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INFLUENCE OF FOREST AND RANGELAND MANAGEMENT ON ANADROMOUS FISH HABITAT IN THE WESTERN UNITED STATES AND CANADA

William R. Meehan, Technical Editor

1. Habitat Requirements of Anadromous Salmonids

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PREFACE

This, the first in a series of publications summarizing knowledge about the influences of forest and rangeland management on anadromous fish habitat in the Western United States, describes habitat requirements of anadromous salmonids--the valuable salmon and trout species that use both freshwater and marine environments. Requirements of these unique fish must be understood before we can explore the effects that natural events and human activities can have on their habitat, and on their ability to maintain productive populations with our increasing use of other forest and rangeland resources. Reports on the effects of natural watershed disturbances and various land use activities will follow.

We intend to present information in these publications that will provide managers and users of the forests and rangelands of the Western United States with the most complete information available for estimating consequences of various management alternatives.

In this series of papers, we will summarize published and unpublished reports and data as well as observations made by resource scientists and managers made during years of experience in the West. These compilations will be valuable in planning management of forest and rangeland resources, and to scientists in planning future research. The extensive lists of references will serve as a bibliography on forest and rangeland resources and their use for this part of the United States.

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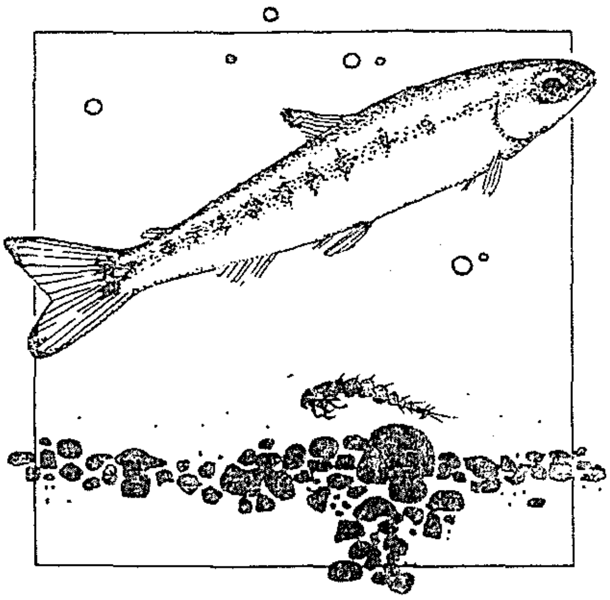
COMMON AND SCIENTIFIC NAMES OF TROUTS FAMILY SALMONIDAE[1/]

Common name	Scientific name
Pink salmon	*Oncorhynchus gorbuscha* (Walbaum)
Chum salmon	*Oncorhynchus keta* (Walbaum)
Coho salmon	*Oncorhynchus kisutch* (Walbaum)
Sockeye salmon (kokanee)	*Oncorhynchus nerka* (Walbaum)
Chinook salmon	*Oncorhynchus tshawytscha* (Walbaum)
Cutthroat trout	*Salmo clarki* Richardson
Rainbow (steelhead) trout	*Salmo gairdneri* Richardson
Atlantic salmon	*Salmo salar* Linnaeus
Brown trout	*Salmo trutta* Linnaeus
Arctic char	*Salvelinus alpinus* (Linnaeus)
Brook trout	*Salvelinus fontinalis* (Mitchill)
Dolly Varden	*Salvelinus malma* (Walbaum)
Lake trout	*Salvelinus namaycush* (Walbaum)

[1/] From "A List of Common and Scientific Names of Fishes from the United States and Canada," American Fisheries Society Special Publication No. 6, Third Edition, 1970, 150 p.

INTRODUCTION

Habitat needs of anadromous salmonids (sea-run salmon and trout) in streams vary with the season of the year and the stage of their life cycle. Upstream migration of adults, spawning, incubation, juvenile rearing, and seaward migration of smolts are the major life stages for most anadromous salmonids. Insofar as possible, we have defined the range of habitat conditions for each life stage that will allow a population to thrive. Throughout this paper, we have included data for salmonids that are not anadromous because they illustrate the range of temperatures, velocities, and depths of waters preferred by salmonids, and these species are generally similar to the anadromous ones.



UPSTREAM MIGRATION OF ADULTS

Adult salmonids returning to their natal streams must arrive at the proper time and in good health if spawning is to be successful. Unfavorable discharges, temperatures, turbidity, and water quality could delay or prevent fish from completing their migration.

TEMPERATURE

Selected salmonid fishes have successfully migrated upstream in water temperatures ranging from 3° to 20°C (table 1). Temperatures above the upper limits have been known to stop the migration of fish.[1/]

Unusual stream temperatures can lead to disease outbreaks in migrating fish, altered timing of migration, and accelerated or retarded maturation. Most stocks of anadromous salmonids have evolved with the temperature patterns of their home streams, and significant abrupt deviations from the normal pattern could adversely affect their survival.

DISSOLVED OXYGEN

Reduced dissolved oxygen concentrations can adversely affect the swimming performance of migrating salmonids. Maximum sustained swimming speeds of juvenile and adult coho salmon at temperatures of 10°-20°C were adversely affected when oxygen was reduced from air-saturation levels (Davis et al. 1963). A sharp decrease in performance was noted at 6.5-7.0 mg/l for all temperatures tested. A similar relation has been observed by Graham (1949) for brook trout. Low dissolved oxygen may also elicit avoidance reactions as noted by Whitmore et al. (1960) and may cause migration to cease. The oxygen levels recommended for spawning fish (at least 80 percent of saturation, with temporary levels no lower than 5.0 mg/l) should provide the oxygen needs of migrating fish.

TURBIDITY

Migrating salmon will avoid or cease migration in waters with high silt loads (Cordone and Kelley 1961, Bell, see footnote 1). Bell cited a study in which salmonid fish would not move in streams where the sediment content was more than 4 000 mg/l. The turbid water resulted from a landslide. Turbid water will absorb more radiation than clear water and thus may indirectly result in a thermal barrier to migration.

BARRIERS

Waterfalls, debris jams, and excessive velocities may also impede migrating fish. Falls that are insurmountable

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[1/] Unpublished report, "Fisheries handbook of engineering requirements and biological criteria. Useful factors in life history of most common species," by M. C. Bell. Submitted to Fish.-Eng. Res. Program, Corps of Eng., North Pac. Div., Portland, Oreg., 1973.

Table 1—Water temperature, depth, and velocity criteria for successful upstream migration of adult salmon and trout.

Species of fish	Temperature range[1]	Minimum depth[2]	Maximum velocity[2]
	°C	Meters	Meters/second
Fall chinook salmon	10.6-19.4	0.24	2.44
Spring chinook salmon	3.3-13.3	.24	2.44
Summer chinook salmon	13.9-20.0	.24	2.44
Chum salmon	8.3-15.6	.18	2.44
Coho salmon	7.2-15.6	.18	2.44
Pink salmon	7.2-15.6	[3].18	[3]2.13
Sockeye salmon	7.2-15.6	[3].18	[1]2.13
Steelhead trout	-	.18	2.44
Large trout	-	.18	2.44
Trout	-	.12	1.22

[1] From Bell (see text footnote 1).
[2] From Thompson (1972).
[3] Based on fish size.

at one time of the year may be passed by migrating fish at other times when flows have changed. Stuart (1962) determined in laboratory studies that ideal leaping conditions for fish are obtained with a ratio of a height of falls to depth of pool of 1:1.25. Figure 1 from Eiserman et al. (1975) depicts the leaping behavior of salmonids observed by Stuart. Given suitable conditions, salmon and steelhead can get past many obstacles that appear to be barriers. Both Jones (1959) and Stuart (1962) observed salmon jumping 2-3 m.

Debris jams, whether natural or caused by human activities, can prevent or delay upstream migration. Chapman (1962) cited a study in which a 75-percent decrease in spawning salmon in one stream was attributed to debris blockage. Debris barriers often form large pools and sediment traps that, if released, could adversely affect downstream spawning areas.

Some logs, leaves, dams, and so on, in streams are beneficial as cover for adult and juvenile fish. All debris jams should be evaluated carefully before they are removed.

Water velocities may exceed the swimming ability of migrating fish at channel constrictions during snow melt and storm runoff. Migration resumes when streamflows and associated velocities have decreased. The swimming abilities of fish are usually described in terms of cruising speed--the speed a fish can swim for an extended period of time (hours), usually ranging from 2 to 4 body lengths per second; sustained speed--the speed a fish can maintain for a period of several minutes, ranging from 4 to 7 body lengths per second; and darting or burst speed--the speed a fish can swim for a few seconds, ranging from 8 to 12 body lengths per second (Bell, see footnote 1; Watts 1974; table 2). According to Bell, cruising speed is used

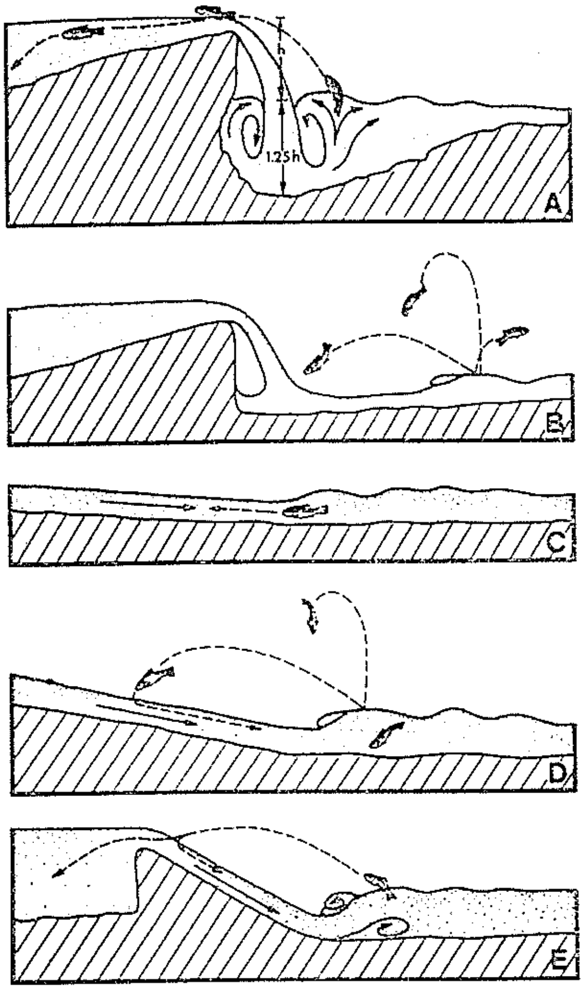


Figure 1—Leaping ability of salmonids (from Eiserman et al. 1975, diagrams drawn after Stuart 1962): A. Falling water enters the pool at nearly a 90° angle. A standing wave lies close to the waterfall where trout use its upward thrust in leaping. Plunge-pool depth is 1.25 times the distance (h) from the crest of the waterfall to the water level of the pool. B. The height of fall is the same, but pool depth is less. The standing wave is formed too far from the ledge to be useful to leaping trout. C. Flow down a gradual incline is slow enough to allow passage of ascending trout. D. Flow over a steeper incline is more than trout can swim against for much distance. Trout may even be repulsed in the standing wave at the foot of the incline. They sometimes leap futilely from the standing wave. E. A shorter barrier with outflow over steep incline may be ascended by trout with difficulty.

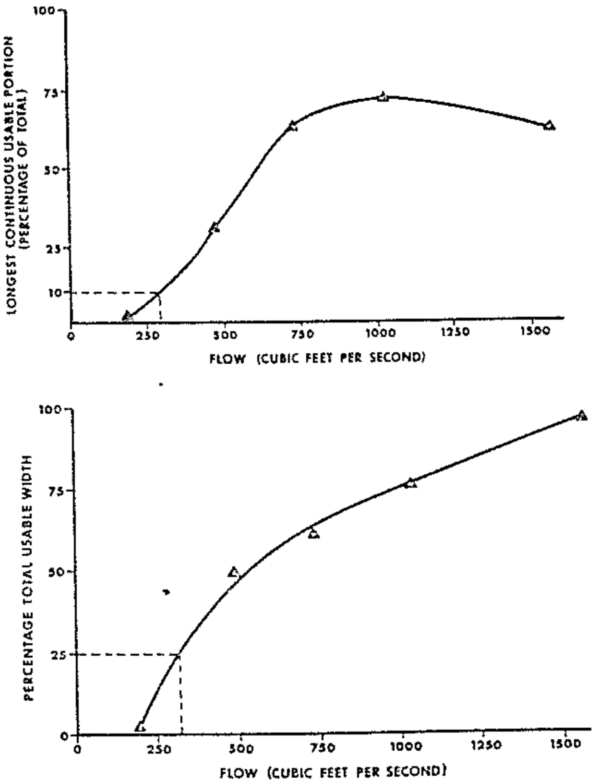


Figure 2—Salmonid passage flow determination (from Thompson 1972).

during migration, sustained speed for passage through difficult areas, and darting speed for escape and feeding. Velocities of 3-4 m/s approach the upper swimming ability of salmon and steelhead and may retard upstream migration.

STREAMFLOW

Migration can also be hampered by too little streamflow and resulting shallow water. Thompson (1972) established passage criteria for various salmonids based on minimum depth and maximum velocities (table 1). Stream discharges that will provide suitable depths and velocities for adult passage (figure 2) can be determined from the criteria and techniques described by Thompson (1972):

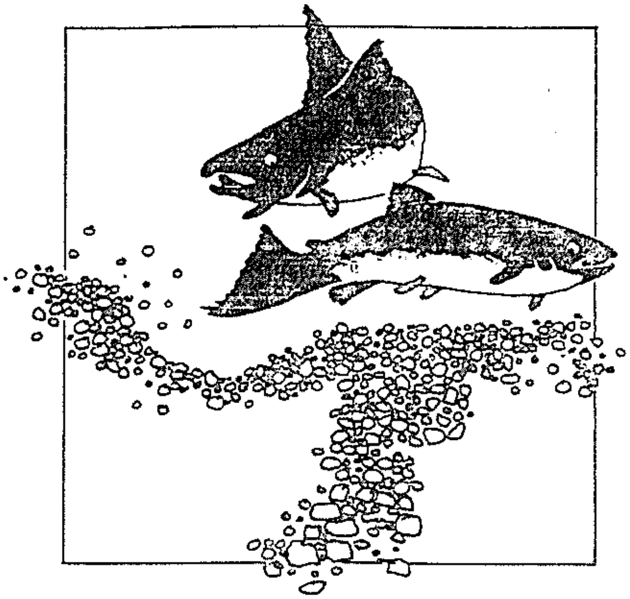
Table 2—Swimming abilities of average size adult salmonids[1/]

Species of fish	Cruising speed	Sustained speed	Darting speed
	Meters per second		
Chinook	0-1.04	1.04-3.29	3.29-6.83
Coho	0-1.04	1.04-3.23	3.23-6.55
Sockeye	0-0.98	.98-3.11	3.11-6.28
Steelhead	0-1.40	1.40-4.18	4.18-8.08
Trout	0-0.61	.61-1.95	1.95-4.11
Brown trout	0-0.67	.67-1.89	1.89-3.87

[1/] From Bell (see text footnote 1).

> ...shallow bars most critical to passage of adult fish are located and a linear transect marked which follows the shallowest course from bank to bank. At each of several flows, the total width and longest continuous portion of the transect meeting minimum depth and maximum velocity criteria are measured. For each transect, the flow is selected that meets the criteria on at least 25 percent of the total transect width and a continuous portion equalling at least 10 percent of its total width.

The mean selected flow from all transects is recommended as the minimum flow for passage. Thompson (1972) noted that maximum acceptable passage flows could theoretically be defined, but we have not attempted to do so in this paper. Baxter (1961) reports that salmon need 30-50 percent of the average annual flow for passage through the lower and middle reaches in Scottish rivers and up to 70 percent for headwater streams.



SPAWNING

Cover, substrate composition, and water quality and quantity are important habitat elements for anadromous salmonids before and during spawning.

COVER

Cover for fish can be provided by overhanging vegetation, undercut banks, submerged vegetation, submerged objects--e.g. logs and rocks, floating debris, and water depth and turbulence (Giger 1973). Cover can protect the fish from disturbance and predation and also provide shade. Some anadromous fish--chinook salmon and steelhead, for example--enter freshwater streams months before they spawn, and cover is essential for fish waiting to spawn. Many spawning areas are relatively open segments on streams where fish are vulnerable to disturbance and predation during redd (nest) construction and spawning. Nearness of cover to spawning areas may be a factor in the actual selection of spawning sites by some species. Johnson et al. (1966) and Reiser and Wesche (1977) noted that many spawning brown trout selected areas adjacent to undercut banks and overhanging vegetation. Reiser and Wesche (1977) speculated that the early spawners and large dominant fish may select areas by cover. As these areas become occupied, the late spawners and small fish are forced to use relatively unprotected sites. Given a choice between two spawning areas, one with cover and one without, the fish would select the area with cover.

TEMPERATURE

Successful spawning of salmonids has occurred in water temperatures ranging from 2.2° to 20.0°C (table 3). A sudden drop in temperature may cause all spawning activity to cease, resulting in lowered nest building activity and reduced production (see footnote 1).

SUBSTRATE COMPOSITION

The suitability of a particular size gravel substrate depends mostly on fish size. Large fish can build redds in large substrate. To determine the substrate composition preferred by various salmonids, many investigators (Burner 1951, Cope 1957, Warner 1963, Orcutt et al. 1968, Hunter 1973, Reiser and Wesche 1977) collected gravel samples from active redds and graded them through a series of sieves. The substrate composition selected in artificial spawning channels reflects the judgment of those who determined the particle sizes best suited for selected species. In the Robertson Creek spawning channels, gravel ranging from 2 to 10 cm was used for pink, coho, and spring chinook salmon (Lucas 1959). In the Jones Creek spawning channel, gravel ranged from 0.6 to 3.8 cm (MacKinnon et al. 1961). The Tehama-Colusa

Table 3—Recommended temperatures for spawning and incubation of salmonid fishes[1]

Species	Spawning temperature	Incubation temperature[2]
	°C	°C
Fall chinook	5.6-13.9	5.0-14.4
Spring chinook	5.6-13.9	5.0-14.4
Summer chinook	5.6-13.9	5.0-14.4
Chum	7.2-12.8	4.4-13.3
Coho	4.4-9.4	4.4-13.3
Pink	7.2-12.8	4.4-13.3
Sockeye	10.6-12.2	4.4-13.3
Kokanee	5.0-12.8	---
Steelhead	3.9-9.4	---
Rainbow	2.2-20.0	---
Cutthroat	6.1-17.2	---
Brown	[3] 7.2-12.8	---

[1] From Bell (see text footnote 1).

[2] The higher and lower values are threshold temperatures at which mortality will increase if exceeded. Eggs will survive and develop normally at lower temperatures than indicated, provided initial development of the embryo has progressed to a stage that is tolerant of colder water.

[3] From Hunter (1973).

Table 4—Water depth, velocity, and substrate size criteria for anadromous and other salmonid spawning areas

Species of fish	Source	Depth	Velocity	Substrate size
		Meters	Cm/s	Centimeters
Fall chinook	Thompson (1972)	≥0.24	30-91	[1] 1.3-10.2
Spring chinook	Thompson (1972)	≥.24	30-91	[1] 1.3-10.2
Summer chinook	Reiser[2]	≥.30	32-109	[1] 1.3-10.2
Chum	Smith (1973)	≥.18	46-101	[1] 1.3-10.2
Coho	Thompson (1972)	≥.18	30-91	[3] 1.3-10.2
Pink salmon	Collings[4]	≥.15	21-101	[1] 1.3-10.2
Sockeye[5]	---[3]	≥.15	[3] 21-101	[1] 1.3-10.2
Kokanee	Smith (1973)	≥.06	15-73	-
Steelhead	Smith (1973)	≥.24	40-91	[6] .6-10.2
Rainbow trout	Smith (1973)	≥.18	48-91	.6-5.2
Cutthroat	Hunter (1973)	≥.06	11-72	.6-10.2
Brown trout	Thompson (1972)	≥.24	21-64	[6] .6-7.6

[1] From Bell (see text footnote 1).

[2] Unpublished data of D. W. Reiser, Idaho Coop. Fish Res. Unit, Moscow. 1978.

[3] Estimated from other criteria.

[4] See text footnote 3.

[5] No specific criteria established.

[6] From Hunter (1973).

spawning channels contain gravel that ranges from 1.9 to 15.2 cm (Pollock 1969). Bell (see footnote 1) states that, in general, the spawning bed in artificial channels should be composed of 80 percent 1.3-to 3.8-cm gravel with the balance up to 10.2 cm. Acceptable ranges of substrate size for various salmonids are summarized in table 4.

REDD AREA

Area of gravel substrate required for a spawning pair varies with the species (table 5). Burner (1951) proposed that a conservative estimate of the number of salmon a stream could accommodate could be obtained by dividing the area suitable for spawning by four times the average redd area. Redd area can be computed by measuring the total length of the redd (upper edge of pit to lower edge of tailspill) and the average of several equidistant widths.

MEASURING REDD AREA

WATER DEPTH AND VELOCITY

Preferred water depths and velocities for various spawning salmonids have been determined by measuring water depth and velocity over active redds (Sams and Pearson,[2] Thompson 1972, Smith 1973, Hooper 1973, Hunter 1973, Reiser and Wesche 1977). These measurements were usually taken at the upstream edge of the redd because that point most closely approximates conditions before redd construction and reflects the depths and velocities selected by the fish. Preferred depth and velocity criteria have been variously defined: Thompson (1972) used a 90-to 95-percent confidence limit; Hunter (1973) used the middle 80-90 percent of the measurements; Smith (1973) used a two-sided tolerance limit within which there was 95-percent confidence that 80 percent of the measurements would occur with a normal distribution; others have simply listed ranges of depth and velocity. Water depth and velocity criteria for salmonids as defined by different investigators are found in tables 4 and 6.

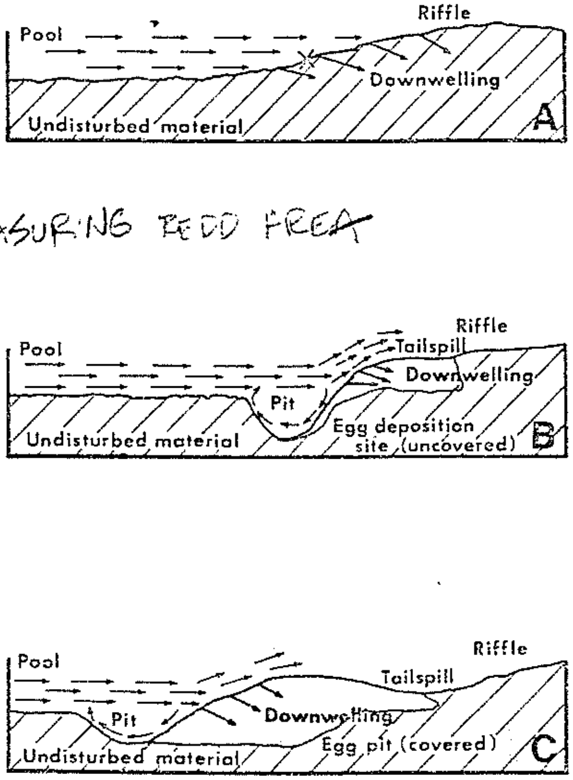


Figure 3—Longitudinal sections of spawning areas (from Reiser and Wesche 1977): A. Convexity of the substrate at pool-riffle interchange induces downwelling of water into the gravel. Area likely to be used for spawning is marked with an X. B. Redd construction results in negligible currents in the pit (facilitating egg deposition) and increased currents over and through (downwelling) the tailspill. C. Egg-covering activity results in the formation of a second pit which may also be used for spawning, as well as covering the eggs in the first pit. Increased permeability and the convexity of the tailspill substrate induces downwelling of water into the gravel, creating a current past eggs, bringing oxygen to them and removing metabolic wastes.

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[2] Unpublished report, "A study to develop methods for determining spawning flows for anadromous salmonids," by R. E. Sams and L. S. Pearson. Oreg. Fish Comm., Portland, 1963.

Table 5—Average area of salmonid redds and area recommended per spawning pair in channels[1]

Species	Source	Average area of redd	Area recommended per spawning pair
		------Square meters-----	
Spring chinook	Burner (1951)	3.3	13.4
Fall chinook	Burner (1951)	5.1	20.1
Summer chinook	Burner (1951)	5.1	20.1
Coho	Burner (1951)	2.8	11.7
Chum	Burner (1951)	2.3	9.2
Sockeye	Burner (1951)	1.8	6.7
Pink	Hourston and MacKinnon (1957)	.6	.6
Pink	Wells and McNeil (1970)	.6-.9	--
Steelhead	Orcutt et al. (1968)	5.4	--
Steelhead	Hunter (1973)	4.4	--
Rainbow	Hunter (1973)	.2	--
Cutthroat	Hunter (1973)	.09-.9	--
Brown	Reiser and Wesche (1977)	.5	--

[1] Modified from Clay (1961).

Many salmonids prefer to spawn at the pool-riffle interchange (Hazzard 1932, Hobbs 1937, Smith 1941, Stuart 1953, Briggs 1953). Tautz and Groot (1975) reported that chum salmon chose to spawn in an accelerating flow, such as that found at a pool-riffle interchange. By placing crystals of potassium permanganate on the gravel surface, Stuart (1953) demonstrated the presence of a downwelling current at these interchange areas and suggested that the current may assist the fish in maintaining its position with a minimum of effort. The gravel in these areas was easy to excavate and relatively free of silt and debris. The nature of currents before, during, and after spawning is shown in figure 3.

STREAMFLOW

Streamflow regulates the amount of spawning area available. D. H. Fry in Hooper (1973) summarizes the effect of discharge on the amount of spawning area in a stream.

> As flows increase, more and more gravel is covered and becomes suitable for spawning. As flows continue to increase, velocities in some places become too high for spawning, thus canceling out the benefit of increases in usable spawning area near the edges of the stream. Eventually, as flows increase, the losses begin to outweigh the gains, and the actual spawning capacity of the stream starts to decrease.

Table 6—Water depth, velocity, and size of substrate measured in spawning areas of salmonids

Species	Source	Depth	Velocity	Substrate	How and where developed	Remarks
		Meters	Cm/s	Centimeters		
Chinook salmon	Hamilton and Remington (1962)	≥0.24	31	--	Oregon-Coquille River	
Fall chinook	Warner[1/] Westgate[2/]	.12-1.22	15-107	--	California-American, and Consumnes Rivers	
	Kier (1964) Rantz (1964)	≥.24	31-92	--	California-Feather, Eel, and Mad River Systems	
	Horton and Rogers[3/]	≥.21	37-107		California-Van Duzen River	
	Chambers et al.[4/]	.30-.46	30-69		Washington-Columbia River and tributaries	$\bar{V}$ at 0.4 ft above bed
	Sams and Pearson[5/]	≥.18	.27-94	--	Oregon - 4 streams in Willamette River Basin	107 redds sampled; $\bar{V}$ at 0.63 depth or 0.2 ft and 0.8 depth from surface
	Thompson (1972)[6/]	≥.24	30-91	--	90-95% confidence interval; Oregon, wide range of streams	440 redds sampled; streams represented a wide variation of hydraulic characteristics
	Smith (1973)	≥.24	30-76	--	Tolerance interval; Oregon, 7 streams with varying hydraulic conditions	50 redds sampled; $\bar{V}$ at 0.4 ft above bed
Spring chinook	Chambers et al.[4/]	.46-.53	53-69	--	Washington-Columbia River and tributaries	$\bar{V}$ at 0.4 ft above bed
	Sams and Pearson[5/]	≥.18	.08-.85	--	Range; Oregon, 3 streams in Willamette River Basin	270 redds sampled; $\bar{V}$ at 0.6 ft depth or 0.2 ft and 0.8 ft depth from surface.
	Thompson (1972)[6/]	≥.24	30-91	--	90-95% confidence interval; Oregon, wide range of streams	158 redds sampled; streams representative of a wide variation of hydraulic characteristics
	Smith (1973)	≥.18	21-64	--	Tolerance interval; Oregon, 7 streams with varying hydraulic conditions	142 redds sampled; $\bar{V}$ at 0.4 ft above bed
	Reiser[7/]	≥.15	14-69	--	Range; Idaho, 5 small streams	58 redds sampled; $\bar{V}$ at 0.6 ft depth from surface
Summer chinook	Reiser [6/] [7/] [8/]	.30-.85	25-109	--	Range; Idaho, Salmon River	50 redds sampled; $\bar{V}$ at 0.6 ft depth from surface
Chum salmon	Thompson (1972)	≥.18	46-97	--	90-95% confidence interval; Oregon, on a wide range of streams	177 redds sampled; streams represented a wide variation of hydraulic characteristics
	Smith (1973)[6/]	≥.18	46-101	--	Tolerance interval; Oregon, 5 streams with varying hydraulic conditions	214 redds sampled; $\bar{V}$ at 0.4 ft above bed.
	Collings [9/]	.15-.53	21-101	--	--	$\bar{V}$ measured 0.4 ft above bed
Coho salmon	Chambers et al.[4/]	.30-.38	37-55	--	Washington, Columbia River and tributaries	Redds measured 0.4 ft above bed
	Sams and Pearson (1963)[5/]	≥.15	14-93	--	Range; Oregon, 4 streams	123 redds sampled; $\bar{V}$ at 0.6 ft depth or 0.2 ft and 0.8 ft depth from surface

Table 6—Water depth, velocity, and size of substrate measured in spawning areas of salmonids—(Continued)

Species	Source	Depth	Velocity	Substrate	How and where developed	Remarks
		Meters	Cm/s	Centimeters		
Coho salmon	Thompson (1972)[6]	≥0.18	30-91	--	90-95% confidence interval; Oregon, 10-12 streams with varying hydraulic conditions	251 redds sampled; streams represent wide variation of hydraulic characteristics
	Smith (1973)	≥.15	21-70	--	Tolerance interval; Oregon, 7 streams with varying hydraulic conditions	128 redds sampled; $\bar{V}$ measured 0.4 ft above bed
Pink salmon	Collings [6] [9]	.15-.53	21-101	--		$\bar{V}$ measured 0.4 ft above bed
Sockeye salmon	Chambers et al.[4]	.30-.46	53	--	Washington	$\bar{V}$ at 0.4 ft above bed
	Clay (1961)	--	53-55	--		$\bar{V}$ at 0.4 ft above bed
Kokanee	Thompson (1972)	.12-.18	24-64	--	90-95% confidence interval; Oregon, wide range of streams	106 redds sampled; streams represent wide variation of hydraulic characteristics
	Smith (1973)[6]	≥.06	15-73	--	Tolerance interval; Oregon, 3 streams with varying hydraulic conditions	106 redds sampled; $\bar{V}$ at 0.4 ft above bed
	Hunter (1973)	.09-.36	12-41	--	Middle 80% of range; Washington, flow 2-30 ft^3/s	177 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 above bed
Steelhead trout		.35-.43	60-69	--	95% confidence interval; Oregon	51 redds sampled
Winter steelhead	Smith (1973)[6]	≥.24	40-91	--	Tolerance interval; Oregon, 11 streams with varying hydraulic conditions	115 redds sampled; $\bar{V}$ at 0.4 ft above bed
	Engman[10]	.10-≥.9	23-117	--	Range; Washington	62 redds sampled
	Hunter (1973)	.21-.70	37-101	0.64-10.16	Middle 90% of range; Washington, 19 streams with varying hydraulic conditions	114 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft above bed
	Hunter (1973)	.12-.36	44-109	0.64-12.70	Range; Washington	19 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft above bed
	Hunter[11]	.23-.50	41-108	--	Range; Washington, on streams of 180 ft^3/s	30 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft above bed
	Hunter[11]	.14-.20	25-34	--	Range; Washington, Satsop River	4 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft above bed
Summer steelhead	Smith (1973)	≥.24	43-97	--	Tolerance interval; Oregon, Deschutes River	90 redds sampled; $\bar{V}$ 83 redds sampled D; $\bar{V}$ at 0.4 ft above bed
	Orcutt et al. (1968)	.21-≥1.52	24-55	1.27-10.16	Range; Idaho, 6 streams in Clearwater and Salmon River watersheds	54 redds sampled; $\bar{V}$ measured at the surface

Table 6—Water depth, velocity, and size of substrate measured in spawning areas of salmonids —(Continued)

Species	Source	Depth	Velocity	Substrate	How and where developed	Remarks
		Meters	Cm/s	Centimeters		
Summer steelhead	Reiser[8]	0.12-.41	38-100	--	Range; Idaho, 3 streams	46 redds sampled; $\bar{V}$ measured at 0.6 ft depth from surface
Rainbow trout	Smith (1973)[6]	≥.18	48-91	0.64-5.18	Tolerance interval; Oregon, Deschutes River	51 redds sampled; $\bar{V}$ at 0.4 ft above bed
	Hooper (1973)	.21-.33	43-82	.64-7.62	Range; California, Feather River	10 redds sampled; $\bar{V}$ at 0.21 above bed
	Bovee (1974)	.15	43-82	--	Estimated from literature	
	Waters (1976)	.09-.90	21-91	--	California, Pit River	
	Hartman (1969)	--	50-90	--	British Columbia, Kootenay Lake	
Cutthroat trout	Hooper (1973)	--	30-91	.16-.64	Range; California	
	Cedarholm (in Hunter 1973)	.08-.15	8-26	--	Range; Washington	3 redds sampled
(resident)	Hunter (1973)	.06-.27	11-38	.64-5.08	Range; Washington, streams 0.5-2.0 ft^3/s	23 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft from bed
(sea-run)	Hunter (1973)	.12-.40	15-56	.64-10.16	Range; Washington, streams 5.0-15.0 ft^3/s	16 redds sampled; $\bar{V}$ at 0.4 ft or 0.25-0.30 ft from bed
Brown trout	Smith (1973) (Hunter 1973)	≥.24	20-68	.64-7.62	Tolerance interval; Oregon, 5 streams with varying hydraulic conditions	115 redds sampled; $\bar{V}$ at 0.4 ft from bed
Brown trout	Thompson (1972)[6]	≥.24	21-64	--	90-95% confidence interval; Oregon, on a wide range of streams	115 redds sampled
	Hooper (1973)	--	30-91	.64-7.62	Range; California	
	Bovee (1974)	≥.15	40-52	--	Estimated from literature	
	Reiser and Wesche (1977)	≥.09	14-46	.64-7.62	Middle 80% of range; Wyoming, 5 small streams	121 redds sampled; $\bar{V}$ at 0.6 ft depth from surface

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[1] Unpublished report, "The relationship between flow and available salmon spawning gravel on the American River below Nimbus Dam," by K. Warner. Calif. Dep. Fish and Game Admin., Sacramento, 1953.

[2] Unpublished report, "The relationship between flow and usable salmon spawning gravel, Consumnes River, 1956," by J. Westgate. Calif. Dep. Fish and Game, Inland Fish. Admin. Rep. 58-2, Sacramento, 1958.

[3] Unpublished report, "The optimum stream flow requirements for king salmon spawning in the Van Duzen River, Humboldt County, California," by J. L. Horton and D. W. Rogers. Calif. Dep. Fish and Game, Water Proj. Branch Admin. Rep. 69-2, Sacramento, 1969.

[4] Unpublished report, "Research relating to study of spawning grounds in natural areas," by J. S. Chambers, G. H. Allen, and R. T. Pressey. Wash. Dep. Fish., Olympia, 1955.

[5] See text footnote 2.

[6] Recommended spawning criteria.

[7] Unpublished data of D. W. Reiser, Idaho Coop. Fish. Res. Unit, Moscow, 1977.

[8] See footnote 2, table 4.

[9] See text footnote 3.

[10] Unpublished progress report, steelhead redd study, by R. G. Engman. Wash. State Dep. Game, Olympia, 1970.

[11] Personal communication, J. W. Hunter, Wash. Dep. Game, Olympia, 1976.

> If spawning area is plotted against streamflow, the curve will usually show a rise to a relatively wide plateau followed by a gradual decline.

Using the criteria described, methods have been developed for recommending stream discharges for spawning. Figures 4 and 5, taken from Collings (1972), exemplify the process of depth and velocity contouring to determine the area suitable for spawning at a given discharge. Another method (Thompson 1972) uses cross channel transects on spawning bars and consists of quantifying the width of the stream at different flows that meet depth and velocity criteria (fig. 6). When measurements have been taken over a wide range of flows, a graph is plotted of flow versus suitable spawning areas (Collings 1972, and fig. 7) or usable width (Thompson 1972, and fig. 8). The optimum spawning flow is defined as the discharge at which the largest spawning area or usable width occurs. Detailed descriptions of spawning flow methodologies are described by Sams and Pearson (see footnote 2), Thompson (1972), Collings (1972, 1974[3/]), Waters (1976), and Stalnaker and Arnette (1976).

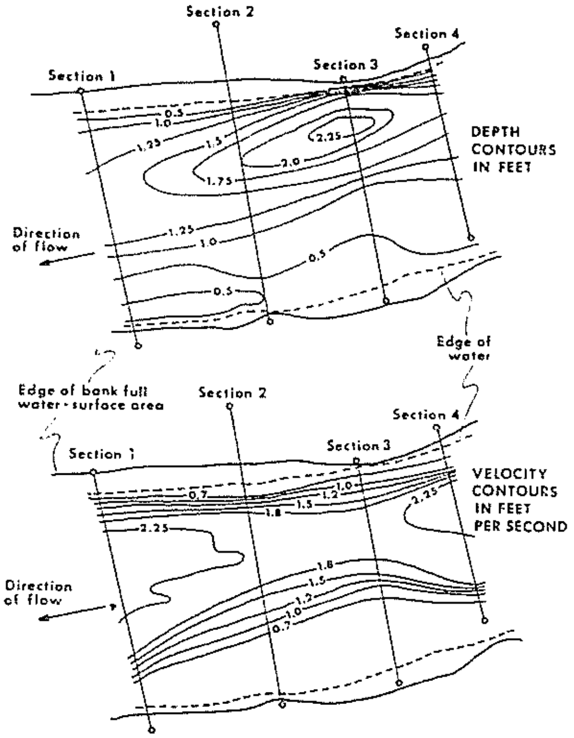
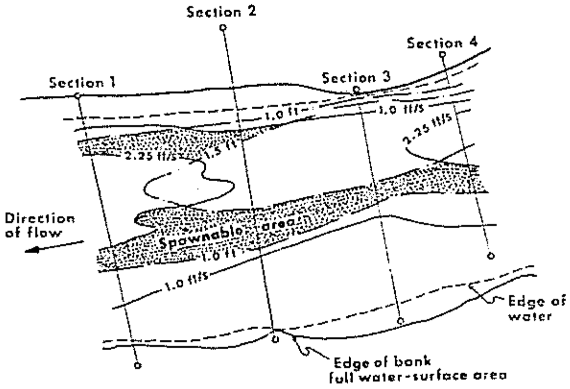


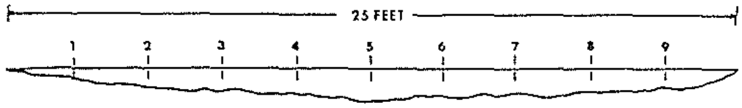
Figure 4—Example of water depth and velocity contouring for one river discharge in a study reach of the North Nemah River (from Collings 1972).



DISCHARGE: 94.6 ft^2
AREA OF PREFERRED DEPTH: 1045 ft^2, BETWEEN 1.0 and 1.5 ft
AREA OF PREFERRED VELOCITY: 1706 ft^2, BETWEEN 1.0 and 2.25 ft/s
AREA PREFERRED FOR SPAWNING: 726 ft^2

Figure 5—Determining area of study reach that is preferred for spawning by fall chinook salmon at one river discharge, North Nemah River (from Collings 1972).

[3/] Unpublished report, "Generalization of spawning and rearing discharges for several Pacific salmon species in western Washington," by M. R. Collings. U.S. Geol. Surv., open file report. 1974.



SPAWNING BAR CROSS SECTION

Station	Depth (feet)	Velocity (feet per second)
1	0.4	1.4
2	.6	1.6
3	.7	1.9
4	.9	2.3
5	1.1	3.1
6	1.0	2.6
7	.8	2.0
8	.7	1.4
9	.6	.9

Spawning flow criteria

Minimum depth = 0.6 ft

Velocity = less than 3.0 but greater than 1.0 ft/s

Flow = width x mean depth x mean velocity

$$\text{Flow} = 25\text{ ft} \times 0.75\text{ ft} \times 1.93\text{ ft/s} = 36\text{ ft}^3\text{/s}$$

Stream width usable for spawning

$$\text{Usable width} = \frac{\text{stream width}}{10} \times \text{usable stations} = \frac{25\text{ ft}}{10} \times 6 = 15.0\text{ ft}$$

Figure 6—Transect method of determining stream width usable for spawning (from Thompson 1972).

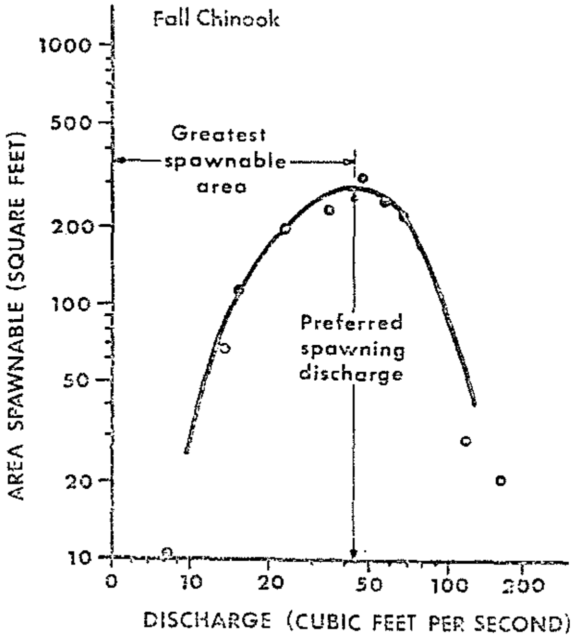


Figure 7—Method (usable area technique) for selecting preferred spawning discharge, North Nemah River (from Collings 1972).

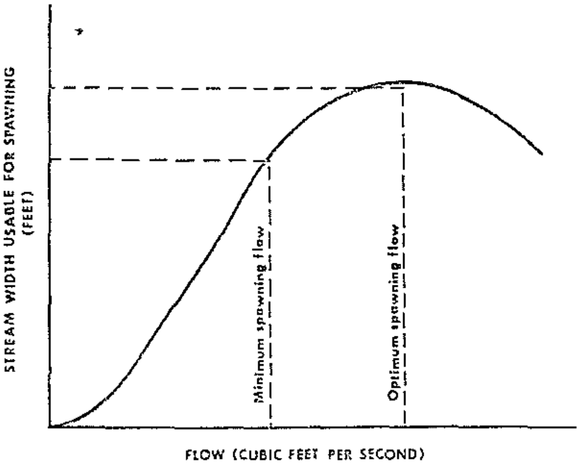
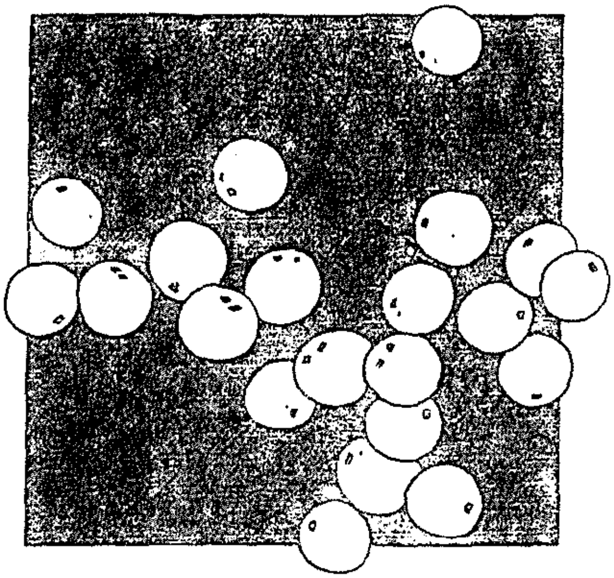


Figure 8—Method (usable width technique) for determining spawning flow (from Thompson 1972).



INCUBATION

Although incubation is inextricably tied to spawning, the habitat requirements of embryos during incubation are different from those of adults while spawning and warrant a separate discussion. When an adult fish selects a spawning site, the incubation environment is also being selected. Successful incubation and emergence of fry, however, is dependent on both extragravel and intragravel chemical, physical, and hydraulic parameters--dissolved oxygen (DO), water temperature, biochemical oxygen demand (BOD) of material carried in water and in substrate, substrate size (percentage fines), channel gradient, channel configuration, water depth (head), surface water discharge and velocity, permeability, porosity, and apparent velocity in gravel.

SURFACE STREAM-INTRAGRAVEL RELATION

Interchange of water in a stream with that in streambed gravels has been demonstrated by Stuart (1953), Sheridan (1962), Vaux (1962). Vaux (1962) stated that the initial source of oxygen in intragravel water is the atmosphere and listed the following three steps for transport of oxygen to the intragravel environment:

- Dissolution of oxygen through air-water interface into stream water.
- Transport of oxygenated water to the stream bottom.
- Interchange of oxygenated water from the stream into the porous gravel interior.

Factors that control the water interchange between stream and gravel bed are: stream surface profile, gravel permeability, gravel bed depth, and irregularity of the streambed surface (Vaux 1962, 1968). Sheridan (1962) noted in salmon spawning areas in southeast Alaska, that ground water contained very little oxygen and that the oxygen content of intragravel water decreased with gravel depth; thus the major source of oxygen in intragravel water is the stream itself. Wells and McNeil (1970) attributed high intragravel oxygen in pink salmon spawning beds to high permeability of the substrate and stream gradient.

Intragravel water temperatures are similarly influenced by temperatures of the stream. Ringler (1970) and Ringler and Hall (1975) observed that temperatures of intragravel water lagged 2-6 h behind those of surface waters in attaining diurnal maximum--a function of the interchange rate of surface and intragravel water.

Apparent velocity (velocity of water moving through gravel)

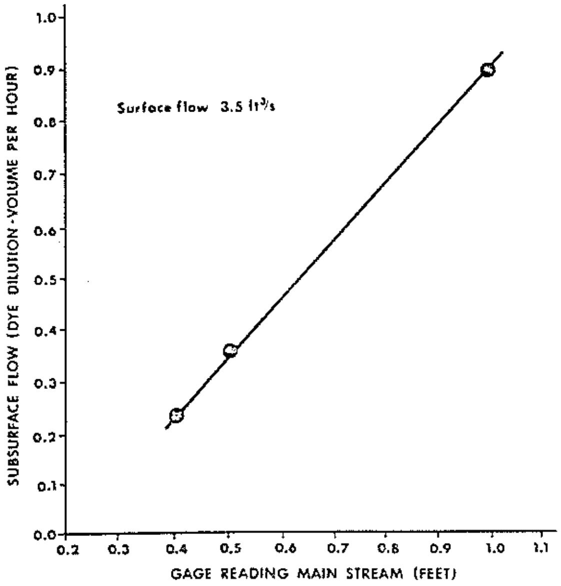


Figure 9—Relation between subsurface water flow 30 cm (12 in) in a controlled-flow side channel and main stream gage readings. The subsurface flow varied with changes in discharge of the main stream adjacent to the controlled-flow side channel (from Wickett 1954, courtesy of the Journal of the Fisheries Research Board of Canada).

is a function of the hydraulic head and the permeability of the gravel (Coble 1961). Thus, as depth of surface water increases, a corresponding increase in apparent velocity can be expected. Wickett (1954) found a direct relation between gage height readings in a stream and subsurface flow (fig. 9). Reduction in permeability from fine sediment deposition will reduce both the interchange of surface and intragravel water and the apparent velocity of the intragravel water (Gangmark and Bakkala 1960, Wickett 1962, Cooper 1965).

DISSOLVED OXYGEN

Critical concentrations of dissolved oxygen have been experimentally determined for salmonid embryos at different

Table 7—Critical levels of dissolved oxygen for salmonid embryos at various stages of development

Source	Species	Stage of development	Days	Temperature units[1]	Critical value of dissolved oxygen
					Mg/l
Wickett (1954)	Chum salmon	Pre-eyed	0	--	0.72
		Pre-eyed	5	--	1.67
		Pre-eyed	12	--	1.14
		Faintly eyed	85	--	3.70
Alderdice et al. (1958)	Chum salmon	--	--	4.0	[2] .72
		--	--	4.8	[2] 1.67
		--	--	48.0	[2] 1.14
		--	--	121.2	3.96
		--	--	162.1	[2] 3.70
		--	--	268.2	5.66
		--	--	353.0	6.60
		--	--	452.4	7.19
Lindroth (1942)	Atlantic salmon	Doomed	--	--	.76
		Nearly hatching	--	--	5.80
		Hatching	--	--	10.00
Hayes et al. (1951)	Atlantic salmon	Eyed	25	--	3.1
		Hatching	50	--	7.1

[1] A temperature unit equals 1°F above freezing (32°F) for a period of 24 h.
[2] From Wickett (1954).

developmental stages (Lindroth 1942, Hayes et al. 1951, Wickett 1954, Alderdice et al. 1958). Critical oxygen levels defined by Alderdice et al. (1958) are those that barely satisfy respiratory demands (table 7). Doudoroff and Warren (1965) believe the critical levels in table 7 are unreliable, because they found that embryos exposed to dissolved oxygen levels below saturation throughout development were smaller and that hatching was delayed or occurred prematurely. From laboratory tests with coho, chum, and chinook, and steelhead eggs by Alderdice et al. (1958), Silver et al. (1963), and Shumway et al. (1964), the following summary of oxygen concentration and egg development has been prepared:

- Sac fry from embryos incubated in low and intermediate oxygen concentrations were smaller and weaker than sac fry reared at higher concentrations, and thus they may not survive as well as larger fry (Silver et al. 1963, and figs. 10 and 11).
- Reduced oxygen concentrations lead to smaller newly hatched fry and a lengthened incubation period (Shumway et al. 1964, and figs. 12 and 13).
- Low oxygen concentrations in the early stages of development may delay hatching, increase the incidence of anomalies, or both. Low oxygen concentration during the latter stages of development may stimulate premature hatching (Alderdice et al. 1958).

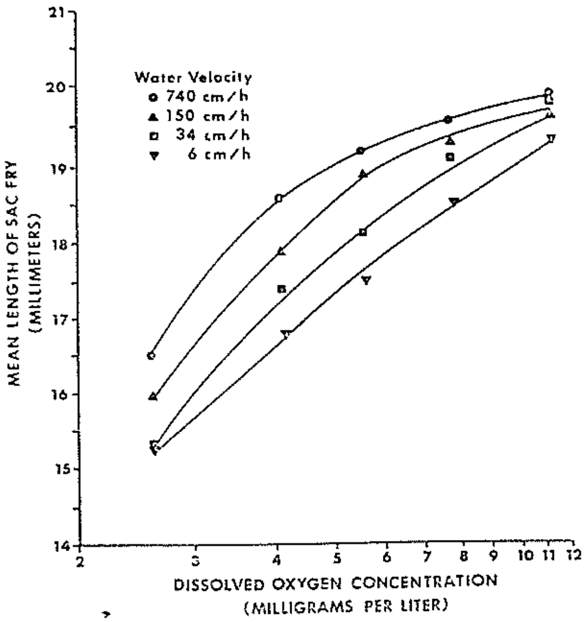


Figure 10—Relation between mean lengths of steelhead trout sac fry when hatched and dissolved oxygen concentrations at which the embryos were incubated at different water velocities and at 9.5°C (from Silver et al. 1963).

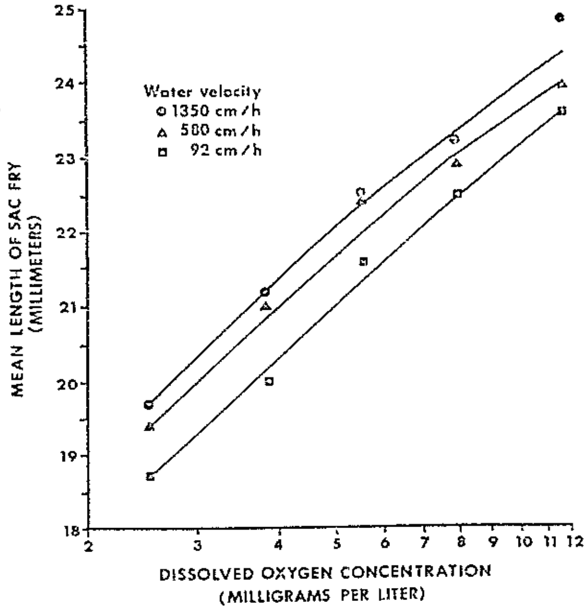


Figure 11—Relation between mean lengths of chinook salmon sac fry at hatching and dissolved oxygen concentrations at which the embryos were incubated at different water velocities and at 11°C (from Silver et al. 1963).

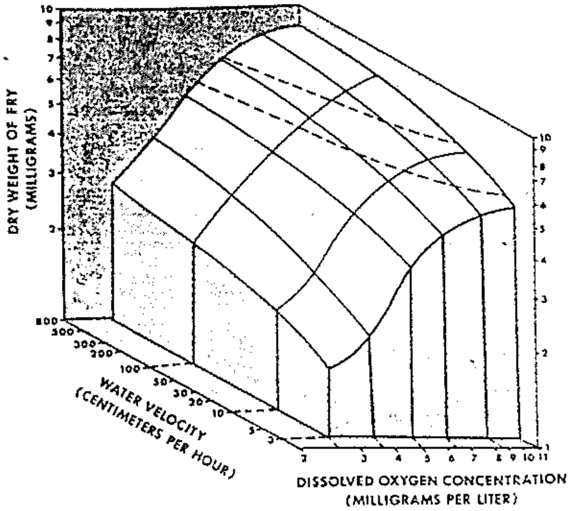


Figure 12—Three-dimensional diagram of effect of oxygen concentration and water velocity on the mean dry weights of newly hatched coho salmon fry. The two broken lines (curves) delimit the reduced oxygen concentrations at different water velocities, and also the reduced velocities at different oxygen concentrations that resulted in reductions of the dry weights of fry to less than 80 percent (upper broken line) and less than 67 percent (lower broken line) of the mean weight of fry that hatched at the highest oxygen concentration and water velocity tested (from Shumway et al. 1964).

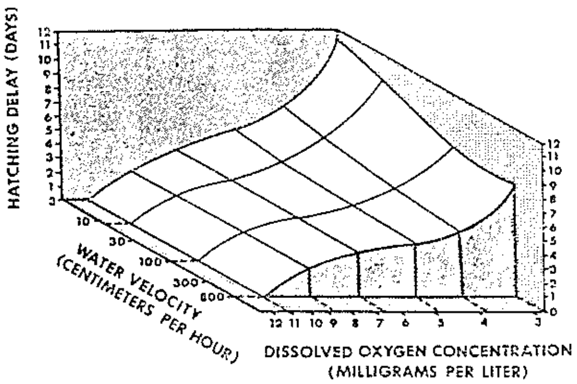


Figure 13—Three-dimensional diagram of "hatching delay" (median hatching time, in days, minus 44) of coho salmon fry in relation to both oxygen concentration and water velocity (from Shumway et al. 1964).

In field studies, Coble (1961) found a positive correlation between steelhead embryo survival and intragravel dissolved oxygen content (fig. 14). A similar relation was reported by Phillips and Campbell (1961) for coho salmon and steelhead (fig. 15). Based on their field experiments, Phillips and Campbell concluded that intragravel oxygen concentration must average 8 mg/l for high survival of coho salmon and steelhead embryos. Brannon (1965) compared newly hatched sockeye salmon fry developed at three different oxygen levels, and found length and other anatomical differences in the three groups (table 8); however, those raised in low oxygen concentrations eventually attained nearly the same weight by the fry stage as did those incubated

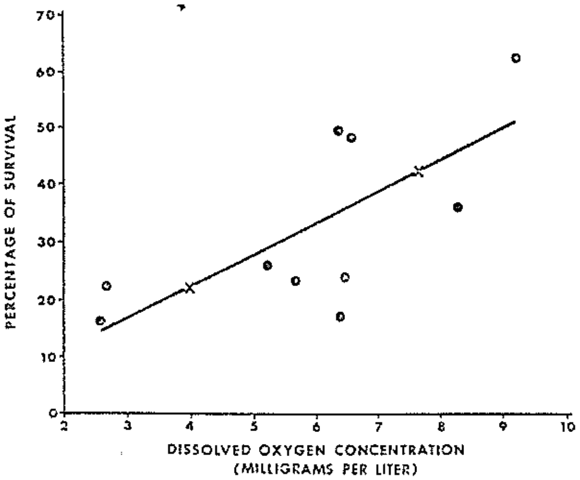


Figure 14—Relation between dissolved oxygen concentration and embryo survival (from Coble 1961).

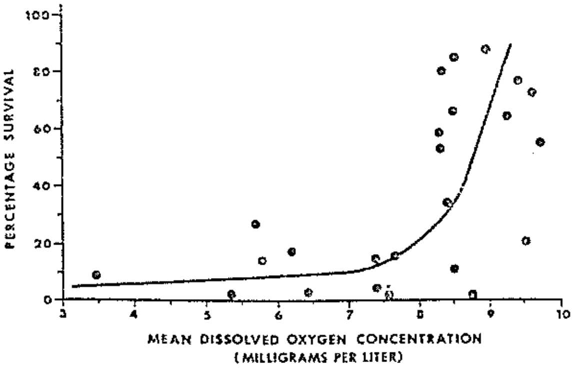


Figure 15—Relation of mean dissolved oxygen to survival of coho embryos, Needle Branch, December 20, 1960, to February 28, 1961 (from Phillips and Campbell 1961).

Table 8—Characteristics of alevins at hatching after being incubated in three oxygen concentrations (from Brannon 1965)

	O_2 concentration (mg/l)		
Description	3.0	6.0	11.9
Temperature units to 50% hatching	1200	1200	1200
Length in millimeters	16.3	18.6	19.7
Yolk sac shape	Spherical	Longitudinal	Longitudinal
Pigmentation	Lightly on head	On head and starting on back	On head and back
Visibility of the dorsal and anal fin rays	Not visible	Distinguishable	Readily visible
Caudal fin development	Forming	Forming	Well advanced

in water fully saturated with oxygen. Although dissolved oxygen concentrations required for successful incubation depend on both species and developmental stage, concentrations at or near saturation with temporary reductions no lower than 5.0 mg/l are recommended for anadromous salmonids.

TEMPERATURE

There are upper and lower temperature limits (thresholds) for successful incubation of salmonid eggs (table 3). Combs and Burrows (1957) and Combs (1965) noted that pink and chinook salmon eggs could tolerate long periods of low temperature, provided the initial temperature was above 6.0°C and embryogenesis had proceeded to a particular developmental stage. Combs and Burrows (1957) believed salmon eggs deposited in water colder than 4.5°C would not produce as viable a fish as eggs spawned into warmer water.

In many streams containing incubating salmonid eggs, water temperatures are colder than 4.5°C during the winter; eggs develop normally and successfully, however, because spawning and initial embryo development occur when temperatures are warmer.

Extremely cold water and air temperature can cause mortality among incubating eggs and fry by the formation of frazil or anchor ice that reduces water interchange. Anchor ice normally forms in shallow water typical of spawning areas and may completely blanket the surface of the substrate and thereby prevent water interchange between stream and gravel. In addition, ice dams may form that can impede flow or even dewater spawning areas. Subsequent melting of the dam may cause floodlike conditions resulting in the displacement and scouring of redds. In an egg planting experiment, Reiser and Wesche (1977) found eggs in

Vibert boxes completely frozen even though buried 15 cm in the substrate and covered with more than 13 cm of water. Anchor ice had formed at least twice during the incubation period. Neave (1953) and McNeil (1966) also noted the problems of freezing on egg survival.

BIOCHEMICAL OXYGEN DEMAND

The oxygen demand of organic matter in the stream may reduce the oxygen concentration, particularly in the intragravel environment. The impact of organic matter in a stream depends on the chemical, physical, and hydraulic characteristics (for example, dissolved oxygen content, temperature, and reaeration capability) of the stream. Excessive recruitment of organic material to a stream may result in reduced oxygen concentrations and detrimental impacts on eggs.

APPARENT VELOCITY

The single most important hydraulic component in the intragravel environment used for egg incubation is apparent velocity, defined as the rate of seepage and expressed as the volume of liquid flowing per unit time through a unit area normal to the direction of flow (Terhune 1958, Coble 1961, Vaux 1968). Apparent velocity is important in bringing dissolved oxygen to the eggs and removing metabolic waste products.

High oxygen levels do not, in themselves, guarantee high egg survival. In two redds with similar dissolved oxygen concentrations but different apparent velocities, embryonic development may be better in the redd with the higher rate of water exchange (Coble 1961). Coble states that, in general, when apparent velocities are low, oxygen concentrations will be low and, when they are high, oxygen levels are usually high. Others have found egg survival related to apparent velocity--for example, Pyper (in Cooper 1965) in sockeye eggs (fig. 16), Coble (1961) in steelhead (fig. 17), Gangmark and Bakkala (1960) in chinook, Wickett (1962) in pink salmon, and Phillips and Campbell (1961) in coho and steelhead. In the last study, high egg survivals were associated with apparent velocities of more than 20 cm/h. Wickett (1962) found low survival in areas where apparent velocities were 0.5-1.5 cm/h and high survivals where velocities were more than 7 cm/h. Silver et al. (1963) and Shumway et al. (1964) related apparent velocity to size of fry at a hatchery. Silver et al. found that size of steelhead and chinook fry depended on apparent velocities, even at velocities as high as 740-1350 cm/h. Shumway et al. found that reduced velocities (3-10 cm/h) resulted in decreased size of fry at all oxygen levels tested (2.5-11.5 mg/l).

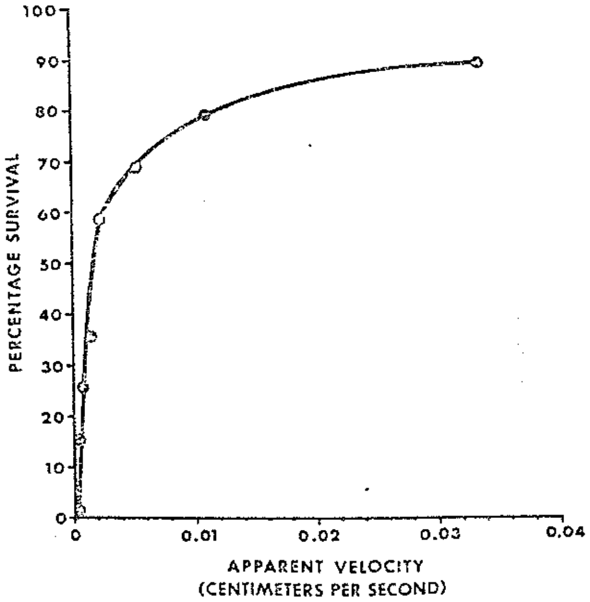


Figure 16—Relation between rate of flow of water through a gravel bed and the survival of eyed sockeye eggs in the gravel (from Cooper 1965).

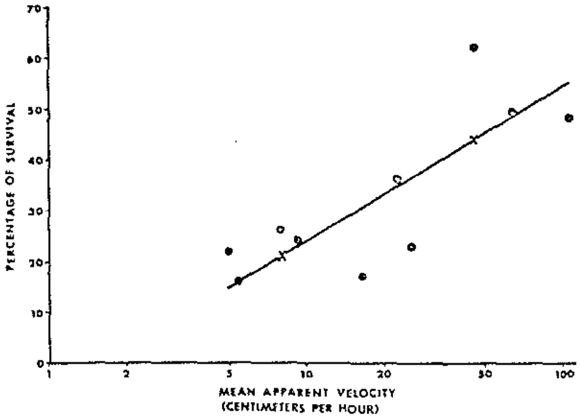


Figure 17—Relation between apparent velocity and embryo survival (from Coble 1961).

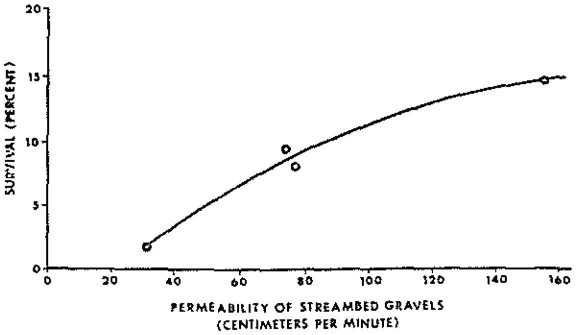


Figure 18—Observed relation reported by Wickett (1958) between permeability of spawning beds and survival of pink and chum salmon to the migrant fry stage (from McNeil and Ahnell 1964).

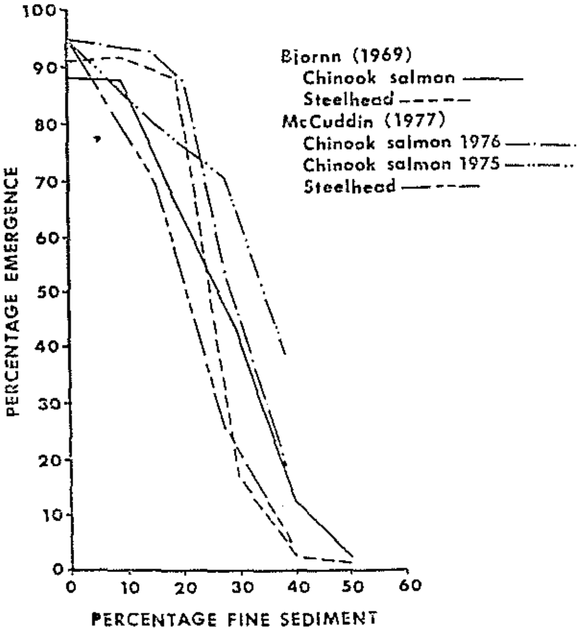


Figure 19—Percentage emergence of fry from newly fertilized eggs in gravel-sand mixtures. Fine sediment was granitic sand with particles less than 6.4 mm.

SUBSTRATE MATERIALS

Spawning bed materials also influence the development and emergence of fry. Permeability of the substrate (the ability of a material to transmit fluids) sets the range of subsurface water velocities (Wickett 1962). Low permeabilities result in lower apparent velocities and reduced oxygen delivery to and metabolite removal from the eggs. Wickett (1958) found that survival of pink and chum salmon eggs was related to permeability (fig. 18). McNeil and Ahnell (1964) concluded that highly productive spawning streams had gravels with high permeability. Permeability was high (24,000 cm/h) when bottom materials had less than 5 percent (by volume) sands and silts that passed through a 0.833 mm sieve and was relatively low (less than 1 300 cm/h) when fine sediments made up more than 15 percent of the bottom material.

Successful fry emergence is hindered by excessive amounts of sand and silt in the gravel. Even though embryos may hatch and develop, survival will be poor if they cannot emerge. Koski (1966) examined redds where eggs had developed normally but the hatched fry were unable to emerge because of sediment. Phillips et al. (1975) found an inverse relation between quantity of fine sediments and fry emergence. Bjornn (1969) and McCuddin (1977) demonstrated that survival and emergence of chinook salmon and steelhead embryos were reduced when sediments less than 6.4 mm in diameter made up 20-25 percent or more of the substrate (figs. 19 and 20).

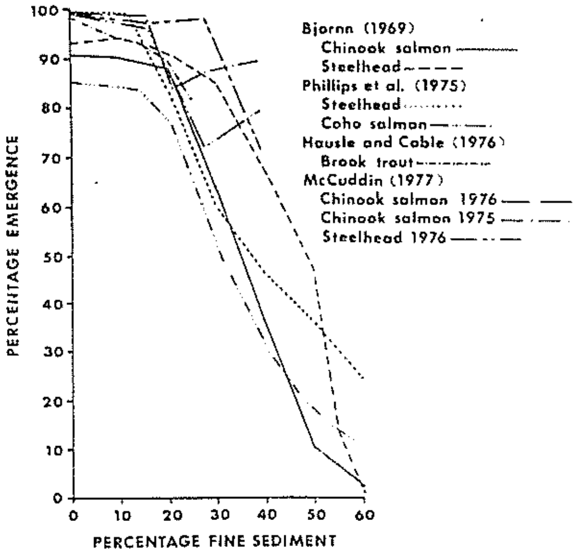


Figure 20—Percentage emergence of swim-up fry placed in gravel-sand mixtures. Sediments were 1- to 3-mm particles in the study by Phillips et al. (1975), less than 2 mm in the study by Hausle and Coble (1976), and less than 6.4 mm in studies by Bjornn (1969) and McCuddin (1977).

STREAMFLOW

Streamflow requirements of incubating salmonid eggs are largely unknown partly because of the lack of information on interactions of surface flows and the intragravel environment. According to Stalnaker and Arnette (1976), most agencies that are concerned with fish habitat do not attempt to deal specifically with streamflows for incubation but only for spawning, on the assumption that flows suitable for spawning will be suitable for incubation. U.S. Fish and Wildlife Service personnel at times have recommended an increase in flow for incubation over that present at spawning (Hale in Hooper 1973). Oregon Department of

Table 9. General habitat guidelines for incubation of salmonid embryos

Parameter	Recommended limit
Dissolved oxygen	At or near saturation; lower threshold - 5.0 mg/l
Water temperature	4°-14°C[1]
Permeability	More than 1 300 cm/h
Sediment composition	Less than 25% by volume of fines ≤6.4 mm
Surface flow	Sufficient to allow fry to emerge
Surface velocity	Velocities should be less than those that scour the redds and displace spawning bed materials
Apparent velocity	More than 20 cm/h
Biochemical oxygen demand	Should not diminish or deplete the dissolved oxygen content below stated levels

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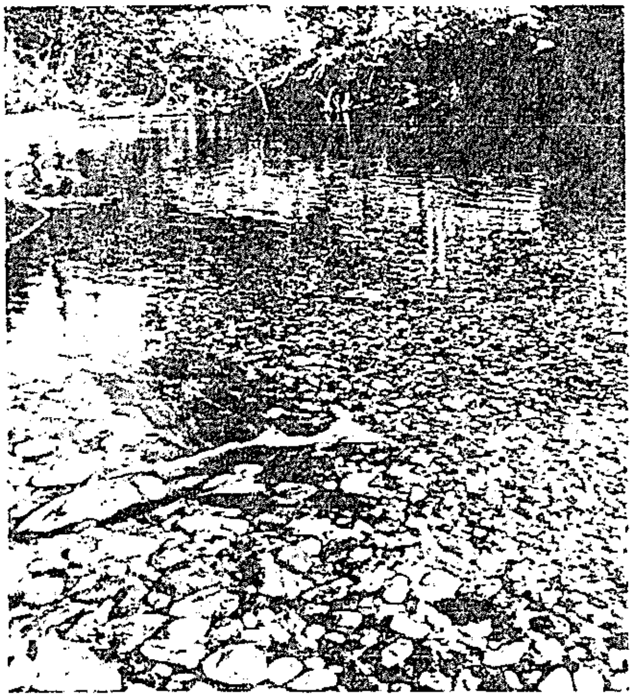
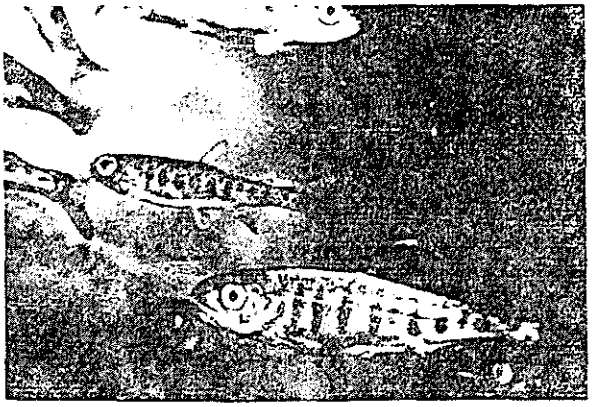
[1] Upper and lower values are threshold temperatures. Eggs will develop normally at lower temperatures provided initial development has progressed to where they become tolerant of cold.

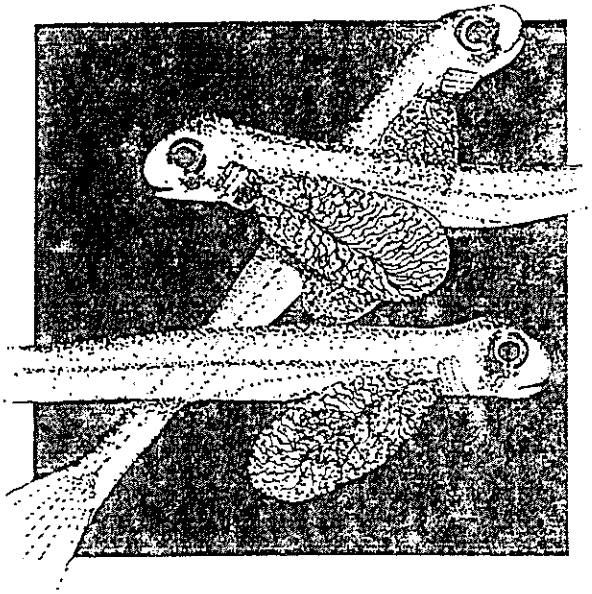
Fish and Wildlife personnel use field observations to judge recommended incubation flows that are often equivalent to about two-thirds of the spawning flow. Thompson (1972), however, pointed out that the two-thirds rule does not always hold, and adequate flow depends largely on the particular stream. Research is currently underway in Idaho and Alaska to quantify the instream flow needs for successful incubation and hatching of salmonid eggs.

Forest practices, such as roadbuilding and clearcut logging, may increase the water yield from a watershed and sometimes contribute to the flooding in a stream (Rothacher 1971). Rapid fluctuations in streamflow can decrease egg survival by disturbing redds and thereby crushing and dislodging eggs. Gangmark and Broad (1956) attributed complete mortality of planted chinook eggs to stream flows that increased 100 times during egg planting. Other investigators have also noted the deleterious effects of flooding on egg survival (Hobbs 1937, Neave 1953, Gangmark and Bakkala 1960, Sheridan and McNeil 1968). As noted by Chapman (1962), abnormally high flow at the wrong time causes increased mortality. Moderately high flows are beneficial in assuring adequate interchange of intragravel and surface waters and improving the oxygen supply to embryos.

Because species-specific incubation criteria have not been developed, generalization is needed to define suitable incubation for anadromous salmonids. General guidelines for salmonid incubation based on the preceding information are presented in table 9.







JUVENILE REARING

Habitat requirements of juvenile anadromous fish in streams vary with species, size, and time of year. The rearing period extends from fry emergence to seaward migration and can range from a few days for chum and pink salmon to 3 or 4 years for steelhead trout. For fish that spend an extended time in fresh water, the quantity and quality of the habitat sets the limits on the number of fish that can be produced. Important habitat components for juvenile salmon and trout are fish food production areas, water quality and quantity, cover, and space. The interaction of some of these habitat components with biological features of the environment have been studied (Giger 1973, Hooper 1973), but specific criteria for rearing habitat have not been completely defined for anadromous salmonids in streams. We will discuss features of stream habitat and relate them to salmonid production where warranted by the data available.

FISH FOOD PRODUCTION AREAS

Density of juvenile anadromous salmonids may be regulated by the abundance of food (perhaps expressed as competition for space) in some streams (Chapman 1966). Food for these salmonids comes primarily from the surrounding land and from the substrate within the stream; the relative importance of terrestrial and aquatic insects varies with stream size, location, riparian vegetation, and time of year.

VELOCITY

According to Scott (1958) and Allen (1959), velocity is the most important parameter in determining the distribution of aquatic invertebrates in streams. Most aquatic invertebrates live in a vertical boundary layer on the stream substrate where velocities are near zero. Water velocities just above the boundary layer, however, are typical of riffle areas (Pearson et al.,[4] Needham and Usinger 1956, Delisle and Eliason 1961, Arthur 1963, Ruggles 1966, Kimble and Wesche 1975, and table 10).

DEPTH

The influence of water depth on aquatic insect production is poorly understood, but Needham and Usinger (1956) and Kennedy (1967) found the largest numbers of organisms in shallow areas typical of riffles. In a study by Kimble and Wesche (1975), mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) were found in depths less than

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[4] Unpublished report, "Factors affecting the natural rearing of juvenile coho salmon during the summer low flow season," by L. S. Pearson, K. R. Conover, and R. E. Sams. Fish. Comm. Oreg., Portland, 1970.

Table 10—Water velocity criteria for aquatic invertebrates

Source	Velocity range
	Meters per second
Kennedy (1967)	0.15-0.91
Pearson et al.[1/]	.15-1.22
Surber (1951)	.15-1.07
Delisle and Eliason (1961)	.15-.91
Hooper (1973)	.46-1.07
Giger (1973)	.30-.61
Needham and Usinger (1956)	.61-1.07
Kimble and Wesche (1975)	>.15
Thompson (1972)	.30-.46

[1/] See text footnote 4.

0.3 m. Hooper (1973) reported that areas of highest invertebrate productivity usually occur in streams at depths between 0.15 and 0.9 m if substrates and velocities are suitable.

SUBSTRATE

Stream substrate composition is another factor that regulates the production of invertebrates; highest production is from gravel and rubble-size materials (Needham 1934, Linduska 1942, Smith and Moyle 1944, Sprules 1947, Ruttner 1953, Cummins 1966, Thorup 1966, Kennedy 1967, Corning 1969, Hynes 1970). Substrate size is a function of water velocity, with larger materials (rubble and boulder) associated with fast currents and smaller materials (silt and sand) with slow-moving water.

Pennak and Van Gerpen (1947) noted a decrease in number of benthic invertebrates in the progression rubble-bedrock-gravel-sand. A similar decrease was noted by Kimble and Wesche (1975) in the series rubble-coarse gravel-sand and fine gravel-silt. Sprules (1947) reported that, in general, the diversity of available cover for bottom fauna decreases as the size of inert substrate particles decreases. Rubble seems to be the most productive substrate. Large rubble substrate provides insects with a firm surface to cling to and also provides protection from the current.

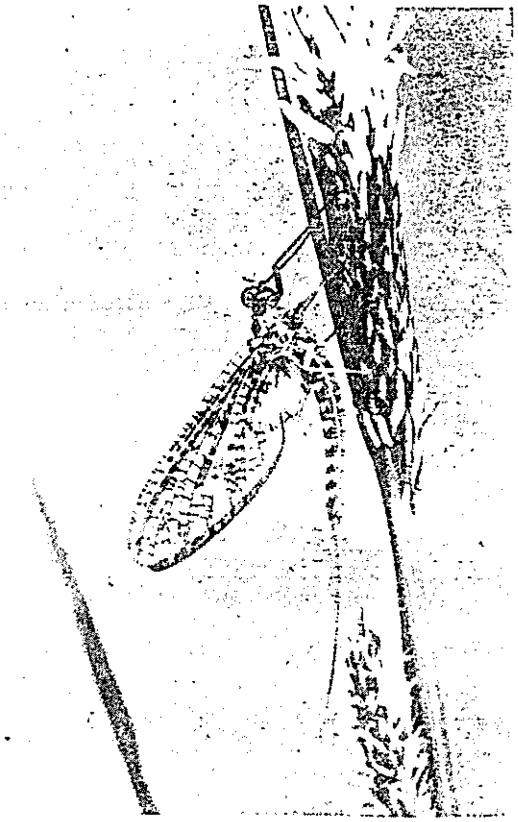
The importance of insects produced in riffles as food for fish is documented by Waters (1969), and Pearson et al. (see footnote 4) reported higher coho production per unit area in pools with large riffles upstream than in pools with small riffles upstream.

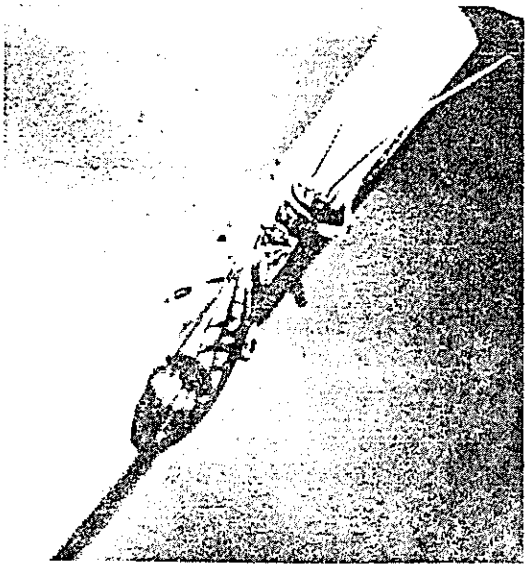
Velocity, depth, and substrate criteria for optimum fish food production are:

Velocity	0.46-1.07 m/s
Depth	0.46-0.91 m
Substrate	Composed largely of coarse gravel (3.2-7.6 cm) and rubble (7.6-30.4 cm)

RIPARIAN VEGETATION

Terrestrial insects are also important food items for salmonids. They may enter streams by falling or being blown off riparian vegetation and by being washed in from shoreline areas by wave action or rapid flow fluctuations (Mundie 1969, Fisher and LaVoy 1972). Once in the stream, these organisms are entrained by the current, become a part of the drift, and are fed upon by fish (Surber 1936, Kelley et al.,[5] Delisle and Eliason 1961, Kennedy 1967, Allen 1969). Plant material that falls into the stream from riparian vegetation may be an important source of food to aquatic invertebrates. Sekulich and Bjornn (1977) found that terrestrial insects were second only to chironomids (midges) in importance as food for juvenile anadromous salmonids in the streams they studied. Groups of insects and other arthropods that may become a part of terrestrial drift include: Diptera (flies), Orthoptera (grasshoppers and crickets), Coleoptera (beetles), Hymenoptera (bees, wasps, and ants), Lepidoptera (butterflies and moths), Homoptera (leaf hoppers), and Araneida (spiders).





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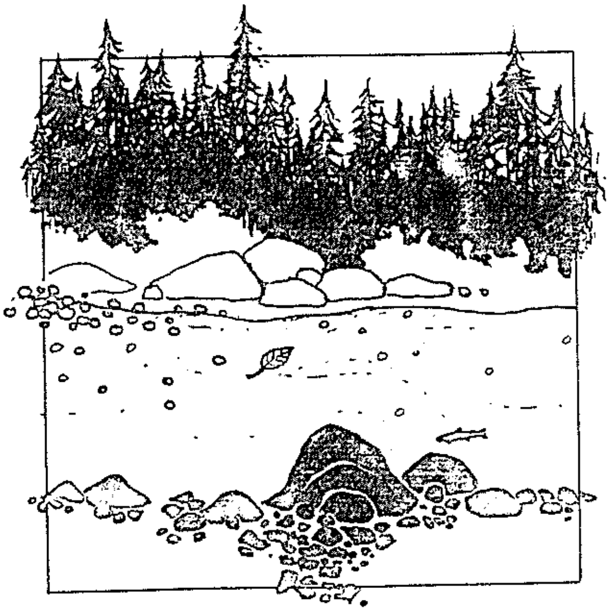
[5] Unpublished report, "A method to determine the volume of flow required by trout below dams: a proposal for investigation," by D. W. Kelley, A. J. Cordone, and G. Delisle. Calif. Dep. Fish and Game, Sacramento, 1960.



WATER QUALITY

Temperature

Salmonids are cold water fish with definite temperature requirements during rearing. Water temperature influences growth rate, swimming ability, availability of dissolved oxygen, ability to capture and use food, and ability to withstand disease outbreaks. Brett (1952) lists the upper lethal temperature for chinook, pink, sockeye, chum, and coho salmon as 25.1°C. The upper lethal temperature for rainbow trout lies between 24° and 29.5°C depending on oxygen concentration, fish size, and acclimation temperature (McAfee 1966). Slightly lower temperatures can be tolerated but are stressful.

Bell (see footnote 1) stated that, in general, all cold water fish cease growth at temperatures above 20.3°C because of increased metabolic activity. Fall chinook fingerlings had increasing percentage weight gains as temperature was increased from 10.0° to 15.7°C, and then weight decreased with a further increase in temperature to 18.4°C (Burrows in Bell, see footnote 1). Baldwin (1956) noted a similar relation for brook trout, with increases in percentage weight gain with increased temperature from 9.1° to 13.1°C and a subsequent decrease in percentage weight gain with temperatures exceeding 17.1°C. At 17.1°C, brook trout feeding decreased and, when temperature reached 21.2°C, the fish only ate 0.85 percent of their body weight per day. By comparison, a 100-mm-long salmonid that weighs 10 g would need to eat about 1.8 percent of its body weight each day to maintain itself and 2.5 percent to grow rapidly in 15°C water.

Salmonids prefer a rather narrow range of temperature in which to live (table 11), and temperature may help regulate density. In laboratory stream channels, Hahn (1977) found twice as many steelhead fry remained in channels with daily fluctuating (8°-19°C) or constant 13.5°C water temperatures than in a channel with constant 18.5°C water. Fry density in a channel with constant 8.5°C water was double that in channels with constant 13.5°C or fluctuating temperatures. Water temperatures in a particular stream vary seasonally, temporally, and spatially (for example, between forested and nonforested areas). Seasonal and temporal changes are largely out of human control; certain land-use practices (for example, channelization or removal of shade trees), however, can change the temperature in sections of streams. If riparian vegetation is removed, exposing the stream to direct sunlight, water temperatures usually increase in summer (Greene 1950,

Table 11—Preferred, optimum, and upper lethal temperatures of various salmonids[1] (from Bell 1973 unless otherwise noted)

Species	Preferred temperature range	Optimum temperature	Upper lethal temperature
	----------°C----------		
Chinook	7.3-14.6	[2] 12.2	25.2
Coho	11.8-14.6	[3] 20.0	25.8
Chum	11.2-14.6	[4] 13.5	25.8
Pink	5.6-14.6	10.1	25.8
Sockeye	11.2-14.6	[3] 15.0	24.6
Steelhead	7.3-14.6	10.1	24.1
Cutthroat	9.5-12.9	--	23.0
Brown	3.9-21.3	--	24.1

[1] From Bell (see text footnote 1).

[2] From an unpublished report, "Fish health and Management: concept and methods of aquaculture," by G. W. Klontz, Univ. Idaho, Moscow, 1976.

[3] From Brett et al. (1958).

[4] From Garside and Tait (1958).

Chapman 1962, Gray and Edington 1969, Meehan 1970, Narver 1972, Moring and Lantz 1974, Moring 1975). Colder winter temperatures may result from loss of canopy and adversely affect egg incubation (Greene 1950, Chapman 1962).

DISSOLVED OXYGEN

The concentration of dissolved oxygen in streams is important to salmonids during rearing. At temperatures above 15°C, concentrations of dissolved oxygen regulate the rate of active metabolism of juvenile sockeye salmon (see footnote 1). Fry (1957) proposed that where the oxygen content became unsuitable, the active metabolic rate decreased. Rainbow trout swimming speeds were reduced 30 and 43 percent when oxygen was reduced to 50 percent of saturation at temperatures of 21°-23°C and 8°-10°C, respectively (Jones 1971). Growth rate, food consumption rate, and the efficiency of food utilization of juvenile coho salmon all declined when oxygen was 4 or 5 mg/l (Herrmann et al. 1962, and figs. 21, 22, and 23).

Juvenile chinook salmon avoided water with oxygen concentrations near 1.5-4.5 mg/l in the summer, but reacted less to low levels in the fall when temperatures were lower (Whitmore et al. 1960).

In a review paper, Davis (1975) examined information on incipient oxygen response thresholds for salmonids (table 12), and developed oxygen criteria with three concentrations (table 13). At the highest concentration, fish had ample oxygen and could function without impairment. At the middle concentration, the average member of a species begins to exhibit symptoms of oxygen

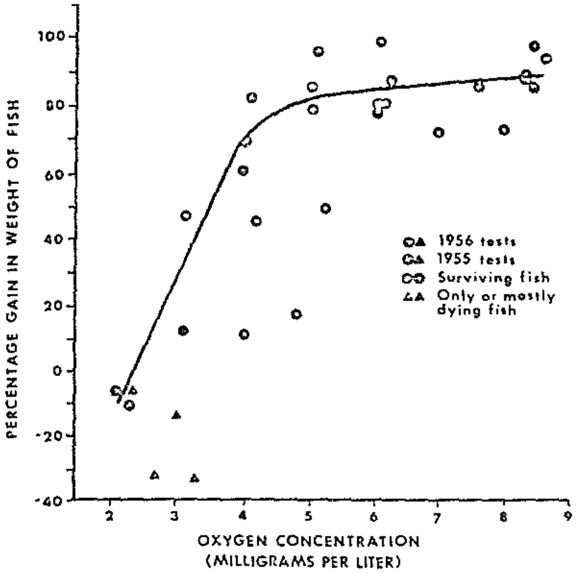


Figure 21—Weight gains (or losses) in 19 to 28 days among frequently fed age-class 0 coho salmon, expressed as percentages of the initial weight of the fish, in relation to dissolved oxygen concentration. The curve has been fitted to only the results of tests performed in 1956. All of the 1956 positive weight-gain values are results of 21-day tests (from Herrmann et al. 1962).

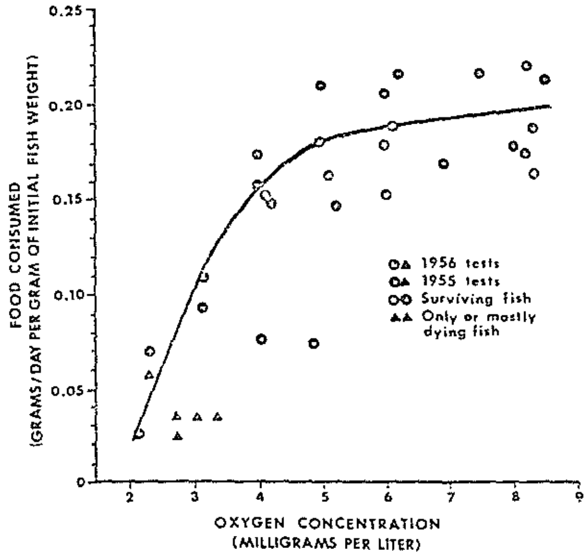


Figure 22—Grams of food (beach hoppers) consumed by frequently fed age-class 0 salmon per day per gram of initial weight of the fish, in relation to dissolved oxygen concentration. The curve has been fitted to only the 1956 data (from Herrmann et al. 1962).

distress; at the lowest concentration, a large portion of the fish population may be affected.

Dissolved oxygen concentrations are normally near saturation, except in small streams with large amounts of debris from logging or other sources (Hall and Lantz 1969) or in larger, slow-moving streams receiving large amounts of municipal or industrial waste.

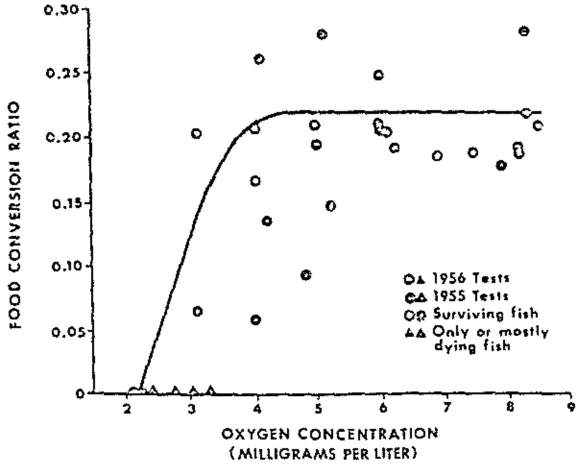


Figure 23—Food conversion ratios for frequently fed age-class 0 coho salmon, or their weight gains in grams per gram of food (beach hoppers) consumed, in relation to dissolved oxygen concentration. A food conversion ratio of zero (not a ratio having a negative value) has been assigned to each group of fish that lost weight. The curve has been fitted only to the 1956 data (from Herrmann et al. 1962).

SUSPENDED AND DEPOSITED SEDIMENT

Suspended and deposited fine sediment can adversely affect salmonid rearing habitat if present in excessive amounts. High levels of suspended solids may abrade and clog fish gills, reduce feeding, and cause fish to avoid some areas (Trautman 1933, Pautzke 1938, Smith 1939, Kemp 1949, Wallen 1951, Cooper 1956, Bachman 1958, Cordone and Kelley 1961). According to Bell (see footnote 1), streams with silt loads averaging less than 25 mg/l can be expected to support good freshwater fisheries. State turbidity standards for Colorado, Wyoming, Montana, and Oregon are set at no more

Table 12—Incipient oxygen response thresholds for various salmonids (modified from Davis 1975)[1]

Species	Source	Size	Temperature	Dissolved oxygen		Response
				Concentration	Saturation	
			°C	Mg/l	Percent	
Arctic char	Holeton (1973)	--	2 ± 0.05	2.18	15.8	Signs of asphixia and loss of equilibrium
Brown trout	Irving et al. (1941)	682-1 136 g	20	4.59	50	Blood not fully saturated with O_2 below this level
Brook trout	Irving et al. (1941)	682-1 136 g	20	4.59	50	" " "
	Graham (1949)	17-65 g	5	8.09	63.2	Onset of O_2-dependent metabolism
	" "	17.65 g	8	5.99	50.7	Reduced cruising speed
	" "	17-65 g	20	9.06	98.8	Onset of O_2-dependent metabolism
	" "	17-65 g	5-20	9.6-6.88	75	Reduced activity all temperatures
	Beamish (1964)	56-140 g	10, 15	5.75-5.18	50.7-51.0	Standard oxygen uptake reduced below this level
Rainbow trout	Irving et al. (1941)	682-1 136 g	20	4.59	50	Below this level, blood is not fully saturated with oxygen
	Randall and Smith (1967)	120-250 g	8.5-15	5.18-7.34	50.7-63.7	Circulatory changes occur, including a slowing of the heart
	Downing (1954)	13.3 ± 1.4 cm	17 ± .5	9.74	100	Any reduction in oxygen led to more rapid death in cyanide
	Jones (1971)	20 mo. old	8-10	5.94-5.67	50	43 percent reduction in maximum swimming speed
	" "	20 mo. old	21-23	4.50-4.34	50	30 percent reduction in maximum swimming speed
	Itazawa (1970)	235-510 g	2.3-13	8.73-6.74	63.1-63.6	Blood not fully saturated with O_2 below this level
	Kutty (1968)	--	15	5.08	50	Altered respiratory quotient, little capacity for anaerobic metabolism below this level
	Randall and Smith (1967)	--	15	5.18-6.47	51.0-63.7	Changes in oxygen transfer factor and effectiveness of O_2 exchange occur
Rainbow trout	Hughes and Saunders (1970)	400-600 g	13.5	5.35	51.0	Breathing amplitude and buccal pressure elevated
	Cameron (1971)	300 g	10, 15, 20	4.71-5.75	50.7-51.3	Blood not fully saturated with O_2 below this level
	Lloyd (1961)	1-11 g	17.5	5.78	60	Toxicity of zinc, lead, copper, phenols increased markedly below this level
Sockeye salmon	Brett (1964)	50 g	20-24	9.17-8.53	100	Available oxygen level appears to limit active metabolism and maximum swimming speed
	Davis (1973)	1 579 g	13	6.74	63.6	Blood not fully saturated with O_2 below this level
	Randall and Smith (1967)	1.5-1.7 kg	15	5.07	50	Elevated blood and buccal pressure, breathing rate increased
Coho salmon	Whitmore et al. (1960)	6.3-11 cm	--	4.5	--	Erratic avoidance behavior
	Hicks and DeWitt (1971)	5.1-14.8 cm	12 ± 1	9.0	83.1	Acute mortality in kraft pulpmill effluent increased below this level
	Davis et al. (1963)	Juvenile	10-20	11.33-9.17	100	Reduction of O_2 below saturation produced some lowering of maximum sustained swimming speed
	Dahlberg et al. (1968)	"	20	9.17	100	" " "
	Herrmann (1958)	"	"	8.0-4.0	87.2-43.6	Growth rate proportional to oxygen level with best growth at 8.0 mg/l, lowest at 4.0 mg/l
Chinook salmon	Whitmore et al. (1960)	6.3-11 cm	summer temp.	4.5		Marked avoidance of this level in summer
	" "	6.3-11 cm	fall temp.	4.5		Little avoidance of this level in fall
	Davis et al. (1963)	Juvenile	10-20	11.33-9.17	100	Reduction of O_2 below saturation lowered maximal sustained swimming speed
Atlantic salmon	Kutty and Saunders (1973)	87-135 g	15	4.5	44-33	Salmon stop swimming at a speed of 55 cm/s at O_2 levels below this; faster swimming requires more oxygen

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[1] Courtesy of the Journal of the Fisheries Research Board of Canada.

Table 13—Response of freshwater salmonid populations to three concentrations of dissolved oxygen (modified from Davis 1975, courtesy of the Journal of the Fisheries Research Board of Canada)

Response	Oxygen	Saturation at given temperatures (°C)					
		0	5	10	15	20	25
	Mg/l	Percent					
Function without impairment	7.75	76	76	76	76	85	93
Initial distress symptoms	6.00	57	57	57	59	65	72
Most fish affected by lack of oxygen	4.25	38	38	38	42	46	51

than 10 JTU, 10 NTU, 5 JTU and 5 NTU over background levels, respectively.[6]

Cordone and Kelley (1961) suggest that indirect rather than direct effects of too much fine sediment damage fish populations. Indirect damage to the fish population by destruction of the food supply, lowered egg or alevin survival, or changes in rearing habitat probably occurs long before the adult fish would be directly harmed (Ellis 1936, Corfitzen,[7], Sumner and Smith,[8] Tebo 1955, 1957, 1974, Tarzwell 1957, Ziebell 1957, Casey,[9] Bartsch 1960, Cordone and Pennoyer,[10] Chapman 1962, Bjornn et al. 1977).

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[6] JTU = Jackson turbidity units.
NTU = Nephelometric turbidity units.

[7] Unpublished mimeographed report, "A study of the effect of silt on absorbing light which promotes the growth of algae and moss in canals," by W. D. Corfitzen. U.S. Dep. Int., Bur. Reclam., 1939.

[8] Unpublished mimeographed report, "A biological study of the effects of mining debris dams and hydraulic mining on fish life in the Yuba and American Rivers in California," by F. H. Sumner and O. R. Smith. Submitted to the U.S. District, Eng. Office, Sacramento, California, from Stanford Univ., 1939.

[9] Unpublished mimeographed report, "The effects of placer mining (dredging) on a trout stream," by O. E. Casey. Annu. Prog. Rep., Proj. F-34-R-1. Water Quality Investigations, Federal Aid in Fish Restoration, Idaho Dep. Fish and Game, Boise, 1959.

[10] Unpublished mimeographed report, " Notes on silt pollution in the Truckee River drainage," by A. J. Cordone and S. Pennoyer. Calif. Dep. Fish and Game, Inland Fish Admin. Rep., Sacramento, 1960.

Deposited sediment may reduce available summer rearing (fig. 24) and winter holding (fig. 25) habitat for fish (Stuehrenberg 1975, Klamt 1976, Bjornn et al. 1977). Bjornn et al. (1977) added fine sediment (less than 6.4 mm in diameter) to natural stream channels and found juvenile salmon abundance decreased in almost direct proportion to the amount of pool volume lost to fine sediment (fig. 26). Because sediment budgets are difficult to determine for each stream, Bjornn et al. recommended using the percentage of fine sediment in selected riffle areas as an index of the "sediment health" of streams. They reasoned that if the riffles contained negligible amounts of fine sediment, then the pools and interstitial spaces between the boulders of the stream substrate would also have negligible amounts of sediment.

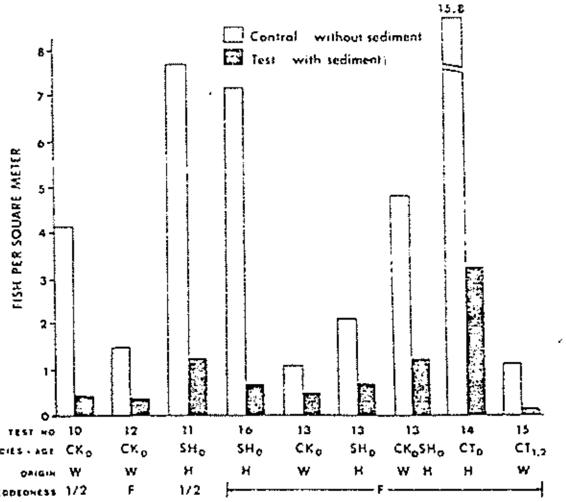


Figure 24—Densities of fish remaining in artificial stream channels after 5 days during winter tests, 1975: W = wild; H = hatchery; ½ = boulders in pools ½ imbedded with sediment; F = fully imbedded; CK_0 = age 0 chinook salmon, SH_0 = age 0 steelhead trout; CT_0 = age 0 cutthroat trout, $CT_{1,2}$ = age 1 cutthroat trout (from Bjornn et al. 1977).

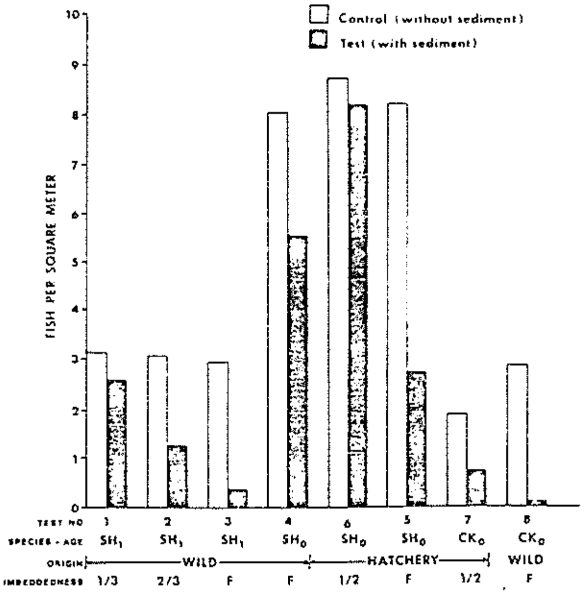


Figure 25—Densities of fish remaining in the Haydon Creek artificial stream channels after 5 days during the summer tests, 1974 and 1975: SH_1 = age 1 steelhead; CK_0 age 0 chinook; ⅓ = key boulders in pools ⅓ imbedded with sediment; F = key boulders in pools fully imbedded (from Bjornn et al. 1977).

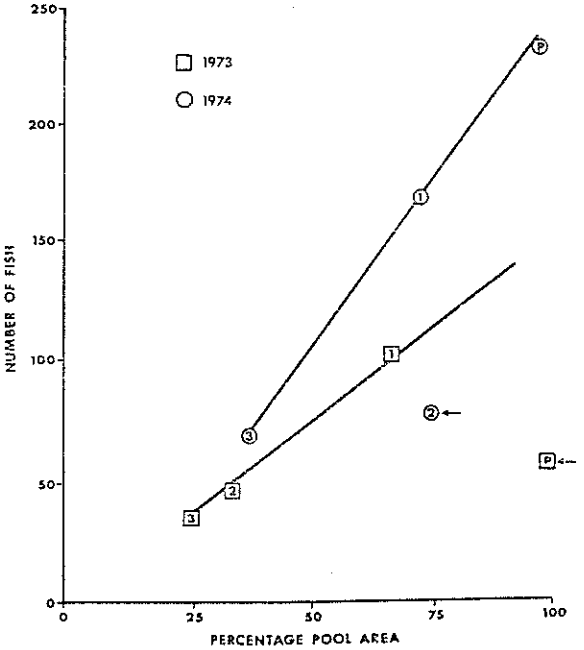


Figure 26—Fish numbers in upper test pool versus percentage pool area deeper than 0.30 m, during the sediment additions into Knapp Creek, 1973 and 1974. Arrows denote observations not used in fitting the regression line. P = prior to addition of sediment; 1 = after first addition; 2 = after second addition; 3 = after third addition (from Bjornn et al. 1977).

COVER

Cover is perhaps more important to anadromous salmonids during rearing than at any other time, for this is when they are most susceptible to predation from other fish and terrestrial animals. Cover needs of mixed populations of salmonids are not easily determined (Giger 1973). Shelter needs may vary diurnally (Kalleberg 1958, Edmundson et al. 1968, Allen 1969, Chapman and Bjornn 1969), seasonally (Hartman 1963, 1965, Chapman 1966, Chapman and Bjornn, 1969), by species (Hartman 1965, Ruggles 1966, Allen 1969, Chapman and Bjornn 1969, Lewis 1969, Pearson et al. (see footnote 4), Wesche 1973, Hanson 1977), and by fish size (Butler and Hawthorne 1968, Allen 1969, Chapman and Bjornn 1969, Everest 1969, Wesche 1973, Hanson 1977).

Overhead cover--riparian vegetation, turbulent water, logs, or undercut banks--is used by most salmonids (Newman 1956, Wickham 1967, Butler and Hawthorne 1968, Baldes and Vincent 1969, Bjornn 1969, Chapman and Bjornn 1969, Lewis 1969, Lister and Genoe 1970, Wesche 1973). Beside providing shelter from predators, overhead cover produces areas of shade near stream margins. These areas are the preferred habitat of many juvenile salmonids (Hartman 1965, Chapman 1966, Allen 1969, Everest 1969, Mundie 1969, Everest and Chapman 1972).

Submerged cover--large rocks in the substrate, aquatic vegetation, logs, and so on--is also used by rearing salmonids. Hoar et al. (1957) and Hartman (1965) observed that newly emerged salmonids tend to hide under stones. Similar behavior is typical of overwintering juvenile steelhead and chinook that seek refuge within rock and rubble substrate in Idaho streams (Chapman 1966, Chapman and Bjornn 1969, Everest 1969, Morrill and Bjornn 1972).

The relative importance of cover is illustrated by experiments in which salmonid abundance declined when cover was reduced (Boussu 1954, Peters and Alvord 1964, Elser 1968) and in experiments where salmonid abundance increased when cover was added to a stream (Tarzwell 1937, 1938, Shetter et al. 1946, Warner and Porter 1960, Saunders and Smith 1962, Chapman and Bjornn 1969, Hunt 1969, 1976, Hahn 1977, Hanson 1977).

STREAMFLOW

Recommended streamflows for rearing habitat have usually been based on the individual components (such as food, cover) of habitat rather than numbers or biomass of fish. Thompson (1972) listed guidelines for developing streamflow recommendations in rearing habitat:

- adequate depth over riffles
- riffle/pool ratio near 50:50
- approximately 60 percent of riffle area covered by flow
- riffle velocities of 0.31-0.46 m/s
- pool velocities of 0.09-0.24 m/s
- stream cover available as shelter for fish.

Such guidelines are obviously based on the food production, cover, and microhabitat needs of fish, rather than the relation between streamflow and fish production.

Streamflow has been related to cover (Kraft 1968, 1972, Wesche 1973, 1974, and figs. 27, 28, and 29); streamflow and pool area to standing crop of fish (Kraft 1968, 1972, Nickelson and Reisenbichler 1977, and fig. 30); standing crop to cover (Wesche 1974, Nickelson and Reisenbichler 1977, and figs. 31 and 32); and standing crop to a habitat quality index (Nickelson 1976, and fig. 33). Such studies suggest a definite relation between stream carrying capacity for fish and discharge.

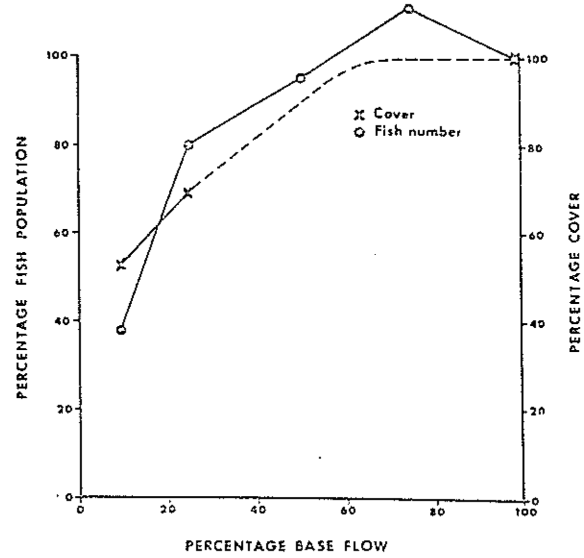


Figure 27—Comparison of percentage reductions of fish numbers and cover in three runs in Blacktail Creek, Montana (data from Kraft 1968, from White 1976).

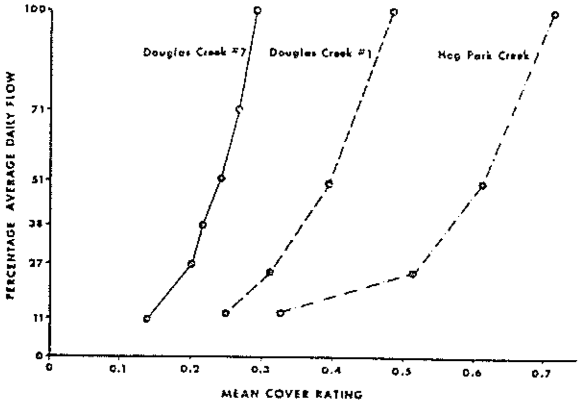


Figure 28—Changes observed in the mean trout-cover rating as flow was reduced at the Douglas Creek No. 1, 7, and Hog Park Creek study areas (from Wesche 1974).

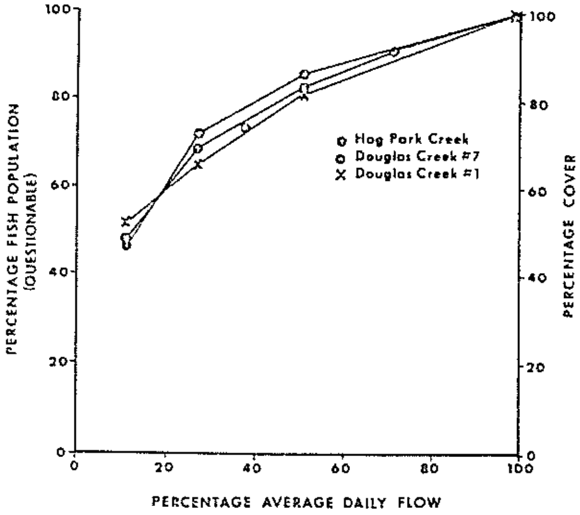


Figure 29—Comparison of percentage of habitat reduction with percentage decrease in average daily flow and hypothetical percentage decrease in fish population (data from Wesche 1974, from White 1976).

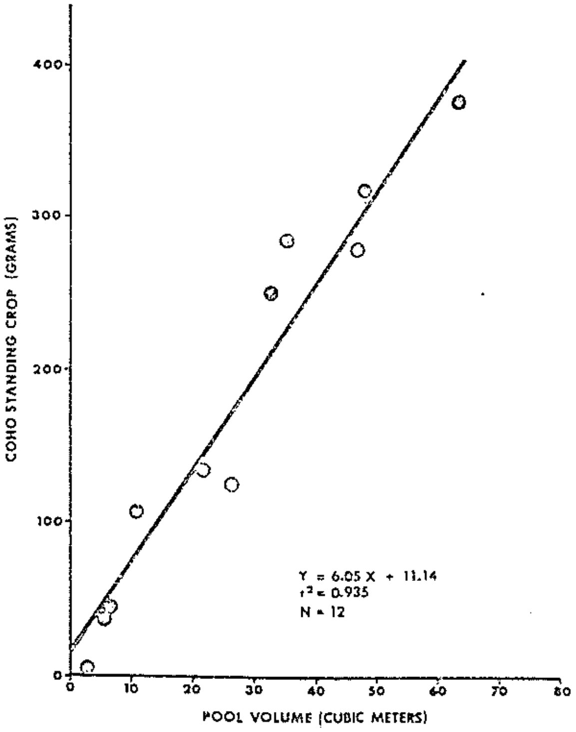


Figure 30—Relation between pool volume and juvenile coho standing crop (from Nickelson and Hafele 1978).

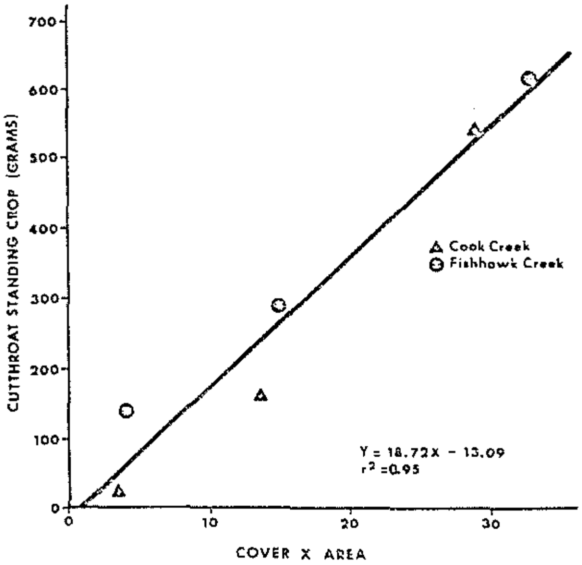


Figure 31—Relation between mean trout cover ratings and standing crop estimates of trout at eleven study areas (from Wesche 1974).

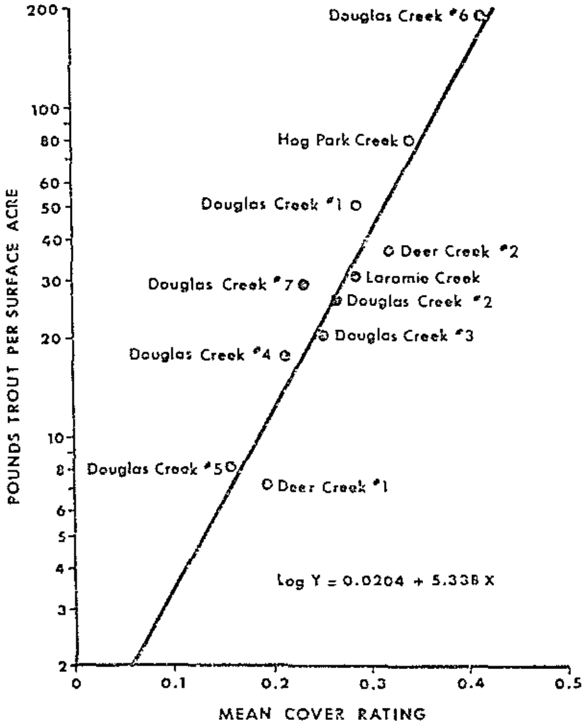


Figure 32—Relation between cover times area and cutthroat trout standing crop in two Oregon coastal streams (from Nickelson and Reisenbichler 1977).

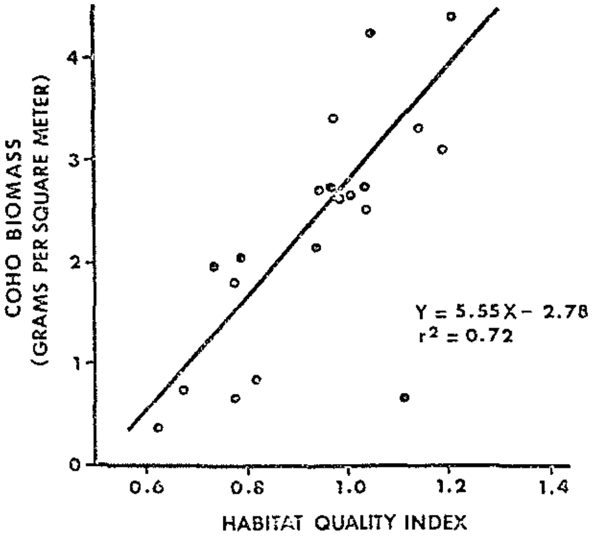


Figure 33—Relation between a habitat quality index and coho salmon biomass in six Elk Creek study sections at flows of 3.00, 2.25, and 1.50 ft³/s (from Nickelson 1976).

SPACE

Space requirements of juvenile salmonids in streams vary with species, age, and time of the year and are probably related to abundance of food (Chapman 1966). The interactions and relation between cover, food abundance, and microhabitat preferences of the various species of salmonids are not well understood; until they are, spatial needs of the fish will be less than adequately defined.

From measurements of fish densities in streams, we have some idea of spatial requirements of juvenile salmonids. Pearson et al. (see footnote 4) Nickelson and Reisenbichler (1977), and Nickelson and Hafele (1978, and fig. 30) found that coho standing crop was directly related to pool volume. Bjornn et al. (1977) found a similar relation for chinook salmon in small streams (fig. 26). Pearson et al. found a close relation between total stream area and coho numbers--perhaps an example of the idea that more space equals more food equals more fish. Food and space are thought to be the most important factors influencing fish density in streams (Larkin 1956, Chapman 1966). Studies in California by Burns (1971) revealed significant correlations between living space and salmonid biomass; decreased living space resulted in increased fish mortality. Not surprisingly, the highest mortality was associated with the summer low flow period. The studies of Kraft (1968, 1972 and fig. 27) and Wesche (1974, and fig. 29) lend support to the concept that reductions in discharge decrease living space and thus decrease numbers and biomass of salmonids.

Changes in streamflow influence velocities and area of riffles more than area of pools. Giger (1973) suggested that if set spatial demands are the primary regulators of fish density in pools, then increasing the flow in streams may not lead to increased abundance. He accepts the logic of Chapman's (1965) idea that spatial requirements of fish control their density below ceilings set by the supply of food. Chapman (1966) suggested that salmonids have a minimum spatial requirement that has been fixed over time by the minimum food supply.

Space needed by fish increases with age and size. Allen (1969) assembled data on densities of salmonids in streams and found positive correlations between area per fish and age or length (figs. 34 and 35). Additional data on densities of salmon and trout with age, size, and locality are presented in table 14 and figure 36. Allen concluded from the data he examined that densities of 10-cm salmonids averaged about 0.17 fish/m^2 (1.7 g/m^2).

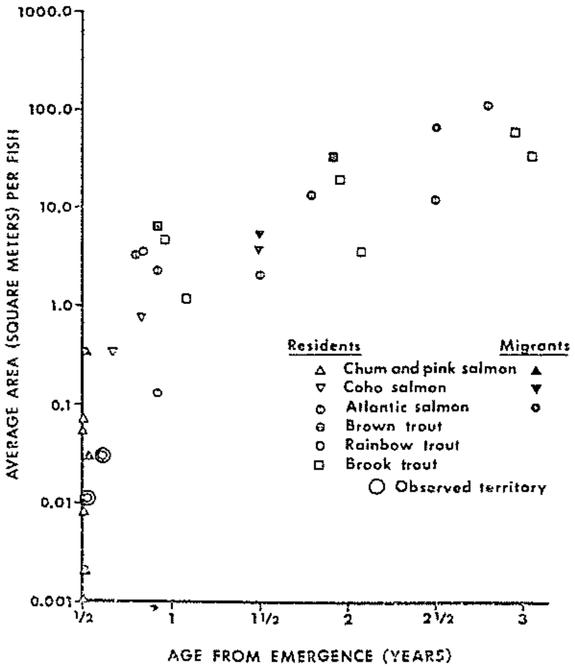


Figure 34—Average area per fish (on a logarithmic scale) against age (from Allen 1969).

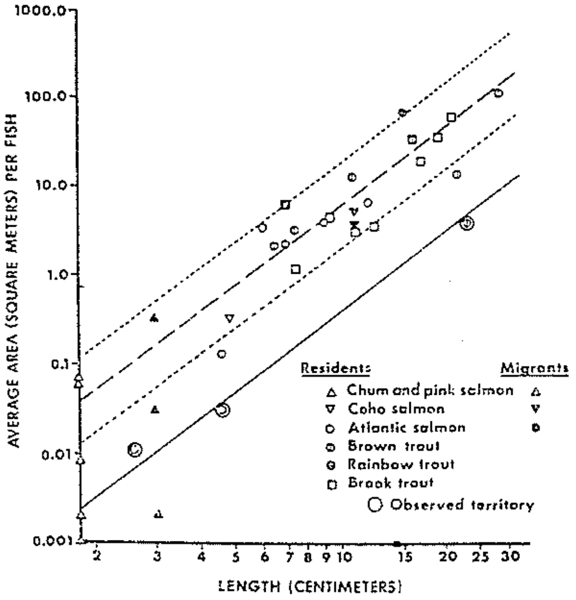


Figure 35—Average area per fish against length on logarithmic scales (from Allen 1969).

Table 14—Densities of salmon and trout in streams

Species	Age/ size	Area/ fish	Fish/ area	Weight/area	Stream size or flow rate	Comments	Reference
	Yr/cm	M^2	M^2	G/m^2			
Pink salmon	egg-alevin	0.001	1000	--	--	B.C.	Hunter (1959)
	" "	.070	14.3	--	--	Washington	Bliss and Heiser (1967)
	" "	.002	500	--	--	Alaska	Hoffman (1965)
	" "	.008	125	--	--		" "
	0+/2	.03	33.3	--	--	B.C.	Hunter (1959)
	0+/2	.002	500	--	--	Alaska	Merrell (1962)
	0+/2	.33	3.0	--	--	B.C.	Wickett (1958)
Chum salmon	egg-alevin	.001	1000	--	--	B.C.	Hunter (1959)
	" "	.056	17.9	--	--	Washington	Bliss and Heiser (1967)
	0+/2	.03	33.3	--	--	B.C.	Hunter (1959)
Coho salmon	0+/2	.33	3.0	--	--	B.C.	Wickett (1958)
	alevin			5-12	--	Oregon	Chapman (1965)
	I+	2.4 (2.94-2.00)	.42 (.34-.50)	2-4		Oregon	Chapman (1965)
	"	3.7	.3	--	--	B.C.	Hunter (1959)
	"	5.5	.2	--	--	B.C.	Wickett (1951)
	"	2.9 (1.92-4.28)	.37 (.26-.52)	--	Avg. flows: range, 41.6-183 ft^3	Oregon	Hall and Lantz (1969)
Chinook salmon	0+	.74	1.35	12.9	Median 4-5 m	Idaho, est. of	Bjornn (1978)
	"	1.69	.59	5.4	6-10 m	summer rearing	" "
						capacity	
	"	(.59-3.301)	(1.70-.30)	(6.4-.86)	Flows range 0.107-1.3 m^3/s	4 streams in	Sekulich and Bjornn (1977)
	"	(.94-2.27)	(1.06-.44)	(4.4-1.01)	" "	Idaho	" "
	"	.53	1.90	--	--	Idaho	Bjornn et al. (1977)
Chinook salmon	I+	3.33	.30	--	--	4 streams in Idaho	Bjornn et al. (1974)
Steelhead trout	0+	.93	1.08	6.1	Medium, width about 4-5 m	Idaho, est. of	Bjornn (1978)
	0+	1.43	.70	3.2	" "	summer rearing	" "
	0+	1.92	.52	3.0	Medium, width about 6-10 m	capacity	" "
	I+	16.67	.06	4.3	Medium, 4-5 m	" "	" "
	I+	33.33	.03	1.9	" "	" "	" "
	I+	5.88	.17	13.0	Medium, 6-10 m	" "	" "
	0+	.59	1.70	(4.4-1.01)	Flows range 0.107-1.3 m^3/s	4 streams in Idaho	Bjornn et al. (1974)
	I+	6.67	.15	" "	--	" "	" "
	0+	3.88	.258	" "	Small	" "	Hanson (1977)
	I+	16.39	.061	--	"	" "	" "
	II+	17.24	.058	--	"	" "	" "
	0+	4.35	.23	--	Medium	" "	" "
	I+	14.49	.069	--	"	" "	" "
	II+	19.61	.051	--	"	" "	" "
	II+	26.14 (m/fish)	.038 (fish/m)	--	Large	Idaho average	Graham (1977)
					(Lochsa River)	densities for	
						three sections; low	
						densities result	
						from low spawning	
						escapements	

Table 14—Densities of salmon and trout in streams —(Continued)

Species	Age/ size	Area/ fish	Fish/ area	Weight/area	Stream size or flow rate	Comments	Reference
	Yr/cm	M^2	M^2	G/m^2			
Steelhead salmon	I+	109.89 (m/fish)	0.009 (fish/m)	--	Large (Lochsa River)	(cont. from previous page)	Graham 1977
	I+	60.06 (m/fish)	.017 (fish/m)	--	Large (Selway River)	" " "	"
	II+	23.47 (m/fish)	.043 (fish/m)	--	" "	" "	" "
	I+	17.84	.056	--	Small tributaries	Idaho, trib. of Lochsa R.	" "
	II+	14.22	.070	--	" "	" "	" "
	I+	32.15	.031	--	" "	Idaho, trib. of Selway R.	" "
	II+	18.12	.055	--	" "	" "	" "
	I+	1.43-1.25	(.7-.8)	--	Small	Idaho, densities are those present in the fall after stocking in early spring	" "
	0+	52.23 (m/fish)	.019 (fish/m)	-	Large (Lochsa River)	Idaho, avg. density for	" "
	0+	204.08 (m/fish)	.0049 (fish/m)	--	" "	3 sections	" "
	0+	22.75	.439	--	Small (trib. streams)	" "	" "
	0+	88.11	.111	--	" "	" "	" "
	0+	.97	1.03	3.69	Flow - 0.27--.56 cms during July-August	Densities are those present in the fall after stocking in early spring	" "
	0+	1.07	.94	6.64	Flow - 0.59-0.95 cms	" "	" "
Atlantic salmon	0+	5.00	.2	2.70	Small streams	Scotland, densities are	Mills (1969)
	0+	1.08	.93	2.94		those present in the fall	" "
	0+	1.25	.80	4.25	" "	after stocking in early	" "
	0+	2.78	.36	2.81	" "	spring	" "
	0+	2.56	.39	2.83	" "	" "	" "
	0+	5.56	.18	1.17	" "	" "	" "
	0+	9.09	.11	.96	Small streams	Scotland, densities are	Mills (1969)
	0+	1.64	.61	1.04	" "	those present in the fall	" "
	0+	6.67	.15	1.18	" "	after stocking in early	" "
	0+	4.55	.22	1.34	" "	spring	" "
	0+	2.56	.39	1.66	" "	" "	" "
	0+	14.29	.07	1.27	" "	" "	" "
	0+	6.25	.16	1.09	" "	" "	" "
	0+	1.85	.54	1.95	" "	" "	" "
	0+	6.67	.15	1.93	" "	" "	" "
Brown trout	0+	.53	1.9	1.6	Mean width 0.9 m	England, small, headwater	LeCren (1969)
	0+	1.67	.6	1.1	2.2 m	streams	" "
	0+	5.00	.2	.2	3.0 m	" "	" "
	0+	5.00	.2	.3	" 3.7 m	" "	" "
	0+	1.0	1.0	2.8	" 2.5 m	" "	" "
	0+	.42	2.4	--	" 6.6 m	" "	" "
	I+	2.00	.5	3.7	" .9 m	" "	" "
	I+	5.00	.2	1.9	" 2.2 m	" "	" "
	I+	5.00	.2	1.1	" 3.0 m	" "	" "
	I+	10.0	.1	1.0	" 3.7 m	" "	" "
	I+	10.0	.1	2.9	" 2.5 m	" "	" "
	I+	5.00	.2	--	" 6.6 m	" "	" "
	2.6-6.5 cm	4.55	0.22	--	Small, widths range 0.6-	Densities are averages of	Hills (1969)
	6.6-10.5 cm	3.13	.32	--	1.5 m, avg. 1.0 m	4 stream sections	" "
	10.6-14.5 cm	7.69	.13	--	" "	" "	" "
	14.6-18.5 cm	16.67	6.06	--	" "	Scotland	" "
	0+/4.5	.13	7.69		" "	England	LeCren (1965)
	I+/6.5	2.20	.45	--	" "	England	Horton 1961
	0+/7	2.30	.43	--	" "	California	Needham, et al. (1945)
	0+/7.5	1.20	.83	--	" "	New Zealand	Allen (1951)
	II+/11	13.0	.77	--	" "	England	Horton (1961)
	I+/22	14.0	.071	--	" "	New Zealand	Allen (1951)
	II+/28	120.0	.008	--	" "	New Zealand	Allen (1951)

Densities of age-0 trout and salmon at the end of their first summer (70-120 mm in length) average about 5 m^2 of stream per fish (mode about 2 m^2). After 2 years of rearing, densities averaged 2-16 m^2/fish, and for larger fish, 15-27 m^2/fish (fig. 36). The spread in densities portrayed in figure 36 results partly from differences in natural or artificial stocking rates, size of stream, and habitat quality.

Juvenile salmonids usually occupy sites in streams referred to as "focal points" from which they venture out to perform other functions (Wickham 1967). Characteristics of these focal points in water velocities, water depths, substrate, and cover represent the microhabitat preferences of the fish (table 15) to remain oriented into the

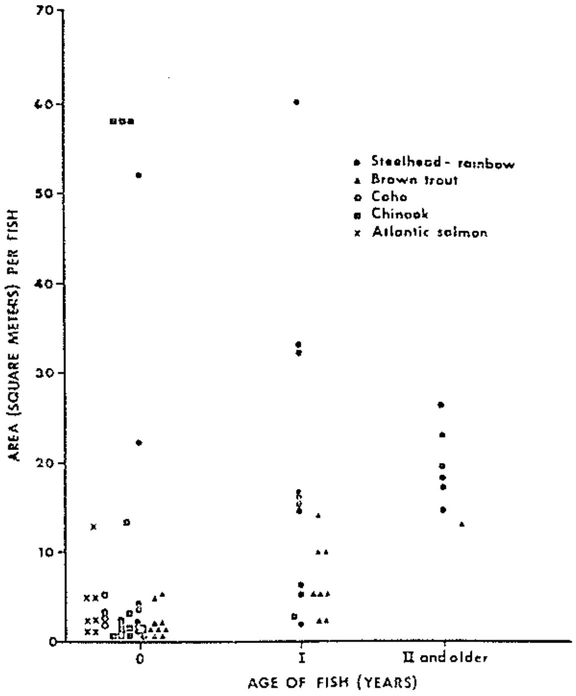


Figure 36—Densities of age 0, I, II, and older salmon and trout in streams usually after 1, 2, 3, or more summers of growth, respectively (see table 14 for sources of data).

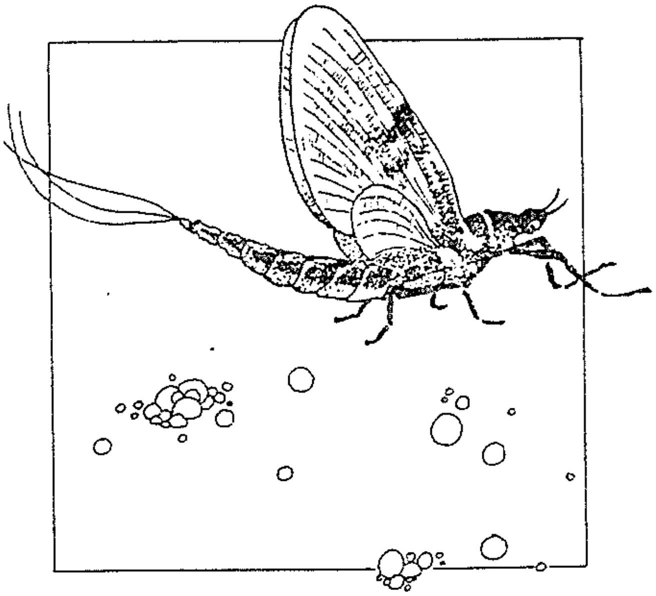
Table 15—Depth, velocity, and substrate microhabitat preferences of salmonids in streams

Species	Reference	Age	Depth	Velocity	Substrate
			M	M/s	Cm
Steelhead	Everest and Chapman (1972)	0	<0.15	<0.15	Rubble
	" "	1	.60-.75	.15-.30	Rubble
	Hanson (1977)	1	.51 mean	.10 mean	10-30
	" "	2	.58 "	.15 "	10-30
	" "	3	.60 "	.15 "	10-30
	Stuehrenberg (1975)	0	<.30	.14 (range .03-.26)	--
	" 4"	1	>.15	.16 (range .05-.37)	--
	Thompson (1972)	0	.18-.67	.6-.49	--
Chinook	Everest and Chapman (1972)	0	.15-.30	<.15	Silt
	Stuehrenberg (1975)	0	<.61	.09 (range .0-.21)	--
	" "	1	<.61	.17 (range .05-.38)	--
	Thompson (1972)	0	.30-1.22	.06-.24	--
Coho	Pearson et al.[1/]	0	--	.09-.21	--
	Thompson (1972)	0	.30-1.22	.05-.24	--
	Nickelson and Reisenbichler (1977)	0	>.30	<.30	--
Cutthroat	Thompson (1972)	0, 1	.40-1.22	.6-.49	--
	Hanson (1977)	1	.51 mean	.10 mean	5-20
	" "	2	.56 "	.14 "	5-30
	" "	3	.57 "	.20 "	5-30
	" "	4	.54 "	.14 "	30

[1/] See text footnote 4.

current (Baldes 1968). Habitat selected by fish is influenced by their ability and the availability of food (Kalleberg 1958, Mason and Chapman 1965, Chapman 1966, Chapman and Bjornn 1969, Everest and Chapman 1972).

In summary, good rearing habitat for anadromous salmonids consists of a mixture of pools and riffles, adequate cover, water temperatures that average between 10° and 15°C during the summer, dissolved oxygen usually at saturation, suspended sediment less than 25 mg/l, and riffles with less than 20 percent fine sediment (less than 6.4 mm in diameter). The optimum combination of stream areas used by aquatic invertebrates and all ages of fish cannot be described until the interrelations between the components are better understood.



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