systems, while not currently as large as the Adams run, are significant and some are increasing in size each cycle. Judging by historical records of the pre-1913 runs and by surveys of available spawning and rearing areas, it is not unreasonable to expect a total, dominant-year spawning escapement of 8,000,000 sockeye above Hope. Before the Hell's Gate disaster, all of the upriver runs were dominant on the 1913 cycle but, at the present time, large runs in the Thompson River watershed are dominant on the 1958 cycle whereas upriver runs such as the Stuart and Quesnel runs, which have a tremendous potential for growth, are dominant on the 1957 cycle. Approximately 60 per cent of the total escapment, or 5,000,000 sockeye, could therefore be expected in any one year.

Fraser River pink salmon also spawn in the years when upriver sockeye runs are dominant. It has previously been shown that the spawning population of pink salmon in the Thompson River increased so rapidly following construction of the Hell's Gate fishways that it may reach 2,000,000 within a few cycles. It is evident, therefore, that replacement of upriver production by means of artificial propagation could reasonably involve the handling of 7,000,000 sockeye and pink salmon in one year out of each four-year cycle, as well as lesser numbers of other species. Collecting, holding, and artificially spawning this number would present many problems that appear insurmountable at the present time.

Some method would have to be developed for diverting these fish into the holding facilities. A barrier dam across the Fraser River at the location of the holding facilities would probably be the most satisfactory solution to this problem. As previously discussed, other possible methods of guiding or diverting adult salmon do not appear to be satisfactory. Since such a dam would be very costly and would interfere with navigation on the Fraser River, the possibility of using the farthest downstream hydroelectric dam, presumably near Yale, as a fish-collection device could also be considered. However, the giant holding and hatchery facilities that would be required could not be located upstream from Hope because of the lack of suitable land area and water supplies. It would therefore be necessary to transport the adults from the proposed power dam near Yale to the holding facilities, which could probably not be located closer than the Harrison-Agassiz area. As previously mentioned, the problems involved in collecting and transporting the large populations of Fraser River sockeye and pink salmon are so great that it appears impractical to attempt such an operation.

It is impossible at present to determine what facilities could be used for successfully holding 7,000,000 sockeye and pink salmon to maturity. In fishway design, each sockeye and pink salmon is assumed to require a minimum of 4 cu. ft. for active movement and 2 cu. ft. for resting. However, maturing fish do not simultaneously occupy more than one level of a retention area. That is, unless they are overcrowded, all of the fish generally remain in a single layer instead of "piling up" several layers deep. Experiments concerning the passage of fish through locks indicate that adult salmon exhibit a state of alarm or uneasiness when confined in volumes of water that allow less than 20 cu. ft. per fish. While conclusive evidence concerning the volume requirements for holding adult salmon to maturity are not available, these criteria suggest that each of the 7,000,000 sockeye and pink salmon would require a holding volume having a surface area of 2 sq. ft. and a depth of 10 ft. The total holding faclities would therefore require a volume equivalent to 28 ponds, each 5000 ft. long, 100 ft. wide and 10 ft. deep. It would be necessary to replace the water in the ponds frequently to supply adequate oxygen and to avoid excessive heating during the summer months. Although research might lead to the development of more practical and efficient holding facilities, it appears that a discharge of 1000 c.f.s. for each pond, or a total of 28,000 c.f.s., would be required.

It must be emphasized that the quality of the water, particularly with respect to temperature, is of paramount importance. Experience suggests that the temperature in holding ponds should be about 55°F, although daily and seasonal variations in temperature probably have considerable physiological significance in the maturation processs. Temperatures higher than 60°F result in excessive mortalities of immature fish and may reduce the survival of the eggs. Low temperatures prolong the maturation period and may affect the survival rates. If a suitable water supply could be obtained in the lower Fraser River area, it could only be developed at tremendous cost. Suitable shade would be required at each holding pond to minimize heating of the water and to provide the shaded, protective areas that fish are known to utilize in nature.

In spite of the most elaborate and costly facilities there could be no assurance of any degree of success in holding millions of Fraser River sockeye and pink salmon. The holding problem is obviously more complex in this case than in those cases in which some success has been achieved in artificial retention. The length of the holding period and the large numbers of fish involved make the problem of artificial retention of upriver races of Fraser River sockeye and pink salmon particularly difficult. The overlap in timing and migration of the various races and species, including coho, chinooks and steelhead as well as sockeye and pink salmon, would complicate the whole operation. Segregating ripe fish from immature fish in the holding areas would involve a great deal of handling, which would probably cause much higher mortality rates than those observed in hatcheries located near the spawning areas. Artificial retention of Fraser River sockeye and pink salmon for lengthy periods in the downriver area could also lead to serious outbreaks of disease. It is evident that loss of eggs resulting from retention and handling of adults would be a serious factor in limiting the production of upriver races of sockeye and pink salmon in hatcheries located in the downriver area.

Facilities required for incubation of the eggs and rearing of the young would require even more involved design considerations and would necessitate extensive facilities even more elaborate than those required for holding of the adults. Some of the physical and biological problems are detailed in succeeeding pages.

EGG INCUBATION

The observed high survival of eggs incubated in hatcheries has long been considered an outstanding advantage of hatchery culture but for various reasons, largely unknown, the subsequent survival rate for hatchery-produced fry is usually much lower than for fry produced in nature. The increased egg-to-fry survival in hatcheries appears to result primarily from the increased amount of dissolved oxygen made available to the eggs and may also be associated with the increased rate of water flow past the eggs, which carries away waste products of metabolism. Whereas natural spawning results in an average survival rate of only about 10 per cent, survival from eggs to fry may occasionally be higher than 90 per cent in hatcheries.

Foerster (1938) conducted tests from 1925 to 1936 at Cultus Lake to compare the numbers of sockeye smolts exiting from the lake from known numbers of eggs. The efficiency of natural propagation was not statistically different from artificial propagation, where the eggs were incubated in a hatchery and the fry released into the lake. For those years in which hatchery-produced fry were released into the lake, the number of fry released was approximately 60 per cent of the total number of eggs available from adult females. During the incubation of eggs in the hatchery, the losses varied from 6.5 to 18.1 per cent to the fry stage. With this loss, and the losses resulting from incomplete stripping and death of unspawned females at the hatchery weir, it was found that the ultimate hatchery product represented approximately 60 per cent of the total number of eggs available from all the females in the run or 80 per cent of the eggs available for stripping. Despite the serious losses caused by retention and handling and the significant loss during incubation, the number of fry produced by hatchery operations was probably much greater than the number of fry that would have been produced from the same number of eggs under natural conditions. Foerster reported, however, that "from a statistical analysis of the data obtained, it is readily apparent that artificial propagation exhibits no significantly increased efficiency, in point of seaward-migrating young sockeye, over natural production."

Very little has been done to determine the reasons why hatchery-produced fry are less viable than those produced in nature. Currently, attempts are being made in some salmon hatcheries to ensure that eggs are incubated under conditions as nearly natural as possible. This involves careful regulation of temperature and light. Water temperatures are controlled in attempts to eliminate excessive mortalities and to permit the transition of the alevins to the feeding fry stage at a time synchronized with the onset of favorable environmental conditions in the spring months. The necessity of obtaining suitable temperatures places severe restrictions on the number of sites available for hatcheries and frequently involves operating problems such as costly pumping from various levels in lakes.

Some experiments have been conducted to investigate the effects of light on incubating eggs and alevins. In nature, eggs are incubated in almost complete darkness. Exposure of film negative placed in spawning gravel at a depth where sockeye eggs are usually deposited failed to show any measurable penetration of light. Sockeye eggs and alevins incubated in darkness showed distinct differences from eggs and alevins exposed diurnally to the indirect daylight encountered in normal hatchery operations. For instance, total egg and alevin mortality was greater among the light-exposed group. Further, terminal swimming speed and endurance were significantly lower in the group exposed to light during incubation and alevinage (Internat. Pacific Salmon Fish. Comm., 1957). In view of these results, eggs in the Commission's Quesnel Field Station have been incubated in darkness. In further efforts to provide an environment similar to that in nature, water temperatures were artificially regulated so that they approached the temperature pattern in the stream from which the eggs were obtained.

An experimental egg incubation station for studying possible improvements in technique was established by the Fisheries Research Board of Canada on Kleanza Creek, a small tributary of the Skeena River that is utilized by a small run of pink salmon. During the period of operation of this experimental hatchery, tray-type incubators capable of holding 10,000,000 eggs were supplied with water drawn directly from Kleanza Creek so as to expose the eggs to the same temperatures as in nature. An attempt was made to maintain the hatchery in darkness during incubation and alevinage. The fry were transferred from the hatchery trays to a light-proof release trough consisting of a 4- by 4- by 4-ft. box with water introduced under a wire-mesh floor and overflowing at the top. As anticipated from prior laboratory experiments, the newly hatched fry remained at the bottom of this box until they reached the normal migrant stage, when they swam up and out and entered the creek through a pipe (Fish. Res. Bd. Can., 1959).

In spite of current optimism concerning possible success in artificial incubation, certain limitations of this aspect of hatchery culture must not be ignored. Losses during adult retention, egg-taking, incubation and fry release may, in some years, cause catastrophic reductions in hatchery output. Disease among the maturing adults or fungus infections during the incubation period can, on the basis of experience, seriously limit production. In addition, failure of the water supply or careless operation is a constant threat.

Through continued research, it may be possible to develop satisfactory methods for artificially incubating salmon eggs and releasing the fry so that the ultimate survival rate of fish produced from eggs incubated in hatcheries may approach that obtained in nature. If and when this stage of development is reached, it might be possible to greatly increase the production of species such as pink salmon that do not require fresh-water rearing. Production of sockeye might also be increased in areas where productivity is now limited by availability of good spawning areas. It will be shown in later sections, however, that artificial rearing of sockeye involves many problems that require extensive research. The physical and biological problems of providing and operating adequate facilities for holding, spawn-taking, and incubation to replace the natural production of millions of spawners appear to preclude the possible utilization of egg-incubation stations as a solution to Fraser River fish-power problems.

WATER QUALITY

Davis (1956) considered water quality as a definite limiting factor in fish-cultural operations and pointed out that several characteristics of water are important. These include temperature, pH, gas content, levels of any pollutants or disease organisms, mineral content and turbidity. Little research has been done, however, to determine essential characteristics of water supplies for hatchery culture.

The most suitable water temperatures for artificial culture no doubt vary among salmonids. Extreme temperatures must be avoided as they generally result in poor growth, reduced efficiency in food conversion, and increased susceptibility to disease. For rearing salmon and trout, water temperatures of 60° and 45°F might be regarded as the upper and lower limits. It seems most desirable to follow the natural temperature cycle during egg incubation so that emergence in the hatchery is synchronized with that in nature. The effects of temperature on the success of egg incubation have been detailed in earlier sections of this report.

Gas content of the water is also an important consideration in fish-cultural operations. The principal gases dissolved in water which have a bearing on its suitability are oxygen, carbon dioxide and nitrogen. High levels of dissolved oxygen are desirable for both incubation and rearing but carbon dioxide and nitrogen are detrimental. Embody (1936) considered that any concentration of carbon dioxide above 15 p.p.m. must be looked upon with suspicion. Levels higher than 2 p.p.m., which is the level normally found in water in equilibrium with the atmosphere, may indicate pollution from organic waste or a deficiency of oxygen. Water supersaturated with nitrogen can produce "gas disease", which is usually fatal to fish. Water sources containing even small quantities of toxic gases such as hydrogen sulphide should be avoided. Removal of these toxic gases may in some cases be a costly process.

Little information is available concerning the relation of hydrogen ion concentration to the suitability of water for fish culture. Embody reviewed some information which suggested that trout are tolerant over the whole pH range of 4 to 9 normally found in natural waters. Ellis *et al.* (1948) observed that in 90 per cent of areas where good fresh-water fish faunas were found the pH range was 6.7 to 8.2. Values outside this range may therefore be undesirable.

Mineral content of water used in hatchery culture may be an important factor controlling productivity but little research has yet been done to indicate its significance. The importance of several minerals has been examined with respect to trout production at the Cortland hatchery in New York. In reviewing the subject of mineral deficiency, Phillips (1959) stated that only one deficiency disease is recognized in fish—that caused by a lack of iodine. He felt, however, that other such deficiencies occurred and probably produced various diseases. Studies at Cortland with radioactive isotopes have been valuable in mineral studies and have demonstrated that calcium, phosphorus, cobalt, and chloride are absorbed directly from the water. The amount of calcium absorbed from the water varied inversely with the amount in the diet. The amount of phosphorus absorbed was in proportion to that present in the water. Phosphorus fertilization resulted in an increased utilization of calcium. Phillips reported that trout placed in low calcium waters from high calcium waters showed a marked increase in their metabolic rate, apparently resulting from osmo-regulatory stress. Phillips speculated that poor survival obtained in some stocking programs may be a function of the mineral content of the stocked waters. In low calcium waters, trout accustomed to high calcium waters may have to expend energy for osmo-regulatory purposes. Even an abundance of natural food might not supply the essential calcium. Poor growth, low survival rates and inefficient food conversion may result. Hatchery water supplies arising from mineral-deficient areas may have to be fortified with the missing essential minerals.

In general, it may be stated that the problem of water quality in hatcheries and other artificial facilities has received a very minimal amount of study, especially with respect to salmon. Nevertheless, indications are that this is a very important problem and in many cases may govern the failure or success of a fish-cultural operation. Much research is necessary before water quality can be evaluated on a sound basis.

NUTRITION

It is becoming increasingly apparent that nutrition of hatchery stocks is another extremely important subject which, generally speaking, has received too little attention in past years. A considerable volume of literature on various feeding techniques, levels of feeding, types of foods, and conversion rates is available. Precise studies of various production diets and chemical comparisons of wild and hatchery fish are relatively recent although these avenues of approach appear to be the most profitable insofar as producing better hatchery fish is concerned.

Nutritional work on salmonids has been conducted at the Cortland Hatchery in New York where studies were initiated over 25 years ago. More recently, a salmon-nutrition laboratory has been established by the United States Fish and Wildlife Service in Washington State. Valuable research on the subject of nutrition has been conducted at both stations.

Significant differences in the chemical composition of wild and hatchery fish are known. While the observed differences between wild and hatchery fish are discussed in a later section, it is important to note that diet does have a significant effect in the production of differences in the two groups (Wood *et al.*, 1957a; Phillips *et al.*, 1957). Wood *et al.* (1957b) demonstrated that a good relationship existed between the mean value of chemical components in the hatchery diet and the mean values of these components in the fish produced. The values of these components in wild fish were distinctly different from those in hatchery fish. Phillips *et al.* (1954) considered that hatchery diets were, in chemical content at least, superior to wild foods. However, the conversion of hatchery food was not as efficient and these authors concluded that the hatchery diet must be lacking in some undetermined way. Presumably, if hatchery diets could be compounded so as to produce fish chemically similar to wild fish, the ultimate survival of the hatchery product would be increased.

Various workers have reported studies that contribute information on basic dietary requirements. Halver (1957a), Phillips and Brockway (1957), and Coates and Halver (1958) have determined vitamin requirements of salmonids. Establishment of test diets has isolated specific deficiency syndromes in chinook salmon. The necessity of several vitamins in production of salmonids has been demonstrated. Phillips and Brockway (1957) demonstrated that deficiency of one of several vitamins affected the growth of trout and in some cases increased their mortality. Coates and Halver (1958) presented data on growth and mortalities of coho salmon fed control and vitamin-deficient diets.

Halver (1954) related various fish diseases to vitamin deficiencies. He also indicated that fish suffering mineral deficiencies were more susceptible to bacterial infection.

Phillips and Brockway (1956), Halver (1957b) and Halver *et al.* (1957) have contributed to an understanding of the importance of amino acids and protein from which these acids are derived on hydrolysis. Phillips and Brockway reported that the protein content of a hatchery diet was 28 per cent while protein comprised only 11 per cent of the wild diet. They also reported that 10 amino acids are required by trout. Halver *et al.* (1957), working with chinook salmon, found that 10 of 20 amino acids were essential.

Phillips and Brockway (1956) maintained that trout diets should not contain more than 9 to 12 per cent of digestible carbohydrate, which is used principally in energy production and in that respect is regarded as "sparing" protein for other purposes. Excessive amounts, however, will induce an overweight condition, reduce stomach capacity and produce abnormal glycogen deposition.

Phillips and Podoliak (1957) have reviewed the role of fats and minerals in trout nutrition. Fats may be burned for energy, stored, cushion vital organs, and act as lubricant or insulation. Certain fats are essential but high levels of dietary fat and overfeeding have some effects that may contribute to a lowered survival. High levels of soft fats contribute to edema, characterized by an accumulation of water in the body spaces. This probably results from poor functioning of the kidney owing to fat deposition. Fatty infiltration of the liver also occurs as a result of high fat diets or overeating.

Phillips *et al.* (1952) reported the effects of addition of supplement fats to the diet of brook trout. Corn oil, cotton seed oil, cod liver oil and salmon oil were tested. The former two were not beneficial while the latter two were effective as a means of increasing growth at the 3 per cent level but were either detrimental or less effective at the 5 per cent level. Phillips and Podoliak (1957) reported that hatchery trout have a higher fat content than wild trout. The fat of hatchery trout was also harder. These authors suggested that the level and character of the body fat may be a factor in survival after stocking. Hess (1935) and Donaldson (1943) showed a degeneration of pancreas and surrounding tissue when excessive amounts of fat or fat and carbohydrate were fed. The islets of Langerhans were reduced and fatty infiltration of the liver occurred in some cases.

The importance of diet is further emphasized by the work of Miller *et al.* (1959). One group of rainbow trout was raised on pellets of dry food, another on liver. After 35 weeks, the two groups were subjected to varying amounts of exercise. The pellet-fed fish had more glycogen stores before exercise, maintained their liver glycogen during exercise but lost half of their muscle glycogen following exercise. In the liver-fed fish, liver glycogen was depleted to one half after fifteen minutes of exercise while muscle glycogen fell to one fifth or lower. The muscle glycogen returned to normal in pellet-fed fish in 12 hours. This period of rest, however, failed to restore muscle or liver glycogen in liver-fed trout. Diet, therefore, may reduce the survival of planted trout by affecting their ability to convert energy stores and to recover from fatigue.

The problem of nutrition has been considered only from the point of view of dietary composition. Conversion of the food is also of importance but it involves a multitude of technique problems, such as the best manner to present the food, frequency of feeding and so forth, details of which are irrelevant in the present discussion. The important conclusions that must be drawn from a review of available literature are that hatchery-fed fish are chemically different from wild fish and further that much remains to be learned concerning diets for artificial rearing of fish. As emphasized by Woodall (1959), fish husbandry is by no means an exact science and much fundamental nutritional research is essential.

DISEASES

Hatchery-raised salmon are subject to a wide variety of diseases. Recognition of the disease problem and the catastrophic nature of an epidemic logically precludes artificial culture of all fish in a particular stream. If all fish of one race were reared in a hatchery, one epidemic could conceivably destroy that particular cycle year. For this reason alone, a significant proportion of each run should be left to spawn naturally. The catastrophic nature of disease has been illustrated by Guenther *et al.* (1959) who reported that, in 1952, of all the sockeye fingerlings reared in the State of Washington 85 per cent succumbed to a virus disease. Leitritz (1959) reported that bacterial gill disease "is one of the most common in California, and year in and year out probably causes more losses than any other. Rainbow trout, as well as salmon, may be infected." The conditions under which the organism responsible for this disease flourishes are water temperatures above 56°F and crowding of fish.

Details of various diseases, symptoms, control measures and so forth are common in the literature. An excellent review of the fish-disease problem is available in the Transactions of the American Fisheries Society for 1953 when a symposium on the subject was held. Van Duijn (1956) and Davis (1956) also deal at considerable length with fish diseases.

Fish diseases are produced by a variety of organisms including the bacteria (mostly myxobacteria), viruses, protozoa and fungi. In addition, diseases such as blue-sac disease may be associated with unfavorable hatchery conditions (Wolf, 1957). Halver (1954) indicated the necessity of adequate diet for bacterial disease prevention. Generally, bacterial diseases flourish over the whole range of temperatures in which fish exist although some occur only over a particular range.

Myxobacteria, the main bacterial disease-producers in fish, cause several diseases of importance on the Pacific Coast of North America. *Chondrococcus columnaris* produces the "warm-water" disease known as columnaris which generally occurs in water above 60°F. Leitritz (1959) reported that the disease is most prevalent in California when water temperatures rise above 56°F. Some strains of columnaris are particularly virulent and can cause death in a few hours. This particular myxobacterium also has a highly resistant microcyst that renders complete eradication difficult. Columnaris has not been reported from the Fraser River, but is a major problem on the Columbia River where multiple dam construction has led to increased water temperatures, changed river environment and concentration of fish below dams and in fish facilities. All three factors may be conducive to the occurrence of the disease. Any developments on the Fraser that increased water temperatures might be expected to result in columnaris infection in this system.

Low-temperature disease, peduncle disease, fin rot, ulcer disease and bacterial gill disease are produced by myxobacteria and can cause severe losses in hatcheres. Furunculosis, also a bacterial disease, occurs most frequently when temperatures exceed 60°F. Epidemics usually occur at temperatures above 70°F. Kidney-disease, a little-understood infection that appears to be bacterially produced, can cause a serious loss of fish and occurs over a wide range of temperature. Drugs provide only temporary control of this disease.

Tuberculosis is another disease of bacterial origin that is causing increasing concern. The disease is relatively uncommon in nature but is apparently fostered by artificial culture. Apparently the bacteria associated with tuberculosis are of several kinds (Wood and Ordal, 1958). This disease was first observed in salmonid fishes in the fall of 1952 in adult chinook salmon returning to the Bonneville hatchery on the Columbia River. Wood and Ordal maintain that there is reason to believe that occurrence of tuberculosis has been profoundly influenced by cultural procedures in salmon and trout hatcheries. Many hatchery-reared chinooks, coho and steelhead were tuberculous when examined on their return as adults. There was a clear indication that the incidence of the disease was proportional to the period of hatchery rearing. Demonstrable tuberculosis occurred much less frequently in rivers containing both wild and hatchery fish. No tuberculosis was found in several wild runs. It appeared that disease transmission was facilitated by the feeding of young salmon with carcasses and viscera from tuberculous salmon. Transmission may also be associated with spawning, as tuberculous eggs have been reported. At present, there are no drugs that can be used to control this disease.

A great number of external and internal protozoan diseases have been associated with hatchery culture. Leitritz (1959) described several of these diseases and outlined methods currently used in attempts to control them. Earp (1958) described a protozoan, *Costia necatrix,* that attacks the gill tissues of fish and eventually causes suffocation. Protozoan diseases have caused serious losses in rainbow trout hatcheries in California. Parasites such as trematode worms and copepods also seem to flourish under hatchery conditions. Davis (1956) discussed several fish diseases caused by fungi, of which the Saprolegniaceae were mainly responsible. Injury or external attack by parasites often permits this disease to obtain a foothold and serious mortalities may result. Susceptibility is greatly increased when fish are suffering from general debility or are living under unfavorable conditions. Eggs are also subject to attack by *Saprolegnia* and at most hatcheries heaviest fungus losses occur at this stage. Development is very rapid on dead eggs and the fungi soon spread to live eggs.

Highly contagious virus infections are also common in hatchery stocks but knowledge of these diseases is very limited. Guenther *et al.* (1959) reported on attempts to determine the mode of transmission of one virus disease that had a particularly serious effect on sockeye in Washington State hatcheries. The most probable source of this virus infection was the salmon viscera that was used for food. Treatments of virus diseases have proved largely ineffective.

Methods of controlling the various hatchery diseases of salmonids are only partially effective. External parasites are usually controlled by applying some chemical to the water to destroy the parasite without injury to the host. Many substances, including sodium chloride, copper sulfate, potassium permanganate, acetic acid, formalin Roccae and pyridylmercuric acetate (P.M.A.), are used in attempts to control external parasites. Control of internal parasites is mainly through a reliance on adequate prophylactic measures. In some instances drugs may be added to the food, sulfamerazene and sulfadiazene being used in attempts to control furunculosis, ulcer disease, and columnaris. Some success has been achieved in attempts to control hatchery diseases but virus infections are little understood and difficult to control. Furthermore, Snieszko and Bullock (1957) report that pathogenic bacteria are capable of producing mutants that have increased resistance to drugs used for their control.

It is evident that hatchery disease, like the nutrition problem, can seriously limit hatchery production. It has previously been mentioned that a committee, in reviewing progress of the Lower Columbia River Rehabilitation Program, recommended that expenditures for enlargement of hatchery facilities be terminated pending evaluation of the effectiveness of Columbia River hatcheries and until the more serious fish diseases are brought under control. While significant progress is currently being made in controlling hatchery diseases, the disease problem constantly plagues hatchery operations. Further, serious new diseases are still being discovered. Complete loss of hatchery production, resulting from resistant forms of disease organisms wiping out the stock, is not impossible.

SELECTIVE BREEDING

Selective breeding of fish has been practiced for many years in attempts to produce desired traits. However, the principles established do not appear to have useful application in hatchery production of salmon. As Vincent (1960) has shown, the hatchery environment results in some selection in favor of characters that produce higher hatchery survival rates. Intentional selective breeding programs, however, attempt to develop specific characters considered desirable for higher survival in artificial or natural environments, such as faster growth, greater egg production, earlier maturity, earlier spawning and greater disease resistance. Donaldson and Olson (1957) reviewed the results of extensive selective breeding experiments with rainbow trout. It has been possible to select for certain characters but the effects of releasing the progeny of selectively bred individuals into the natural environment have not yet been studied. It is possible that a reversion to the original state would soon occur under the pressures of natural selection. Huxley (1942) reported a reversion of domestic pigs to a form resembling the wild type when selectively bred animals were released into the natural environment in New Zealand. Presumably the wild forms had an advantage over the fatter, more sluggish domestic forms in competition for food and reproduction. There is also some indication that selectively bred fall-spawning rainbow trout revert to the spring-spawning habit when planted in lakes and streams.

Evidence suggests that selective breeding designed to develop and accentuate traits considered desirable for artificial propagation may result in a reduction in survival in later stages of the life cycle after the fish are released into the natural environment. Vincent (1960) evaluated the differences in growth, resistance to accumulated metabolites, high-temperature tolerance, various behavior responses and stamina of wild and domesticated brook trout. The domesticated stocks had been reared in hatcheries for approximately 90 years. A second group of fish came from hatchery-stock brook trout that had spent one year in a lake immediately prior to spawning. The wild fish came from a small lake in the Adirondack Mountains. The domesticated stocks grew more rapidly in the hatchery than the wild fish. On the other hand, the wild-stock fish were more resistant to accumulated metabolites and had a higher temperature tolerance. Wild fish also had more stamina and had behavior traits that would be regarded as leading to higher survival in nature. Progeny of wild fish showed higher survival than progeny of domesticated fish when both were released into the natural environment.

Certain characteristics of a species that are not necessarily conducive to maximum survival under average conditions may be important for survival under unusual or extreme conditions. Serious consequences could result when stocks of fish are propagated for a few characters that appear desirable during the relatively short period of hatchery culture because the genetic constitution of populations adapted to a specific natural environment represents a compromise of all the forces of natural selection on the whole life of the animal. The problems of selecting for certain characteristics desirable in hatchery culture without eliminating other important traits are difficult to appreciate because many genetic principles are involved. Recognition of the concept of the gene-complex is particularly important as the expression of one gene is apparently influenced by its genic environment, which may include some or all of the other genes. Gene expression can be altered not only by the presence of other genes but also by their position.

There can be no doubt that selective breeding has been and will continue to be a valuable technique in animal husbandry, where the stock is retained for the whole life cycle, but the applicability of selective breeding in fisheries culture, where the stock must survive in the natural environment for part of the life cycle, remains very much in doubt. Intentional selective breeding of fish for characters considered desirable in hatchery culture may have serious adverse effects on the ability of the fish to survive in the natural environment. Further, since artificial control is effective only for part of the life cycle of anadromous fish such as sockeye and pink salmon, it appears very unlikely that adapted strains of these species could be developed by selective breeding.

EVALUATION OF HATCHERY PRODUCT

There is much evidence to indicate that hatchery-reared fish are less able to survive in the natural environment than are wild fish. Most of the available information concerns trout planted in lakes and streams inhabited by resident populations. Miller (1958) reviewed much of the pertinent work and cited many instances of differential survival rates. He concluded that it is a firmly established fact that hatchery-reared trout, when superimposed on a resident population, suffer very heavy mortalities whether in streams or lakes. Miller (1954) described an experiment in which hatchery-reared and wild cutthroat trout were released into a mountain stream occupied by resident trout. Compared with pond-reared hatchery trout, wild trout showed a survival more than 10 times as great over the first winter and a still larger comparative survival over the second winter. The results showed three grades of survival: high, associated with no hatchery background; intermediate, for hatchery fish reared first in hatchery ponds then in a natural stream; and low, associated with usual pond-rearing methods. It would appear, therefore, that low survival rates were directly associated with some factor or factors involved in hatchery culture.

Various authors have suggested possible reasons for the observed differences in viability of hatchery and wild fish. Schuck (1948), for instance, listed 10 possible reasons, including stability of water, temperatures, domestication, selection of brood stock for good hatchery qualities, freedom from predation, planting methods, hatchery diets, methods of feeding, and exercise. Many authors have stressed the lack of natural selection during hatchery existence as a possible reason for low survival of hatchery fish. Miller (1958) dealt with the role of competition between resident and introduced stocks, suggesting that in the early stages of competition for niches and food with resident trout, introduced trout are continuously exercising and as a result exhaust stores of some metabolite and die either of acidosis or starvation.

Chemical and physiological comparisons of hatchery-reared and wild fish suggest differences that may account for the relatively low survival rate of hatchery-reared fish. Whereas Phillips *et al.* (1954) showed that hatchery diets were chemically superior to natural diets, chemical analyses of wild and hatchery-reared trout showed that wild trout were superior in all chemical constituents tested (Phillips *et al.,* 1957). Wild trout contained significantly less water, more protein, more ash and less fat. Further, the fats were relatively less saturated. Wood *et al.* (1957a) also noted differences between wild and hatchery-reared fish. These authors compared the chemical composition of wild and hatchery fish of five species of Pacific salmon and four species of trout, concluding that salmonids reared under artificial conditions show marked consistent differences in body composition in comparison with wild salmonids. Protein and mineral levels were lower and lipid values were higher in the hatchery fish than in wild fish. As the period of artificial rearing was increased, these differences became more pronounced. Hatchery fish had more fat in the liver and viscera. Ceroid deposition was greater in the wild fish, suggesting that the fatty acids were more highly unsaturated.

Other workers have indicated extensive differences between wild and hatchery fish. Morphological differences, for instance, have been reported. Lower erythrocyte counts and hemoglobin levels, abnormal fatty degeneration of the liver and extensive fatty degeneration of the pancreas have also been described for hatchery fish. Phillips and Podoliak (1957) felt that an edema, characterized by an accumulation of water in body cavities, may be caused by abnormal fat deposition in the kidney. The normal functioning of this organ may therefore be impaired and osmo-regulation could be seriously affected. The suggestion that artificial propagation adversely affects the osmo-regulatory function is possibly supported by the observation that marine survival rates for hatchery-reared coho are less than one third those for wild coho (Salo and Bayliff, 1958). Miller *et al.* (1959) demonstrated the importance of diet in affecting the ability of fish to accumulate and mobilize energy stores and to recover from fatigue.

Brett *et al.* (1958) showed that young coho raised in circular tanks, where they appeared to exercise more strenuously than in standard hatchery ponds, displayed a higher sustained cruising speed and showed greater endurance than unexercised coho. The rigors of the natural environment may therefore be a significant factor in contributing to the higher quality of wild fish.

Differences in behavior and disease susceptibility may also account for differential survival rates of wild and hatchery-reared fish. Fields (1957) noted that the light-avoidance response was not as pronounced in hatchery-reared fish as in wild fish. Behavior patterns having survival value may not be well developed or precise in hatchery-reared fish. Further, hatchery fish may also be more susceptible to disease but this possibility has not been explored. It is known, however, that hatchery fish are frequently diseased at the time of release.

Research has shown that there are significant chemical and behavior differences between wild and hatchery-reared fish. It has been suggested that these differences account for the low survival rate of hatchery fish in relation to wild fish. However, greater numbers of fry and yearling can generally be produced in the protective hatchery environment. Artificial propagation may be feasible, therefore, if the lower survival rate does not negate the benefits of producing greater numbers of seaward migrants. Comparisons must therefore be made between the ultimate survival rates for natural and artificial propagation before the feasibility of hatchery culture can be completely assessed.

Natural and Artificial Propagation of Sockeye Salmon

To evaluate artificial propagation as a possible means of compensating for loss of upriver sockeye populations of the Fraser River watershed it is necessary to determine the over-all efficiency of hatcheries in producing adults from releases of seaward migrants. Young sockeye would have to be hatchery-reared for one year to the seaward-migrant stage because natural lakes in the lower part of the watershed are not adequate for rearing the upriver runs.

Very little information on hatchery culture of sockeye salmon is available. Large-scale culture of this species in British Columbia was discontinued over 20 years ago. Relatively few attempts at artificial propagation of sockeye have been made in other areas in recent years. The degree of success of hatchery culture of sockeye is not well-documented, particularly with regard to rearing to the smolt stage.

The most comprehensive comparison of natural and artificial propagation of sockeye salmon was made by Foerster (1938), who conducted experiments at Cultus Lake to determine whether incubation of eggs in hatcheries was more efficient than natural spawning. Efficiency of production was determined on the basis of the numbers of smolts produced from known numbers of eggs. Hatchery incubation to the fry stage was employed in three years, eyed eggs were planted in two years, and natural spawning was permitted in three years. The results have been discussed in the section entitled "Egg Incubation". Data pertinent to the present discussion are shown in TABLE 11.

Foerster calculated the survival rates during the egg-to-smolt stage on the basis of (1) the total number of eggs available in all females in the run and (2) the number of eggs stripped, or deposited. "Stripped" eggs were

TABLE 11—Relative efficiencies of natural and artificial propagation of sockeye salmon at Cultus Lake. (From Foerster, 1938.)

METHOD OF PROPAGATION	BROOD YEAR	SMOLTS PRODUCED	PERCENTAGE SURVIVAL TO SMOLT STAGE FROM:	
			Eggs Available	Eggs Stripped Or Deposited
Natural Spawning	1925	183,400	1.13	1.13
	1927	2,456,200	1.04	1.05
	1930	788,400	3.23	3.23
Fry Plants	1926	336,200	3.90	4.54
	1929	349,900	2.38	2.76
	1932	100,700	1.71	2.42

taken from the fish for hatchery incubation and "deposited" eggs were placed by the fish in the natural spawning areas in Cultus Lake. Survival rates, from eggs to smolts, were higher when based on the number of eggs stripped or deposited because significant numbers of fish died before maturing and some eggs were retained in fish during stripping operations. These losses amounted to about 20 per cent in the hatchery operations but were not significant in natural spawning. As far as the present discussion is concerned, the only meaningful comparison is that between survival rates to the smolt stage based on the total number of eggs available from the run. Since all of the run would have to be artificially propagated in any attempt to compensate for loss of upriver spawning and rearing areas, the 20 per cent egg loss involved in hatchery operation must be considered as an unavoidable disadvantage of hatchery culture.

Foerster suggested that the calculated survival rates for natural propogation were low because of a scarcity of males at Cultus Lake, resulting in incomplete spawning and fertilization. The highest efficiency of reproduction occurred in 1930 when the sexes were nearly equal. Males were much less numerous than females in the other two years. Although Mathisen (1955) showed that even a considerable excess of females over males did not appreciably influence the success of spawning or egg deposition in a small stream in Alaska, unpublished information collected on the beach-spawning race in Cultus Lake showed that a ratio of 1 male to 3 females resulted in lower percentage deposition than when the sex ratio was approximately equal. There was also evidence of lowered survival of deposited eggs when there was a shortage of males. Foerster calculated another set of survival rates to determine the average survival rate if the sexes had been equal in all three years. Evidence collected by the Commission seems to validate this approach.

For natural propagation, the observations showed an average survival rate from eggs to smolts of 1.80 per cent. However, Foerster estimated that the average survival rate would have been 2.86 per cent if the sexes had been equal. The average survival rate for fry plants was 2.51 per cent. From a statistical analysis of the data, including survival rates for plants of eyed eggs, it was found that there was no statistically significant difference in survival rates for the three methods. It must be stressed that these experiments did not involve rearing of sockeye.

It has been noted previously that transplantation of hatchery-reared sockeye fingerlings has proved ineffective as a means of rehabilitating barren spawning and rearing areas of the Fraser River watershed. The fact that transplants of eyed eggs have been more effective than transplants of hatchery-reared sockeye may indicate an important weakness in artificial rearing.

The suggestion that artificial propagation of sockeye is less effective than natural propagation is supported by an experiment conducted at the Quesnel Field Station on Horsefly Lake in 1949. (Internat. Pacific Salmon Fish. Comm., 1954). In this test, 302,000 eggs from the native Horsefly River sockeye run were hatchery-reared to the fingerling stage while the major part of the run was allowed to spawn naturally. Approximately 94,000 fingerlings were released in November 1950 in Quesnel Lake, the natural rearing area for the Horsefly race of sockeye. Comparison of the returns of four-year-olds to the Horsefly River and to the hatchery suggested that the survival rate, as expressed by the number of returning adults produced from the total number of eggs available in the brood year, was 0.13 per cent for hatchery propagation and 0.55 per cent for natural propagation. Extensive observations were made to accurately enumerate all of the returning adults, including hatchery-reared fish that might have strayed from their "home stream". Although the results are based on only one experiment, the magnitude of the difference between the two survival rates suggests that in this instance artificial propagation of sockeye was considerably less effective than natural propagation.

Attempts at hatchery propagation of sockeye salmon on the Columbia River have apparently not been entirely successful. Extensive operations, necessitated by the construction of Grand Coulee Dam, included transplants of adult sockeye to downstream tributaries and culture of eggs in hatcheries for release as fry or smolts. Details of the work are outlined by Fish and Hanavan (1948). Cultural operations were centered at the Leavenworth hatchery on the Wenatchee River, with substations located on the Entiat and Methow Rivers. Fish (1948) reported on the success of these operations, maintaining that the large returns of sockeye in 1946 and 1947 were the results of hatchery operations and not the results of relatively small escapements allowed to spawn naturally. In spite of the optimism expressed, it is significant that in later years disease wiped out two years' production of the Leavenworth hatchery and that the returning runs to which these years' production would have contributed were apparently of a magnitude comparable to those years in which the hatchery stocks were believed to have made a significant contribution. It appears that the hatchery operations did not contribute to the run to as great an extent as was first believed. The lack of published data makes a detailed consideration of the success of the hatchery operations difficult and no conclusions on the relative efficiency of natural and artificial propagation of sockeye in this area are possible. No sockeye runs have been maintained to date by rearing young sockeye to the smolt stage in hatchery ponds as a substitute for the lake environment.

Natural and Artificial Propagation of Other Salmonids

Hatchery culture of certain salmonids is extensively practiced on the Pacific Coast. Although few critical attempts have been made to measure the effectiveness of artificial culture, it is apparent that hatcheries have been successful in some cases in significantly increasing the production of certain species and certain races of salmon. Hatcheries are currently being used to maintain salmon populations in some streams where natural spawning and rearing areas are limited. It must be stressed, however, that these populations are very small in relation to the millions of salmon produced naturally in the

Fraser River system. Further, in those instances where some success is being achieved in hatchery culture, it appears that the individual races of the species involved are much more tolerant to artificial propagation than are sockeye. Hatcheries appear to be effective in the culture of coho and certain races of chinooks in the coastal climatic area but consistent success has not been achieved in artificial propagation of sockeye, pinks, chums and spring chinooks.

That hatchery culture is effective in increasing the production of coho and fall chinooks is apparent from data published in reports of the various agencies engaged in culture of these species. The annual variations in the numbers of adults returning are of considerable interest. In some years the rate of return is high whereas in other years only moderate returns are obtained, demonstrating the importance of variable, and sometimes unknown, factors in periodically limiting the success of hatchery operations. If these controlling factors could be eliminated, hatcheries could make a more consistent and significantly greater contribution to total salmon production but extensive research, which must necessarily be on a long-term basis, is obviously required for determining the reasons for the failure of hatchery culture to operate successfully in all cases.

Salo and Bayliff (1958) reported that hatchery culture of coho salmon was more productive than natural propagation in Minter Creek, which is a small stream in Washington State draining directly into salt water. This stream is capable of producing about 25,000 to 35,000 yearling coho annually. The survival of hatchery fish was maximal when the young were reared for 9 to 12 months and then released into the natural environment of Minter Creek some time before the period of seaward migration. Salo and Bayliff determined that the maximum natural production from Minter Creek could be obtained with about 300 female spawners and an equal number of males. It was therefore recommended that this number of fish be allowed to spawn naturally and the remainder be taken into the hatchery for artificial propagation.

Using data from Minter Creek and nine other State of Washington hatcheries, Ellis and Noble (1959) presented an analysis of the contribution of salmon hatcheries to the commercial and sport fisheries. Survival rates in several releases of marked hatchery-reared coho and fall chinooks were given and average survival rates for unmarked fish estimated. For marked coho, an average survival rate from yearlings to adults of 0.435 per cent was calculated, based on return of adults and jacks to hatcheries from releases of hatchery-reared yearlings. These workers concluded that hatchery-culture operations were economic. However, with respect to the present discussion of hatchery propagation of Fraser River sockeye and pink salmon, it must be emphasized that the conclusions were based on the production of coho and fall chinooks, not on species and races that appear less tolerant to hatchery culture.

Data presented in both of the above-mentioned reports indicate an inverse relationship between survival rate and numbers of hatchery fish released in each group. While the mechanism responsible for this apparent relationship is not undersood, its implication for large-scale hatchery production is obvious. Even if Fraser River sockeye and pink salmon could be propagated in hatcheries, this indicated relationship suggests that very low returns would be obtained because extremely large groups of young fish would have to be released in the localized lower river area.

Another significant point with respect to Fraser River salmon populations is that the use of non-local stocks of salmon for hatchery culture is considered a poor management practice by those agencies having extensive experience in hatchery culture. The release of over 1,000,000 marked fall chinook fingerlings has demonstrated that local stocks are more than four times as productive, in terms of the numbers of adults returning, as imported stocks (Wash. Dept. Fish., 1959). This information suggests that hatcheries would not be efficient for propagating upriver salmon populations of the Fraser River system in downriver areas far removed from their native spawning and fresh-water rearing areas.

Many studies have suggested that hatchery-reared fish are less viable than fish reared in the natural environment. Hobbs (1948) maintained that hatchery operations, as practiced in New Zealand, resulted in greater losses than would have occurred if the fish had been allowed to spawn naturally. Miller (1954, 1958) demonstrated a high mortality rate of hatchery-reared cutthroat trout as compared with resident trout but, under different experimental conditions Adelman and Bingham (1955) and Nielson *et al.* (1957) maintained that there was no differential survival between wild and hatchery-reared trout.

HATCHERIES AS COMPENSATION FOR LOSS OF UPRIVER POPULATIONS

Consideration of hatchery culture in this report has been directed towards an evaluation of the possibilities of propagating sockeye and pink salmon in downriver areas as a means of compensating for the loss of upriver spawning and rearing areas that would be destroyed or made inaccessible by dam construction in the Fraser River system.

The first problem that must be considered in this evaluation is the holding of immature adults for egg-taking. Fresh-water migrations of several hundred miles are not uncommon for some upriver sockeye races. Considering the time required for migration plus that required for fish to reach maturity on the spawning grounds, it is evident that the interception of migrating adults in the lower river area for fish-cultural purposes would necessitate long holding periods. Some races would have to be held for at least 50 days, assuming that fish retained in artificial holding ponds would survive and mature at the same rate as under natural conditions. Upriver pink salmon would have to be retained about 20 days before reaching maturity. In spite of the most elaborate and costly facilities there could be no assurance of any degree of success in collecting, holding and artificially spawning millions of Fraser River sockeye and pink salmon for fish-cultural operations in the lower river area. Further, there is no assurance that suitable water supplies for holding the required number of adult salmon could be economically obtained in the lower river area.

Other facets of hatchery operations are of significance. Quality of the water supply may control hatchery production but the required characteristics of water for optimum salmon culture are as yet little understood. Temperatures, mineral content, and levels of dissolved gases are obviously important. Few aspects of hatchery culture are of more significance than the problem of nutrition. Various workers are studying dietary requirements for hatchery culture but much additional research is required. Disease is another important factor that limits hatchery production. One epidemic may destroy a year's production of a hatchery. While some diseases can be controlled, satisfactory treatments have not been discovered for others. Further, mutants occur that are resistant to established disease-control methods. It is evident that continued research efforts are required in all of these factors that limit the efficiency of hatcheries.

Available evidence suggests that hatchery fish are less able to survive in the natural environment than wild fish, but, for certain races of certain species, the greater number of young fish released from hatchery operations offsets the high mortality rates and total production is therefore increased. Significant chemical, physiological, and behavior differences between hatchery and wild fish have been demonstrated. When fertilized eggs are placed in hatcheries, survival to the free-swimming fry stage is much higher than in nature but experiments with sockeye at Cultus Lake showed that artificial propagation, which involved releases of fry and planting of eyed eggs, was not a significant improvement over natural production in terms of yearling seaward-migrant sockeye produced. Survival rates for hatchery fry were much lower than for wild fry. This work did not involve hatchery rearing to the smolt stage. Hatchery-reared sockeye fingerlings released into Quesnel Lake also had a much lower survival rate than wild sockeye reared in the same lake. Efficiency of hatchery production of coho salmon was apparently greater than natural production in Minter Creek, a small Washington State stream. Studies have also shown that certain hatcheries are capable of economically producing coho and fall chinooks for the commercial and sports fisheries. Throughout the history of salmon culture, some hatcheries have increased the total production of certain species and races but, for unknown reasons, other hatcheries have either failed to increase the runs or have actually decreased them.

Those who propose that hatcheries could be utilized in the lower river area to replace salmon spawning and rearing areas that would be made inaccessible by dam construction in the Fraser River system have made extravagant claims concerning potential values of hatchery culture. The physical and economic feasibility of hatchery culture appear to have been given little consideration by proponents of dam construction. Without considering the reduced survival of the hatchery product, the so-called advantages of hatcheries have been expressed in terms of the number of eggs required in a hatchery to produce one smolt compared with the number of eggs required under natural conditions.

Most fisheries conservationists, on the other hand, carefuly point out that hatchery culture involves a multitude of problems. For instance, Clay and

Larkin (1959), in considering the possibilities of artificial propagation in solving Fraser River fish-power problems have stated: "The practical difficulties are easy to visualize. First of these is holding of the adult salmon until the eggs are mature. There would be no point in building hatcheries near the headwater spawning areas which are capable of doing a better job naturally. Any advantage of a hatchery facility would be in placing it below a major dam thus obviating the necessity of a fishway. However, most schemes for power development of the Fraser require mainstem dams several hundred miles from the spawning grounds of the sockeye. In consequence when the salmon arrived at a dam they would not be fully mature. There is no way known of maturing the eggs outside the body of the salmon, and there is therefore no alternative to holding the adults until the eggs are ready for fertilization. Since the runs number in the millions this would be a staggering undertaking. It might also be futile because under these holding conditions a large percentage of the salmon may completely fail to achieve maturity.

"Problems of rearing the young fish would also be immense. A modern salmon hatchery capable of rearing 2 million sockeye to seagoing size costs approximately $1,000,000 and at least $60,000 annually for operation. The Adams River run alone would require 100 such hatcheries to equal the natural production of seaward migrants. The super-hatchery installation required would have 16,000 standard-size rearing ponds, an inflow of several thousand c.f.s. and a labor force of over 2000. Other lesser runs which are concurrent with the Adams run would require additional space. Even with all this effort to duplicate the numbers that would be produced naturally, the low survival rate of the hatchery-raised fish would fail to duplicate the natural return of adults."

By making an allowance for the low survival rate of hatchery-reared fish, Smith (1960) attempted to arrive at a more detailed estimate of the size and cost of hatchery facilities that would be required for producing the 1958 Adams River sockeye run of 18,000,000 adults. He stated, however, that neither hatcheries nor any other kind of artificial rearing are considered acceptable as substitutes for natural production of salmon. Making the assumption that the survival figures for hatchery-reared coho and chinook salmon in Washington State hatchery operations would apply in the case of Fraser River sockeye, he calculated that 3,450,000,000 eggs would have to be taken and 1,800,000,000 seaward migrants released. As shown in earlier sections of this report, the assumption that survival rates obtained in hatchery culture of coho and fall chinook also apply in the case of Fraser River sockeye is certainly not justified but Smith's hypothetical calculations probably give an indication of the minimum size and cost of the facilities that would be required. Smith calculated that the rearing facilities alone would require a total pond area of over 1300 acres and a discharge of more than 13,000 c.f.s. The capital outlay for the incubation and rearing facilities was estimated at $478,000,000 with an annual operating cost of $125,000,000. No estimate was made of the cost or physical requirements of facilities for holding the maturing adults prior to egg-taking.

It must be emphasized that these calculations were made only for the Adams River sockeye run. Artificial propagation of other Fraser River sockeye, pink, chinook and coho populations that spawn in the upriver area would necessitate proportionate increases in the size and cost of the facilities.

After outlining some of the many weaknesses of artificial propagation of upriver races of Fraser River salmon, Smith concluded: "Adequate escapement of spawning stocks, vigorous protection of the streams used by migratory fish, together with sufficient natural spawning and rearing areas, probably will result in the production of many times the numbers of salmon that can be produced by presently known hatchery methods."

In spite of the lack of optimism among fisheries conservationists concerning the proposal to propagate major Fraser River salmon populations in downriver hatcheries, it seems likely that hatcheries might be developed to serve a useful function in certain types of localized fish-power problems. On streams supporting small salmon populations, hatcheries might provide an adequate substitute for natural production where limited spawning and rearing areas are unavoidably destroyed by power installations. In a general review of salmon conservation in relation to proposed power development in the Fraser River system, Larkin (1956) emphasized the limited applicability of salmon hatcheries in solving or ameliorating fish-power problems. He suggested that hatcheries should be used primaritly to offset any unavoidable mortality, and then only after all other alternatives that might be cheaper and more effective are explored. Further, hatcheries should handle only a small fraction of a total run because of the catastrophic aspect of hatchery operations and because of the physical problems of building and operating immense hatchery establishments. Larkin stated that hatcheries were a "last-ditch" alternate for handling all the fish of a given run, as one serious epidemic, a failure in the water supply, or any such catastrophe could virtually eliminate a race that relies on hatchery culture.

At the present time, artificial propagation is not a safe and proven method of maintaining even small, localized stocks of Fraser River sockeye and pink salmon. Further research may reveal methods whereby hatcheries could provide significant benefits in the production of localized populations, especially if rearing to the seaward-migrant stage is not involved. However, attempting to propagate all of the upper Fraser River salmon populations in a hatchery system, which would probably have to be larger than all of the salmon hatcheries of the world, would not only endanger the large fishing industry that relies on Fraser River salmon but might even result in the practical elimination of this valuable fisheries resource.

Artificial Spawning Areas

The stability of environmental conditions and increased subsurface flows associated with artificial spawning areas have resulted in egg-to-fry survival rates approximately four to eight times higher than under natural conditions. Experiments with artificial spawning areas are being conducted in several locations in efforts to obtain high egg-to-fry survival rates, as in hatcheries, while avoiding the handling and artificial culture that reduces survival of fish in later stages of their life cycle. In artificial spawning areas, spawning, incubation and fry emergence are entirely natural except that the environmental conditions are improved and more stable. The fish are permitted to spawn naturally, thus avoiding the necessity to capture, hold and artificially spawn them. Preliminary results indicate that in certain situations artificial spawning areas may provide a more efficient and more economical method of salmon culture than hatcheries. Experiments are currently being conducted with two types of artificial spawning areas—the upwelling type and the stream type.

UPWELLING-TYPE ARTIFICIAL SPAWNING AREAS

Upwelling-type artificial spawning areas are comparable to natural springs, which provide spawning areas in certain lakes and streams where ground water percolates upwards through gravel. This type of spawning area may consist of an artificially constructed pond with a grid of perforated water supply pipes covered by a layer of selected gravel. Water from the pipe grid flows through the perforations and percolates up through the gravel. Movement of the water mass above the gravel is negligible.

Realizing the possibilities of artificial spawning facilities in certain areas of the Fraser River system, the Commission conducted a series of experiments to determine the relationships between rate of subsurface flow, flow distribution, placement of eggs, and other factors that would provide high egg survival rates. These experiments suggested that high egg mortality rates occurring in nature were caused, to a large extent, by inadequate flow or inadequate distribution of the flow through natural gravels. Incubation of eggs in gravel under controlled conditions demonstrated a positive correlation between egg survival and rate of flow (FIGURE 25). These laboratory studies were conducted in gravel beds 1.0 ft. square, with water introduced at the bottom and discharged at the top. Rate of flow, expressed in millimeters per hour, was determined by measuring the total volume of flow per unit of time and dividing by the total cross section of the gravel bed. There was a pronounced reduction in egg survival at flow rates of less than 100 mm. per hr. The mechanics of water flow through gravels of several different compositions showed that the most uniform distribution of flow was obtained when the fines (under ⅛-in. diameter) and large sizes (over 2-in. diameter) were excluded. When water was introduced into an 18-in.-deep gravel bed through perforated pipes located at the bottom and spaced 12 in. apart, gravel ranging in size from ¼ to ¾ in. in diameter gave much better flow distribution than other gravels tested.

An artificial spawning area of the upwelling type was constructed in 1953 at Horsefly Lake. Adult sockeye captured in Horsefly Lake were placed in this artificial spawning area. It consisted of an 18-in.-deep bed of gravel, 90 ft. long by 17 ft. wide with water introduced at the bottom through 30 perforated iron pipes spaced 3 ft. apart. The gravel ranged in size from 1.5-in. diameter to sand. Water depth above the gravel surface was 2 ft. The area was divided into three sections having flows of 0.25, 0.50 and 0.75 c.f.s. Nominal rates of percolation were 540, 1080 and 1620 mm. per hr. respectively. Egg survival increased with increased rates of flow in this test but in subsequent tests, with gravel from which the fines had been removed, the same tendency was not evident. As shown in TABLE 12, the rate of fry production in this artificial facility from the 1953 brood was high as compared with that occurring in nature.

TABLE 12—Survival to fry stage of eggs in the Horsefly Artificial Spawning Ground.

Brood Year	1953	1955	1956	1957	1958
Brood Stock	Horsefly	Stellako	Stellako	Horsefly	Stellako
Eggs deposited	283,000	522,000	1,521,000	872,000	807,000
Fry emerged	131,000	280,000	311,000	589,000	521,000
Per cent survival	46%	54%	20%	68%	65%

Following this initial success, another spawning area was constructed in 1955 in which design improvements were incorporated. The new area was 80 ft. square, divided into eight individual sections each 20 ft. by 40 ft. (FIGURE 35). The bed consisted of a 4-in. layer of coarse gravel (¾ to 2 in.) covered by a 14-in. layer of spawning gravel. Two types of gravel were used in the 14-in. spawning layer. Gravel consisting of particles ranging in size from ¼ to ¾ in. was used in four of the eight secions while ⅛ to 2 in. gravel was used in the other four. Water was introduced near the bottom of the gravel bed through a grid of 1-in.-diameter polyethylene pipes spaced 12 in. apart, each having a single row of ¼-in.-diameter holes at 3-in. centers. The pipes were laid with the holes directed downward. Two rates of flow, 100 and 500 mm. per hr., were used in conjunction with each gravel type. The low-flow rate was chosen on the basis of the previously described laboratory experiments which suggested that egg survival declined markedly for percolation rates of less than 100 mm. per hr. or 0.041 U.S. g.p.m. per sq. ft. The high-flow rate chosen was 0.205 U.S. g.p.m. per sq. ft.. Total discharge for the 80-ft.-square spawning bed was 1.75 c.f.s. All of the water for the artificial spawning area was pumped from Horsefly Lake. Intake depths of 3.5, 50, and 82 ft. were used to obtain adequate control of water temperatures.

The egg-to-fry survival rates obtained in these experiments are shown in TABLE 12. In some years fish were permitted to spawn in specific sections of the artificial spawning grounds while eggs, either green or eyed, were planted in other sections. There appeared to be no consistent difference in survival between naturally deposited eggs and the artificially planted eggs. With the exception of 1956, survivals were much higher than under natural conditions. The low survival of the 1956 brood was caused primarily by unavoidable

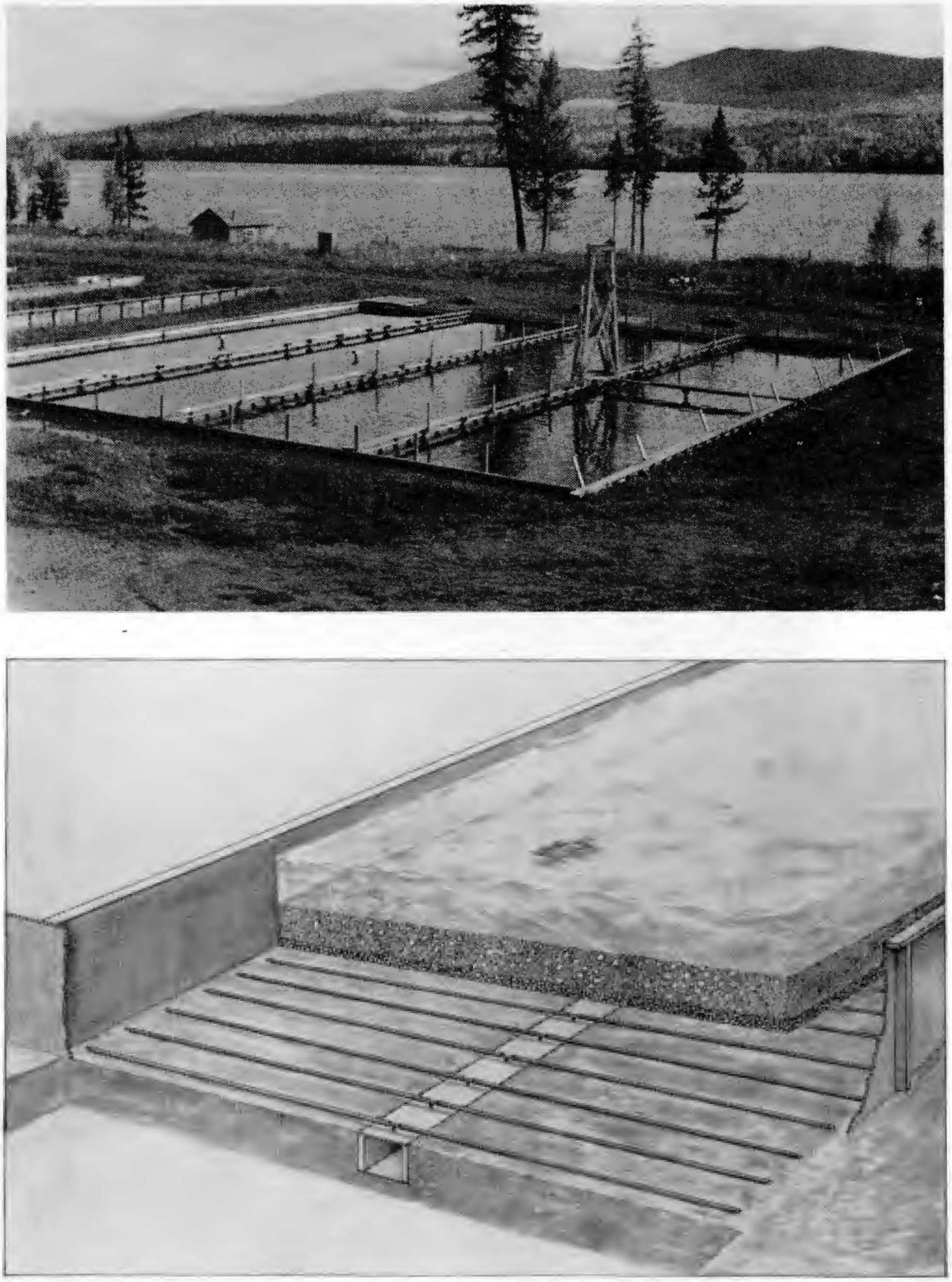

FIGURE 35—Upwelling-type artificial spawning area at Horsefly Lake.

delays in transporting and planting some of the eggs. In addition, the heaviest rate of planting was employed that year and it is possible that this factor may have contributed to the lowered survival.

Results of experiments conducted at the Horsefly artificial spawning area show that mature sockeye will spawn successfully in an artificially prepared and temperature-controlled spawning medium and that egg survival rates are much higher than in natural spawning areas. While there is no reason to believe that fry produced in artificial spawning areas are less viable than naturally incubated fry, the experimental installation at Horsefly Lake has not been effective in producing a self-perpetuating population of sockeye. This shortcoming, however, is believed more likely a function of the lake environment than of the quality of fry produced in the artificial spawning area. Very few smolts have migrated out of Horsefly Lake in proportion to the numbers of fry released from the artificial spawning area and from hatchery operations. All the fry released in Horsefly Lake were the progeny of transplants of eggs or adults from other areas. Several possible reasons for the lack of seaward migration have been suggested, including the sensitivity of sockeye to their native environment and the possible effects on seaward migration of several physical characteristics of Horsefly Lake that are unique among rearing lakes of the Fraser River system (Internat. Pacific Salmon Fish. Comm., 1960).

Similar artificial spawning areas have recently been constructed at McNary Dam on the Columbia River, Baker River in Washington State and Great Central Lake on Vancouver Island.

The experimental facility for chinooks at McNary Dam consists of both the upwelling-type artificial spawning area and the controlled-flow spawning channel (Wash. Dept. Fish., 1959). An upper section, 100 ft. by 150 ft., consists of an upwelling-type spawning area. The percolation rate, or apparent velocity, created by a flow of 4 c.f.s. over the 15,000 sq. ft. of area is approximately 290 mm. per hr. Water is supplied to the area through perforated pipes buried 2 ft. apart in the gravel bed. More than 90 per cent of the gravel is smaller than ½ in., with less than 5 per cent smaller than ¼ in. It has been reported that very few chinooks spawn in the upwelling area. Since stream-spawning sockeye spawn successfully in the upwelling area at Horsefly, the apparent reluctance of chinooks to utilize the area at McNary may represent a species difference or may be a behavior trait associated with the small size of gravel.

An artificial spawning ground constructed by the Washington State Department of Fisheries on Channel Creek, tributary to Baker River, is designed for use by sockeye salmon and is similar in many respects to that at Horsefly Lake. An upwelling-type spawning area was constructed to substitute for lake spawning areas inundated by construction of a hydroelectric dam. Evidence of practicality of the initial channel used by the 1958 run is reported by the Washington Department of Fisheries (1959). A larger unit was constructed for the 1959 spawning run.

Experiments are currently being conducted by the Canada Department of Fisheries to study a unique application of upwelling-type artificial spawning areas as a substitute for loss of natural lake spawning areas. Development of

Great Central Lake on Vancouver Island for hydroelectric power will increase the elevation of the lake and lake spawning areas might therefore be rendered unsuitable for sockeye. An experimental installation constructed in 1959 in Great Central Lake consists of a 50- by 100-ft. grid of perforated pipes laid on the beach and covered with selected spawning gravel. The grid is laid on a slope, from about 5 to 60 ft. below the lake surface. Water is piped to the grid from a nearby creek. Experiments planned for 1960 and succeeding years are designed to determine the effectiveness of this type of artificial spawning area.

STREAM-TYPE ARTIFICIAL SPAWNING CHANNELS

Experiments have demonstrated that controlled-flow artificial spawning channels provide an effective method of obtaining egg-to-fry survival rates substantially higher than in natural streams. Artificial spawning channels resemble natural streams but are constructed of improved spawning gravel and involve provision of stable discharges, depths and velocities considered optimum for spawning and egg incubation.

The initial development of a controlled-flow artificial spawning channel was located at Jones Creek near Hope, B.C., 80 miles above the mouth of the Fraser River. The project was designed to maintain pink, chum and coho spawning populations after most of the flow of Jones Creek had been diverted for hydroelectric development. On the basis of work reported by Wickett (1952), which showed that the survival of pink and chum salmon eggs could be significantly increased by regulation of the stream flow, the Canada Department of Fisheries decided that a small, controlled-flow spawning channel would compensate for loss of natural spawning areas in Jones Creek. The installation, which was completed in 1954, is described by Hourston and MacKinnon (1957). The channel is 2000 ft. long and 14 ft. wide at the water surface, with washed gravel ranging in size from ¼ to 1½ in. placed to a depth of 12 to 18 in. (FIGURE 24). Difference in elevation between the intake and outlet is 16 ft. Weirs were installed at 100-ft. intervals to control depth and velocity. Drops at these weirs vary from 4 to 12 in. Average discharge is 20 c.f.s., with a flow of 25 to 30 c.f.s. during the spawning period and 15 c.f.s. at other times of the year.

In 1954, 2,738,000 eyed eggs obtained from Skeena River pink salmon were planted in the channel at a rate of 2700 eggs per sq. yd. Fry output represented about 42 per cent of the live eggs planted or 37 per cent of the number of eggs taken on the Skeena River (Neave and Wickett, 1955).

In 1955, 400 native pink salmon and 160 native chum salmon spawned in the channel, resulting in a potential deposition of 428,000 pink salmon eggs and 251,000 chum salmon eggs. Egg-to-fry survival rates were 37 per cent for pinks and 30 per cent for chums. Hourston and MacKinnon *(ibid.)* stated: "The results of the first year's operation of the channel are considered encouraging and certain modifications in connection with silt control indicate that survival could be increased. In general, it is felt that this type of installation will be of value, not only in asociation with power developments but also as a fish culture technique for increasing the production of salmon."

Various problems have arisen in operation of the channel but most if not all of the problems are of a minor nature and are being avoided in artificial spawning channels currently being designed or constructed. Ice jams forming below the weirs and eventually covering most of the channel have temporarily excluded flow from the gravel. Silt deposition produced by flooding and erosion of the banks has been a further problem. Egg-to-fry survival has evidently been adversely affected by these conditions, particularly in later years. Survival of eggs deposited naturally by the return from the previously mentioned off-year plant of pink salmon in 1956 and an additional planting of eggs from the Skeena was only .10 per cent to the emergence stage (Can. Dept. Fish., 1959). This low survival was attributed to ice jams and silting. Observed depth and velocity preferences of the spawners, described in a previous section on 'Spawning and Egg Incubation", suggested that the channel should have been deeper and slower for optimum spawning conditions.

Construction of an experimental stream-type artificial spawning area at McNary Dam has been mentioned earlier. The channel consists of 12 sections measuring 22 ft. wide by 175 ft. long, separated by resting pools. The upper six sections contain graded gravel of which 100 per cent passed a 3-in. screen, more than 90 per cent passed a 2½-in. screen and less than 5 per cent passed a ½-in. screen. The lower six sections originally contained sandy pit-run gravel, of which more than 95 per cent passed a 6-in. screen. This gravel was found to contain too high a proportion of fines and was therefore replaced with coarser gravel similar to that in the upper six sections. Discharge during the spawning period was 60 c.f.s. plus the 4 c.f.s. overflow from the previously described upwelling pond. This development has demonstrated that chinook salmon will spawn in artificial, controlled-flow spawning channels but egg-to-fry survival rates have not been high because a number of operating problems, particularly high temperatures, have been encountered (Wash. Dept. Fish., 1959).

At least two races or stocks of fall chinooks were available for use in the McNary channel. The 'local" chinooks were believed to be fish that spawned in the vicinity of McNary, either in the main Columbia or smaller tributaries. These fish were ready to spawn when moved into the channel after mid-September. The "upriver" chinooks were the other stock and were evidently destined for spawning areas well above McNary Dam. They were not mature and required long periods of retention before reaching maturity. Spawning of the "local" chinooks was more successful than that of the "upriver" chinooks. From a total of 396 carcasses recovered, it was determined that 57 per cent of the females in the channel died unspawned and 6.3 per cent died partially spawned. In September, when the carcasses could not be identified as "local" or "upriver", 82.5 per cent of the females died unspawned. In October, November and December, however, it was found that of the 105 "local" carcasses recovered, 7.6 per cent died unspawned and of the 153 "upriver" carsasses recovered, 68 per cent died unspawned. As previously noted, low survival rates during the periods of holding and spawning have been attributed to high water temperatures.

In 1959, the Canada Department of Fisheries constructed a controlled-flow spawning channel in Robertson Creek, a secondary outlet of Great Central Lake on Vancouver Island. This channel is 2500 ft. long, with a bottom width of 35 ft. Designed for a discharge of 100 c.f.s., the channel is operated at an average depth of about 1.5 ft. and a velocity of 1.5 f.p.s. Spawning gravel to a minimum depth of 15 in. was placed directly on the channel subgrade. The gravel was washed and graded, with 100 per cent passing a 4-in. screen and not more than 20 per cent passing a ¾-in. screen. Channel bottom slope is 0.0006. The objective in constructing the channel was to increase salmon runs in the area, to improve fish-culture techniques in the use of spawning channels and to investigate conditions necessary for efficient use of water in rearing pre-migrating chinook and coho salmon. Attempts will be made to establish a run of pink salmon and to enlarge the present small runs of coho and chinook salmon. As an initial test, nearly 2,000,000 eyed pink salmon eggs were obtained from Indian River on the North Arm of Burrard Inlet and planted in the channel in 1959. Survival from eyed eggs to emergent fry was over 90 per cent.

A stream-type spawning channel is scheduled for construction in 1960 at Seton Creek in the Fraser River system to compensate for spawning area flooded by construction of Seton Dam. The initial development will provide about 6700 sq. yd. of additional spawning area for Seton Creek pink salmon. The channel is being designed so that it can be extended in length to provide a total of 17,000 sq. yd. of spawning area. Designed for a discharge of 40 c.f.s., the channel will have a bottom width of 19 ft. and an initial length of about 3000 ft.

ROLE OF ARTIFICIAL SPAWNING AREAS

Use of artificial spawning areas as a method of increasing salmon production is quite new but preliminary results suggest that the method holds promise. Egg-to-fry survival, although possibly not as high as that of a well-run hatchery, is generally much higher than that occurring in nature. Further, some of the shortcomings of hatchery culture are not associated with production in artificial spawning grounds. As far as is known, fry produced in artificial spawning areas are as viable as naturally produced fry. Ultimate survival to the adult stage of fry produced in artificial spawning areas might therefore be higher than in hatcheries.

That artificial spawning areas are capable of producing high egg-to-fry survival rates is becoming increasingly apparent. Greatest success may be expected when artificial spawning areas are used in conjunction with native spawning areas so that production may be augmented without involving transplanted populations. In situations where spawning areas are limited or survival is highly variable due to environmental fluctuations, artificial spawning grounds might assist in stabilizing or increasing fry production.

Possible use of artificial spawning grounds in downriver areas if dams were constructed on the Fraser would be limited. They would be of little value in sockeye production because of the lack of extensive lake rearing areas. Further, transplantation of upriver sockeye populations to downriver areas would have little chance of success because of the long holding periods that would be required for the adults and because of the extensive differences in environmental conditions between upriver and downriver areas. It appears, however, that the Thompson River run of pink salmon, which has increased markedly since the removal of the block at Hell's Gate, may have originated from the main Fraser River stock that spawns in the main stem immediately below Hope. If such is the case, it would appear that pink salmon are possibly more tolerant of environmental variations and might be cultured in downriver artificial spawning areas.

At the present state of knowledge, however, artificial spawning areas in the downriver area would not provide adequate compensation for the loss of natural upriver spawning areas, even for pink salmon. Many of the reasons have already been discussed under the heading of hatchery culture. The construction and operation of extensive artificial spawning grounds and the collection and holding of large numbers of upriver salmon in the downriver area would present many problems. Further, artificial spawning areas, or any other method of natural or artificial culture, might be completely unsuccessful because upriver dam construction might change the environmental conditions in the lower river and estuary in such a manner as to adversely affect survival.

Increased Natural Production in Unaffected Areas

Certain methods of increasing natural production in areas unaffected by hydroelectric development warrant consideration as a means of compensating for production that would be lost if dams were constructed in upriver areas of the Fraser River system. Lake fertilization and predator control are biological possibilities, while stream clearance and provision of access to new areas are physical methods that might lead to increased production.

LAKE FERTILIZATION

Fertilization has long been recognized as a technique for increasing the productivity of a body of water. The Chinese have apparently been using organic fertilizers in carp ponds for more than 2000 years . In recent times, workers have increased fish yields many-fold through chemical fertilization of small ponds. Varying results have been obtained in attempts to increase production in lakes, however. In the aquatic environment, fertilization is aimed at increasing the supply of nutrients required for the development of phytoplankton populations, which form the basis of the aquatic food chain. Increased abundance of these basic producers, in theory at least, leads to an increased production of intermediate consumers (zooplankton, insects and other benthic fauna) which in turn may increase the production of the ultimate consumers, the fish. Artificial enrichment of a lake's nutrient supplies is by no means a simple or well-understood technique because numerous factors inherent in fresh-water metabolism affect the process and outcome of artificial fertilization. Physical, chemical and biological factors must be considered. Until the variability and interaction of these factors is understood, artificial fertilization cannot be much more than haphazard in approach.

Fertilization of bodies of water generally increases the production of lower members of the food chain, but this increase does not necessarily result in increased production of fish. Maciolek (1954) noted that population increases following fertilization were most pronounced among the lower organisms. Single species, rather than whole groups, tended to show greatest gains. In the great majority of lakes that have been artificially fertilized, either the growth of fish has not been increased or the effects on fish populations have not been measured. If artificial fertilization is to have beneficial results it is apparent that the desired species of fish must be capable of benefiting from increased production of specific lower organisms. Furthermore, lake fertilization can be of no value in fish production unless that production is specifically limited by a deficiency in water quality or a lack of food in the lake. No benefits can be obtained, for example, where fish production is limited by the availability of spawning area, by adverse temperatures or by other possible factors. It is also possible that fertilization may increase the survival of young fish but development may be hindered at a later stage by some other limiting factor, thus tending to produce large populations of stunted individuals.

Several experimenters have reported increases in production of lower organisms as a result of the use of artificial fertilizers. Langford (1950) reported a marked increase in phytoplankton in Algonquin Park lakes three weeks to a month after fertilization. Abundance declined rapidly following occurrence of peak numbers and was not increased by additional fertilization. The zooplankton population increased relatively less than the phytoplankton. Ball (1950) reported that fertilization produced a heavy plankton-algae bloom in the first summer and a very heavy growth of filamentous algae the following summer. In these tests, a cold-water lake, a characteristic environment of trout and salmon, responded less favorably to fertilization than a warm-water lake. Wales (1946) reported no increase in abundance of plankton or bottom organisms following fertilization of Castle Lake, California, with soy-bean oil. Fertilization of Lake Nussensee, an oligotrophic lake in Austria, resulted in two species of green algae becoming the dominant phytoplankters. One of the species proved to be a satisfactory food for the zooplankter, *Daphnia* (Hasler and Einsele, 1948).

Benefits from fertilization, in the form of increased growth and production of fish, have by no means been spectacular. Ball and Tanner (1951) applied inorganic fertilizer to a small warm-water lake in Michigan. An increase in phytoplankton was observed and increases in bottom fauna and zooplankton were inferred. Improved growth rates of centrarchids (bluegills and sunfish) were also noted. Production of filamentous algae was high following fertilization. An increase in growth of speckled trout in a small New Brunswick lake was attributed to artificial fertilization (Smith, 1954). Nelson and Edmondson (1955) reported data from four years of artificial fertilization of Bare Lake, a 120-acre, unstratified sockeye-producing lake on Kodiak Island, Alaska. Addition of nitrogen and phosphorus fertilizer was followed by a large and prolonged increase in photosynthesis. Phytoplankton populations increased following fertilization and, since there were indications of increases in egg production of rotifers, it was suggested that the zooplankton populations had also benefited. Young salmon migrating seaward were larger following fertilization of the lake, suggesting an increase in their food supply. Fertilization of large sockeye-rearing lakes has not been attempted because of the inconclusive results of many experiments conducted on smaller lakes and because of the high cost of such an experiment.

Tampering with natural lake metabolism has in some cases proved detrimental to fish populations. Ball (1950) reported winterkill in two fertilized lakes where none had been noted for the previous 10 years. Ball and Tanner (1951), in discussing fertilization of a small lake, noted that increased production of filamentous algae interfered with spawning of centrarchids. The nests apparently could not be kept free of algae and were eventually abandoned, thus reducing spawning areas. Winterkill was also observed. It has been noted that instead of plankton blooms, fertilized lakes frequently produce large mats of algae, which on decay tend to reduce oxygen and in some cases lead to winterkill.

One of the more important objections to artificial fertilization is that there is no assurance that the desired or economically important species of fish will be favored exclusively or at all. Undesirable species may benefit to a greater extent than desirable species, thus increasing competition and generally negating the effects of fertilization . As an example, Nelson and Edmondson (1955) and Nelson (1959) reported that the growth rate of young sockeye was increased by fertilization of Bare Lake in Alaska but Benson (1958) suggested that the Dolly Varden *(Salvelinus alpinus malma)* had increased in abundance and their predation on immature salmon might offset any apparent gains from fertilization. Shifts in the composition of fish populations of a lake following enrichment have been reported. Hasler (1947) discussed the changes that occurred in a lake as a result of a large inflow of domestic sewage, which produced an eutrophic condition much as occurs after artificial fertilization. The trout and whitefish populations were eventually replaced by coarse fish.

The necessity for frequent refertilization of a body of water to maintain any increase in productivity that might be produced is another disadvantage. Various factors influence the rate and frequency at which fertilizer must be applied. A high flushing rate would necessitate more frequent fertilization. Thermal stratification, which often limits the distribution of organisms, may trap nutrients in lower regions of a body of water. Nutrients added to a lake often disappear quite quickly from solution, apparently largely through deposition in the bottom soils. Hayes (1951) stated that 90 per cent of the added nutrients disappear from the water in a few weeks. The remaining 10 per cent may lead to an increase in plant and animal growth.

Even if artificial fertilization of large sockeye-rearing lakes was known to have practical advantages in increased production of sockeye, the economic advantages might be negligible. At the present time, cost of fertilizing a large body of water is prohibitive. While no data are available to indicate the quantity or cost of fertilizer required for deep, sockeye-rearing lakes, Rounsefell and Everhart (1953) reported that fertilization of small, shallow ponds with little outflow costs about $15 to $20 per acre annually. Hasler and Einsele (1948) reported a calculation of A. H. Wiebe for Norris Reservoir which indicated that the cost for a single application, if fertilizers were applied at the low rate recommended by pond culturists and with no allowance for increased depth, would be $352,000 ($11 per acre). Although experimentation in lake fertilization is at an early stage at the present time, it seems likely that the cost of fertilizing sockeye-rearing lakes would be much higher than the figures reported above. The magnitude of the problem of fertilizing Fraser River sockeye-rearing lakes becomes more apparent when the size of the lakes involved is considered. For the most part they are large lakes. They range in size from Cultus Lake (1550 acres) to Shuswap Lake (76,500 acres) and as a group have a mean area of approximately 27,000 acres. Most of the large producers have a mean depth of 200 to 300 ft. Available evidence indicates that frequent application of fertilizers would be required. Considering this fact and the size of the lakes, it seems unlikely that artificial fertilization would be practical and economical.

Artificial fertilization as a technique for increasing production or survival in a large body of water cannot be regarded as having practical significance at the present time. Too little of lake metabolism is known to predict the resultant changes in lake chemistry and the net effect on the plant and animal populations. Indications are that detrimental effects of lake fertilization could outweigh any gains. Further, it is likely that the cost of continually fertilizing large sockeye-rearing lakes would be prohibitive. It does not seem likely, therefore, that artificial fertilization could be employed to increase production of sockeye in a few lakes of the Fraser River system to compensate for loss of production in other lakes utilized for hydroelectric development.

CONTROL OF PREDATORS AND COMPETITORS

In recent years there has been an increasing amount of interest shown in the control of predator and competitor species as a means of increasing the survival of commercially important fishes. Numerous workers have demonstrated a very significant mortality among juvenile salmon during their lacustrine existence, much of which is no doubt the result of interspecific competition and predation. Superficially, it seems reasonable to assume that higher fresh-water survival of salmon would be obtained if the undesirable species could be either completely or partially removed.

The two species of salmon under consideration in this report present different problems with regard to attempts at predator control. The pinks, migrating seaward immediately after emergence from the gravel, are only in fresh water a short time. Nevertheless, predation can result in serious losses. For instance, Hunter (1959) showed that predation in a small coastal stream tended to be numerically relatively constant and that in years of low production up to 85 per cent of the pink and chum salmon fry were lost through predation. Very little opportunity is available in the Rraser River system for controlling fish populations that prey on pink salmon fry. Control of predators of this species seems not only difficult to evaluate but also impractical in large rivers. Therefore, this review is concentrated on possible control in lakes with a consideration of its value to young sockeye salmon, which spend at least one year in lakes prior to seaward migration.

Complete eradication by toxicants has frequently been used in small bodies of water. All fish are eliminated and a desired species stocked when the lake becomes non-toxic. This approach is not practical in bodies of water supporting young salmon because elimination of the young of any year-class would result in the loss of that particular cycle. Prolonged toxicity would likely affect fish of more than one cycle year.

The success of the toxicants in eliminating all the fish is not at all certain, especially in large lakes. Rotenone, the most common fish poison, has not been effective in deep lakes. Thermal stratification in the summer prevents complete distribution of the poison, while low water temperatures at other times of the year reduces its effectiveness. Toxaphene is apparently more effective in large lakes and is less expensive than rotenone but it is lethal to many forms of life. Stringer and McMynn (1958) reported the elimination of amphipods, dragonfly and damselfly nymphs and midge larvae in toxaphene-treated lakes. Elimnation of many of the lower forms of life may have far-reaching effects on lake productivity but the prolonged toxicity of toxaphene-treated lakes appears, at present, to be the major disadvantage of this poison for sockeye-rearing lakes.

Other problems involved in sockeye-rearing lakes would seem to preclude the use of this technique as a means of increasing production. These lakes, as previously mentioned, are generally very large and deep. Further, the construction and maintenance of barriers for preventing re-entry of all but the desired species would present unprecedented problems on the large rivers flowing into and out of the major rearing lakes. It would be necessary to pass only the desired species, in many cases both adults and juveniles, over the barriers without allowing other species into the lake. Success would be difficult to achieve, particularly if large numbers of fish were involved. River navigation would also be adversely affected. Since barriers do not appear feasible, periodic re-poisoning would be required. Satisfactory control in this manner without seriously affecting salmon production would be unlikely.

In the field of salmon biology, more consideration has been given to the partial removal of undesired competitors and predators. The most pertinent predator-control study is that on Cultus Lake, described by Foerster and Ricker (1941). In this lake, the squawfish was the main predator of young sockeye. In an effort to reduce the fresh-water mortality of about 96 per cent of the young sockeye in Cultus Lake, extensive gill-netting operations were instituted in 1935 and continued through 1938. The nets were selective for intermediate-sized squawfish, sampling the largest and smallest only occasionally. The populations of squaw and char over 200 mm. were reduced to about one tenth of their original abundance. Coho salmon and trout populations were much less affected. The average survival rate of young sockeye was apparently increased about 3 1/3 times. The authors presented data suggesting that the experimental predator control operations, from May, 1935 to June, 1938, resulted in a saving of 3,800,000 migrants and an estimated yield of 380,000 adult sockeye. They further concluded that the value of sockeye saved by predator control was many times greater than the cost of the netting operations.

Unpublished data obtained after 1938 leave some doubt as to the ultimate success of the predator control operations. Netting in 1940 and 1941 indicated a marked increase in the populations of predator fish, suggesting that the survival of small fish of the predator species had been inproved as a result of the removal of the adult predators. Further, other factors became more significant in controlling the sockeye production when the number of adult squawfish was reduced. In 1939, sockeye survival to the smolt stage was considerably lower than in earlier years of the predator control work. Further, the smolts were the smallest of any year from 1925 to 1942. The most logical explanation of this phenomenon seemed to be that over-population of the lake had increased intraspecific competition to such an extent that growth and survival of young sockeye had been reduced. Sea survival of this group was also unusually low. Foerster (1954) has shown that sea survival is directly related to the size of downstream migrants and that percentage return of adults is inversely related to the numbers of smolts. Unpublished data also suggest that, independent of smolt size, runs consisting of large numbers of smolts have a lower sea survival than runs consisting of smaller numbers of smolts. The removal of one factor controlling sockeye production appears to allow other controlling factors to assume greater importance. Conclusive results were not obtained in the Cultus Lake work in spite of 11 years of netting to remove predators. The interspecific and intraspecific relationships in predator and prey populations in a lake are evidently more complex than they might at first appear.

Predator control studies have also been conducted in New Brunswick. In small east coast lakes, the eel, *Anguilla rostrata,* is the main predacious fish. White (1933) demonstrated serious predation by eels on salmon fry.

Smith (1948) considered the eel as both a predator and competitor of trout and reported that their removal in Bill's Lake, New Brunswick, was followed by a definite improvement in angling for speckled trout. In a review of the work on Crecy Lake, Smith (1955) noted that lake fertilization alone did not produce a long-term increase in yield of trout to anglers although the growth rate of trout was increased. However, the control of predator populations, which included the eel as well as fish-eating birds and mammals, was associated with an increase in survival of planted trout. Smith believed that trapping eels in the lake and preventing entry of elvers into the lake contributed to this increased survival. In this small lake, predator control in conjunction with lake fertilization seems to have had beneficial effects. However, the experiments at Cultus Lake have more bearing on predator control and its effects on sockeye salmon. The results of this study were incomplete and further study seems desirable before definite conclusions are drawn.

Control of competing species of fish is a further theoretical possibility for increasing natural production. Rawson and Elsey (1950) conducted one such study in Pyramid Lake, Alberta. Trout production was reported to be poor and it was felt that the longnose sucker *(Catostomus catostomus)* and the mountain whitefish *(Prosopium williamsoni)*, which competed with trout for food, were contributing to this poor production. Suckers and trout competed for amphipods while the whitefish and trout competed for aquatic insects as well as cladocerans. A seven-year program of removal of fish from this lake, directed primarily at the suckers, eliminated the older age classes and reduced the average weight of the suckers caught from 5.5 oz. in the first year to 1.6 oz. at the end of the experiment. The survival rate of young suckers increased although no change in the growth rate was observed. The removal of suckers was not accompanied by any noticeable improvement in the survival of trout either during the period of removal or for three years afterwards.

In an experiment reported by Ricker and Gottschalk (1941), 45 tons of carp *(Cyprinus carpio)*, 20 tons of quillback suckers *(Carpiodes sp.)* and 6 tons of buffalo fish *(Megastomatobus* and/or *Ictiobus* spp.*)* were removed from Bass Lake, Indiana. Seining of coarse fish in 1935 resulted in a decreased abundance as evidenced by 1936 net catches. The lake, which was turbid prior to the removal operation and was characterized by a decline in the availability of game fish, began to clarify in 1936 and the vegetation in the lake increased in quantity and extent. The abundance of game fish increased rapidly and angling improved. No significant reversion to the original state had occurred by 1940. While this study involved removal of a competing species, ecological changes also resulted that may have contributed to the increase in game fish production through an improvement of the habitat.

Work that has been done on control of predator and competitor species is largely inconclusive and there is need for much further study. All lakes studied have been relatively small. At Cultus Lake, by far the smallest sockeye-producing lake of the Fraser River system, predator control produced encouraging results initially. However, increased survival of the young of the main predacious species left the ultimate result in doubt when the work was discontinued. Work in Eastern Canada indicated an increased survival of trout associated with control of eel populations. On the other hand, no benefit to trout was observed in Pyramid Lake, Alberta, after removal of competing species. No assurance of success in the control of predator or competitor fish as a means of increasing the survival of young salmon can be offered until more information is available concerning lake population dynamics and other factors limiting salmon production.

A further major consideration, even if some success were assured, would be the cost of extensive removal of predator or competitor species. The major sockeye-rearing lakes are many times larger than Cultus Lake and there is no doubt that any attempts to remove a significant number of undesirable fish would involve a considerable labor force and a substantial expenditure of money, probably on an annual basis, to maintain the predator or competitor populations at the desired low level.

STREAM CLEARANCE

The main objective of the Lower Columbia River Development Program as outlined by Laythe (1950) was the maintenance of anadromous species at the highest possible level of abundance. One approach on the Columbia, which might also be suggested as compensation for proposed dam construction on the Fraser River, was to remove or provide access around natural and man-made obstructions. In this way areas of potentially productive water would be opened up and production of salmon possibly increased. While some opportunity for development of this type exists in the lower reaches of the Fraser River, there is no possibility of compensating for loss of upstream spawning and rearing areas in this manner.

VALUE OF ARTIFICIAL AIDS TO NATURAL PRODUCTION

A review of possible means of increasing natural production in areas unaffected by water-use developments to compensate for losses incurred in other areas has been presented. Artificial fertilization of lake rearing areas was considered as a means of increasing production and survival of young salmon during their lacustrine existence. While this technique has been valuable for pond culture of fish and has even improved fishing in some small lakes, the difficulties and disadvantages involved are numerous and may outweigh any benefits. The cost of treating large lakes would probably be prohibitive. Further, since the effect of the fertilizer is temporary, frequent fertilization would be required. The influence of the fertilizer on plant and animal populations and the direction in which any changes would proceed are largely speculative. It is entirely possible that more harm than good would result because predator or competitor species might be favored by fertilization at the ultimate expense of the desired species.

Control of predators and competitors of salmon during fresh-water residence was also reviewed. It was concluded that the use of toxicants for complete eradication of the predator populations of a large lake would involve several unsolved problems and would be undesirable in that toxicants would eliminate at least one year-class of young salmon. Removing significant portions of the populations of undesirable species by gill-netting, seining or other means in attempts to increase salmon survival were considered. Quite apart from economic considerations, it was concluded that the ultimate result of this approach had not yet been determined and that until further experimental work was done and the dynamics of lake populations evaluated, there was insufficient justification for large-scale predator-control attempts. Another important disadvantage of predator control is that trout, which are also valuable, would probably have to be destroyed before predator control could be effective in any attempt to increase salmon production.

Stream clearance and provision of passage to inaccessible areas was briefly considered. In the lower parts of the Fraser River below proposed water-use projects, relatively little increase in production could be anticipated by provision of better access to little-used areas.

In summary, it appears doubtful that the loss in production that would result from hydroelectric development of upriver areas of the Fraser River could be compensated for by artificially increasing natural rates of production in downriver areas. Further, even if some increase in production were possible by these means, the economy would still suffer. If any of these approaches were at all feasible they could be utilized to increase present production.

Conclusions Concerning Alternatives to Natural Production for Sockeye and Pink Salmon

In the foregoing section of this report, artificial propagation of Fraser River sockeye and pink salmon has been examined in relation to the suggestion that alternatives to natural production might be employed to increase salmon production in the lower river area and thus compensate for spawning and rearing areas that would be lost if dams were constructed in the upriver area. An integrated power and flood control development would involve all areas of the Fraser River watershed above Hope, which is approximately 100 miles above the mouth. The lower area, which is not suitable for dam construction, would remain for salmon and trout production.

Transplantation of upriver populations to spawning and rearing areas downstream from Hope would probably not contribute significantly to salmon production. Stocks of sockeye and pink salmon in the lower river area appear to be adequate for complete utilization of the available natural spawning and rearing environments. Further, transplantation of salmon populations is not easily achieved because genetic and environmental limitations control the suitability of donor stocks for specific recipient streams. Transplants of sockeye fingerlings have not been successful in the Fraser River system but some success appears to have been obtained in transplants of eggs and adult salmon. So many problems are involved in re-establishing large populations by transplants of adults or eggs that these methods do not seem feasible for millions of Fraser River sockeye and pink salmon. The biological limitations of the transplantation principle and the limited spawning and rearing areas available in the Fraser River system below Hope preclude the use of this technique as a method of compensating for loss of upriver production.

Examination of hatchery culture as an alternative to natural propagation suggests that techniques have not been developed to the stage where a resource as valuable as the sockeye and pink salmon of the Fraser River should be entrusted entirely to hatchery production. Retention of immature adult salmon for egg-taking purposes may result in high mortality in the pre-spawning stage, especially where the fish have to be held for extended periods such as would be necessary for upriver races of Fraser River sockeye. Losses of eggs during incubation can reach catastrophic proportions as a result of disease or possible adverse effects on the eggs of extended retention of the adults. More research must be conducted to define basic requirements of water supplies for successful hatchery operation. Certain levels of dissolved minerals in hatchery water supplies are apparently associated with successful hatchery operation. Hatchery nutrition has also been inadequately studied. Differences in chemical composition of wild and hatchery fish have been demonstrated and it is considered that these differences result, at least in part, from deficiencies in the hatchery diet. In spite of the most advanced hatchery technology, wild fish have been shown to be chemically superior to hatchery fish. Similarly, disease is considered to be an important factor controlling hatchery production. In spite of much research, prophylactic measures currently in use do not provide adequate control. Selective breeding, while possibly of some significance in trout propagation, appears to be of no value in culture of anadromous fish.

At the present time there is no justification for concluding that hatcheries would provide a practical substitute for natural production of upriver runs of Fraser River sockeye and pink salmon. The artificial nature of the hatchery environment seems to be associated with the production of fish that are less viable than those produced in nature. In both fresh water and in the ocean, the survival of hatchery-produced fish is usually lower than that of wild fish. However, for coho and certain races of chinooks, the increased number of fish produced in the hatchery environment sometimes offsets the reduced survival rate so that total production is increased. Available information indicates that hatchery culture of Fraser River sockeye and pink salmon would be ineffective. Many unsolved problems would certainly be involved in any attempt to propagate upriver populations in downriver hatcheries. The necessity to hold millions of adults for spawn-taking purposes would pose tremendous problems. The rearing of young sockeye for one year to the seaward-migrant stage would also pose many problems and would be very costly. Further, because of size and cost considerations as well as the catastrophic aspect of hatchery culture, only part of each race of salmon should be used in hatchery operations, the remainder being allowed to propagate naturally. This would be impossible in any attempt to propagate upriver races of Fraser River sockeye and pink salmon in hatcheries located in the downriver area. Artificial propagation of large numbers of Fraser River sockeye and pink salmon certainly seems unwise until sufficient knowledge can be accumulated to give a greater assurance of success.

Artificial spawning areas were considered as being useful for increasing the production of fry. The improved spawning and incubation conditions afforded in artificial spawning areas result in more efficient spawning and much higher rates of eggs-to-fry survival. While it might be feasible to increase production of pink salmon in the lower part of the watershed by means of artificial spawning areas, production of sockeye could probably not be greatly increased because of the lack of adequate lake rearing areas.

Other methods that might be employed to increase production of sockeye and pink salmon in areas of the Fraser River watershed not affected by water utilization projects were also considered. Artificial lake fertilization appeared impractical as a method of increasing the productivity of large sockeye rearing lakes. Similarly, it did not seem likely that stream clearance and control of predators and competitors could, from a practical viewpoint, significantly contribute to sockeye and pink salmon production.

Three basic factors must be emphasized in any consideration of alternate methods of producing Fraser River sockeye and pink salmon. First, the possible value of any alternatives may be seriously questioned on the basis that if it could be demonstrated that particular techniques would benefit fish production in the Fraser River system these techniques would be applied independent of any necessity to compensate for production lost due to dam construction.

Second, the subtle effects of upriver dam construction on environmental conditions in the lower river and estuary and on productivity of downriver runs must also be considered. It is conceivable that the combined adverse effects of environmental changes in the lower river and estuary might limit production of salmon to such an extent as to nullify any compensatory efforts. For instance, some data have been presented which suggest that high spring discharges are conducive to high ocean survival of sockeye smolts. Similarly, discharge appears to affect the timing of certain adult sockeye migrations into the Fraser River. Low spring and summer discharges appear to cause Adams River sockeye to arrive on their spawning grounds too late for most effective spawning and egg incubation. Dam construction and the associated regulation of the river would reduce the combined spring and summer discharge and might therefore reduce the effectiveness of any attempts to increase salmon production in the lower river.

Finally, it is important to consider that fish produced in the lower river area are not recognized by the fishing industry as being of comparable quality to upriver fish. The high fat and protein content of upriver salmon makes them particularly desirable for canning as they demand premium prices. Even if it were possible to compensate for loss of upriver production by producing more fish in the lower river area, the quality of the fish might deteriorate considerably.

Suggestions for a simple solution to Fraser River fish-power problems are somewhat similar to efforts currently being implemented to salvage Columbia River salmon populations. Laythe (1950) stated: "The gradual decline of the

Columbia River salmon fishery has been brought about through deforestation, pollution, over-fishing, unscreened water diversions, and construction of dams within the watershed. The latter is believed to be the major contributing factor.

"Present water-development programs of the U.S. Bureau of Reclamation and the Corps of Engineers have accelerated the organization of a conservation plan for the maintenance of the salmon and steelhead fishery before the proposed dams bring about further diminution of the runs. This plan . . . consists of the maximum development and management of the fish runs in tributaries of the lower Columbia River basin." The program, planned for completion over a 10-year period, included:

1. Removal of obstructions on lower Columbia River streams to open up areas formerly inaccessible for spawning and rearing.
2. Abatement of pollution.
3. Screening of water diversions and construction of fishways in lower Columbia River streams.
4. Transplantation of upriver runs.
5. Extension of hatchery culture.
6. Establishment of fish refuges in which conflicting developments would not be permitted.

The first three objectives are not necessarily related to this rehabilitation program since they had already been undertaken by the fisheries agencies responsible for maintaining and increasing production in these areas. Of the remaining three objectives, only the last two have been implemented. While transplants were carried out during the Grand Coulee Dam salvage program, no transplants have been made under the lower Columbia program. Fish refuges were established in a few streams but the principle of fish refuges has been rejected by the courts and construction of high dams in these areas has already started. The greatest effort in the rehabilitation program has been directed towards construction of new hatcheries and remodelling and enlarging existing hatcheries on tributaries of the lower Columbia River. Twenty hatcheries have been rebuilt or newly constructed (Leffler, 1959). However, a committee has recently recommended that expenditures for enlargement of hatchery facilities be terminated pending determination of the effectiveness of the lower river hatchery program and until the more serious fish diseases are brought under control. It was also recommended that greater emphasis be placed on research, particularly in regard to hatchery diets and diseases *(ibid.)*.

It must be concluded that the various alternatives to natural production that have been considered in this report would not offer a simple or dependable solution to Fraser River fish-power problems.

DISCUSSION

This evaluation of known and possible effects of proposed dam construction on production of Fraser River sockeye and pink salmon has emphasized that there is considerably more involved in fish-power problems than the obvious necessity of passing fish over dams.

An important concept in considering multiple-water-use proposals is that salmon are adapted to a limited range of environmental conditions. The whole life history is adjusted to, or integrated with, the natural environmental cycle. As long as the environmental variations are well within the tolerance limits of the salmon, the rates of reproduction and survival are relatively high. Upriver races of Fraser River sockeye, as compared to other races of the same species in other river systems, appear to have a very limited tolerance to environmental variations. Upriver stocks of pink salmon may also be relatively intolerant to environmental change, although little information has as yet been accumulated concerning the tolerances of this species. In spite of the most efficient facilities for passing fish, construction of dams on the Fraser River system could destroy the sockeye and pink salmon resources unless complete knowledge was available in advance of dam construction concerning the specific tolerances of each race as well as the total effect of each proposed dam in changing the natural environmental conditions.

The seriousness of many problems associated with hydroelectric development can be readily visualized. Problems of passing fish over dams, flooding of spawning areas, diversion of flow to other watersheds and mortalities of seaward migrants in spillways and turbines are obvious. Many of the fish-power problems encountered on other river systems would be magnified on the Fraser because of the much larger numbers of fish involved and the particular intolerance of upriver sockeye races to migratory delay. It has been estimated that fish facilities at proposed Fraser River dams would have to be designed to pass 750,000 adult sockeye in a single day. This is far more than the total number of all species of salmon passed over Columbia River dams in a whole year. Delayed upstream passage is known to have serious consequences. While the obvious problems that can also arise during the construction of dams have not been specifically discussed in this report, it is important to realize that serious fish losses sometimes occur during the construction period.

Whereas certain problems of fish passage and environmental changes resulting from dam construction are evident, many other problems, which may be equally important, are much less apparent and more difficult to evaluate. Primarily, these are associated with the more subtle environmental changes. Temperature and discharge changes, for instance, may alter the behavior of migrant salmon in such a manner as to reduce their survival or reproductive ability. Many of these subtle changes have not been adequately explored but it must be emphasized that even minor environmental changes could have disastrous effects. Experience on other river systems suggests that each new dam introduces problems in fisheries conservation that were not previously known. Dam construction in the Fraser River system, involving the conservation of other species and races particularly sensitively adapted to the environmental conditions, could reveal new problems that cannot be anticipated at the present time.

Consideration of the Fraser River fish-power problem as a whole suggests that there is no easy solution. Whereas advocates of dam construction have proposed that hatcheries in the downriver area would compensate for loss of natural production in upriver areas, critical examination of this proposal indicates that it would be unsatisfactory. For many reasons, hatcheries would not be adequate for this purpose. Other alternatives, including transplantation of affected populations, artificial spawning areas, and increased natural production in unaffected areas, appear of little or no value as potential methods of compensating for loss of upriver sockeye and pink salmon production.

The need for comprehensive and long-term basic research concerning salmon biology and fish-power problems has been emphasized throughout this report. Extensive research programs have recently been initiated. Basic research, designed to yield more information concerning the physiology, behavior, tolerances and environmental relationships of Pacific salmon, is progressing at an accelerated pace in both Canada and the United States. Much work is being done to investigate problems that might be created by dam construction. Applied research, aimed at studying the known effects of dams and possible methods of alleviating specific adverse effects, has also been accelerated in recent years. However, in spite of these extensive research efforts, there is at present no basis for presuming that a complete solution, or even a partial solution, to Fraser River fish-power problems will be obtained in the near future.

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