Transactions of the American Fisheries Society 113:142–150, 1984

64

Effects of Chronic Turbidity on Density and Growth of Steelheads and Coho Salmon[1]

JOHN W. SIGLER,[2] T. C. BJORNN, AND FRED H. EVEREST[3]

Idaho Cooperative Fishery Research Unit[4]
University of Idaho, Moscow, Idaho 83843

Abstract

Chronic turbidity in streams during emergence and rearing of young anadromous salmonids could affect the numbers and quality of fish produced. We conducted laboratory tests to determine the effect of chronic turbidity on feeding of 30–65 mm long steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch* in straight and oval channels. Fish subjected to continuous clay turbidities grew less well than those living in clear water, and more of them emigrated from channels during the experiments.

Received February 28, 1983 Accepted December 4, 1983

Yearling and older salmonids can survive high concentrations of suspended sediment for considerable periods, and acute lethal effects generally occur only if concentrations exceed 20,000 mg/liter (see reviews by Cordone and Kelly 1961; Sorenson et al. 1977), but little is known about the effects of turbidity on newly emerged young. Many streams used by salmonids for spawning in disturbed watersheds are subject to chronic turbidity. Fish reared in such streams might not grow as rapidly, or be as socially fit, as those produced in clear streams. In our paper, we evaluated the effects of chronic turbidity on growth and densities of young steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch*.

Methods

Physical Facilities

We used two types of laboratory streams to insure that results were not artifacts of a single apparatus. We conducted replicate pairs of tests in 1978 and 1979 in (1) a pair of indoor oval channels, 3.7 m wide × 4.9 m long, located at the University of Idaho, and (2) two pairs of linear raceways, 1.2 m wide × 21 m long, on a translucent plastic-covered area at the Hayden Creek Research Station.

The four raceway channels at Hayden Creek Research Station had substrate arranged in riffle–pool configurations with large (10–15-cm) cobble distributed in a set pattern throughout each channel unit. A trap was attached to the downstream ends of each section (Fig. 1). Each pair of upper and lower channels was operated as a test unit.

The oval channels consisted of two essentially identical units, one above the other (Hahn 1977) (Fig. 1). Rearing space in each channel was about 10 m long and 60 cm wide (usable space, 6 m^2); pools were 30 cm deep and riffles 7–15 cm deep. Substrate was arranged in riffle–pool configuration with cobble placed in a set pattern throughout the substrate. A paddlewheel was used to maintain water velocities. Fine-mesh screen separated the paddlewheel from the rearing section. Free egress from the channels was provided by downstream and upstream traps.

We regulated turbidity, water velocity, temperature, and photoperiod in the oval channels. Carrying capacity of each was about 30 young fish, 30–55 mm long, in clear water. The Hayden Creek raceways were larger, enabling us to use larger numbers of fish, and we controlled turbidity, flow rate (velocity), and, to some extent, temperature. Photoperiod was natural.

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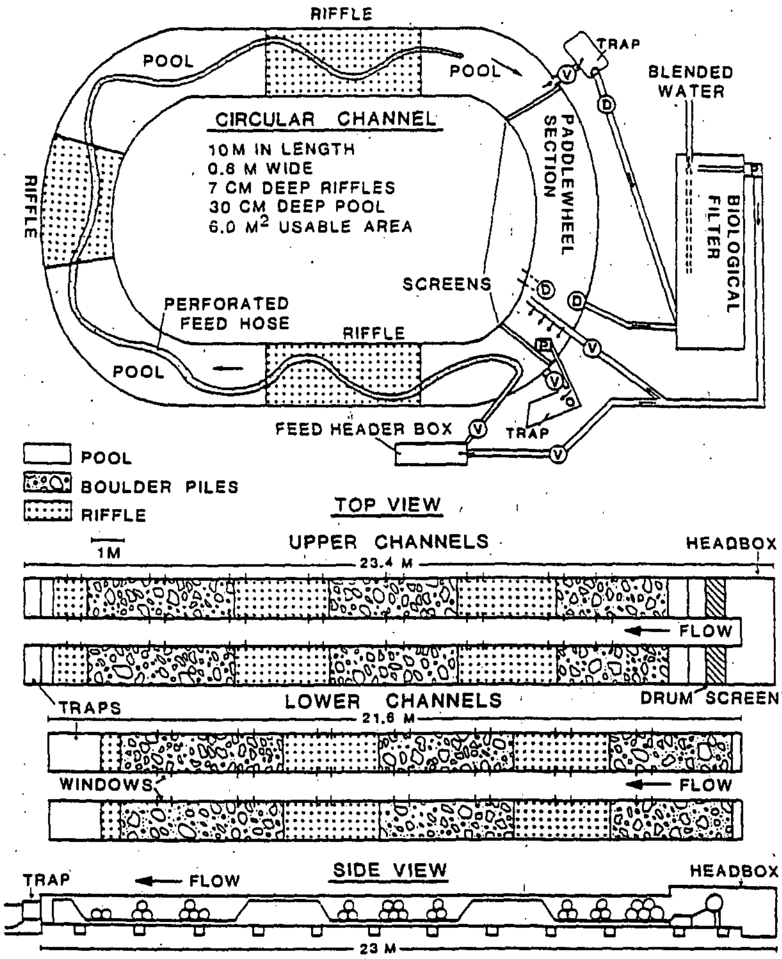
[1] Based on a dissertation submitted by John W. Sigler as partial fulfillment of the requirements for the Doctor of Philosophy in Fisheries Management.

[2] Present address: W. F. Sigler and Associates, Post Office Box 1350, Logan, Utah 84322.

[3] Present address: United States Forest Service, Forest Science Laboratory, Corvallis, Oregon 97331.

[4] The Unit is jointly supported by University of Idaho, Idaho Department of Fish and Game, and the United States Fish and Wildlife Service.



IGURE 1.—*Generalized schematic of raceway channels at Hayden Creek Research Station and oval channels at University of Idaho showing the channel configurations, location of riffle and pool areas, and traps. (V = valve, D = drainline or drain, and P = pump.)*

Turbidity

We used clays, fireclay and bentonite, to create rbidity in the tests. Fireclay used in the 1978 sts, largely kaolinite as determined by X-ray ffractograms, was distinctively different from e montmorillonite-based bentonite clay in size, hesion, and cation exchange capacity. Bennite clay used in the 1979 tests, as indicated X-ray analysis, had a structure that more sely resembled the vermiculite structure of tural west-coast clays.

Clay was mechanically dispensed to all test annels. We added fireclay as a dry powder in the 1978 tests, using a modified lawn fertilizer spreader to achieve a near constant delivery. In the 1979 tests with bentonite clay, we pumped a wet slurry into the channels through a series of time clocks and valves that enabled us to maintain nearly constant turbidity in the channels.

Turbidity, in nephelometric turbidity units (NTUs), was significantly correlated with suspended material (mg/liter) filtered from the water (NTU = 10.0 + 0.178[mg/liter]; r^2 = 0.764) and with bentonite clay (mg/liter) added to the water (NTU = 5.49 + 0.162[mg/liter];

TABLE 1.—*Results of turbidity tests with steelheads in two oval channels, 1978 and 1979. Beginning mean weights and lengths for both turbid- and clear-water channels are based on a separate sample of 25 fish taken at time fish were placed in channels.*

	Fish			Mean size of fish released		Mean size at end of test		Mean daily length increase (mm)	Mean daily weight increase (g)	Density at end of test	
Test (duration) Turbidity (NTUs)[a]	Released	Entering trap	Removed at end of test	Length (mm)	Weight (g)	Length (mm)	Weight (g)			Fish/m^2	g/m^2
Test 1 (14 days)											
Clear water	299	180	32	30.2	0.25	41.3	0.63	0.79	0.027	5.3	3.9
Clear water	305	162	27	29.7	0.26	40.6	0.62	0.74	0.026	4.5	2.8
Test 2 (14 days)											
Turbid water (143)	100	58	35	30.8	0.26	38.5	0.52	0.55	0.019	5.8	3.0
Turbid water (192)	100	63	3	30.9	0.27	35.3	0.38	0.32	0.008	0.5	0.2
Test 3 (14 days)											
Turbid water (167)	110	71	0	31.4	0.29					0.0	0.0
Turbid water (241)	110	61	0	31.4	0.29					0.0	0.0
Test 4 (14 days)											
Turbid water (232)	200	147	1	27.3	0.24	30.0	0.32	0.19	0.006	0.2	0.1
Turbid water (265)	160	121	1	27.3	0.29	29.0	0.20	0.12	0.003	0.2	0.0
Test 5 (14 days)											
Turbid water (77)	130	90	40	29.9	0.25	35.8	0.38	0.42	0.009	6.7	2.5
Turbid water (57)	130	103	33	29.9	0.25	36.3	0.38	0.46	0.009	5.5	2.1
Test 6 (21 days)											
Clear water	110	76	23	38.2	0.44	46.9	0.84	0.42	0.019	3.8	3.2
Turbid water (80)	110	68	24	38.2	0.44	45.8	0.77	0.36	0.016	4.0	3.1
Test 7 (15 days)											
Clear water	120	110	8	29.1	0.21	31.6	0.23	0.19	0.002	1.3	0.3
Turbid water (72)	120	105	2	29.1	0.21	34.0	0.20	0.15	−0.001	0.3	0.1
Test 8 (19 days)											
Clear water	120	102	6	31.5	0.26	36.8	0.40	0.53	0.014	1.0	0.4
Turbid water (51)	120	96	2	31.5	0.26	34.0	0.26	0.25	0.000	0.3	0.1
Test 9 (17 days)											
Clear water	100	92	4	43.0	0.65	50.3	0.87	0.56	0.017	0.7	0.6
Turbid water (59)	100	66	32	43.0	0.65	43.5	0.68	0.04	0.002	5.3	3.6
Test 10 (19 days)											
Clear water	130	114	10	45.7	0.72	49.6	0.93	0.19	0.010	1.7	1.6
Turbid water (45)	120	95	15	45.7	0.72	45.4	0.72	−0.01	0.000	2.5	1.8

[a] NTU = nephelometric turbidity unit.

$r^2 = 0.926$). We first created turbidities of 100–300 NTUs, but fish either left the channels or died. Subsequently we created turbidities mostly in the 25–50-NTU range. At 50 NTUs, visibility was limited to 2–5 cm.

Fish and Feeding

Steelhead and coho salmon were used in the tests to determine interspecific differences in reactions to turbidity. Steelhead eggs and juveniles were from Dworshak National Fish Hatchery, Ahsahka, Idaho, and coho salmon eggs were from the Sandy State Fish Hatchery, Oregon.

At the start of each growth test, we introduced 100–160 fish into each oval channel and 135–1,200 into each raceway channel. Migration traps were kept closed 24–48 hours after the first fish were introduced. Initial mean weights and lengths were determined from a

: 2.—*Results of turbidity tests with steelheads in four raceway channels, 1979. Beginning mean weights and lengths based on a separate sample of 25 fish taken at time fish were placed in channels.*

	Fish			Mean size of fish released		Mean size at end of test		Mean daily length in-crease (mm)	Mean daily weight increase (g)	Density at end of test	
duration) ·bidity (NTUs)[a]	Re-leased	Enter-ing trap	Re-moved at end of test	Length (mm)	Weight (g)	Length (mm)	Weight (g)			Fish/m²	g/m²
ı (14 days)				27.6	0.23						
ır water											
pper channel	950	452	357			33.5	0.41	0.39	0.012	17.1	7.0
ower channel	425	128	208			35.0	0.46	0.49	0.015	8.4	2.1
:bid water (48)											
'pper channel	950	636	176			31.0	0.25	0.23	0.002	8.5	3.9
ower channel	425	480	4			33.5	0.39	0.39	0.011	0.2	0.1
2 (19 days)				29.4	0.22						
ar water											
Jpper channel	1,200	448	498			37.1	0.56	0.41	0.018	23.8	13.4
.ower channel	800	188	352			37.5	0.62	0.43	0.021	4.0	1.4
rbid water (38)											
Jpper channel	1,200	913	84			33.6	0.36	0.22	0.007	14.5	8.9
.ower channel	800	839	20			34.2	0.37	0.25	0.008	0.8	0.3
3 (17 days)				26.8	0.20						
:ar water											
Jpper channel	1,000	314	386			38.0	0.62	0.66	0.024	18.4	11.3
Lower channel	700	236	540			37.4	0.58	0.62	0.023	9.9	3.6
ırbid water (49)											
Upper channel	1,000	570	208			33.4	0.36	0.39	0.009	22.2	12.9
Lower channel	700	263	230			32.8	0.35	0.35	0.009	9.5	3.3
: 4 (19 days)				37.9	0.56						
ıear water											
Upper channel	900	119	697			47.8	1.44	0.52	0.046	33.3	48.0
Lower channel	585	14	531			46.6	1.33	0.46	0.040	5.8	4.7
urbid water (42)											
Upper channel	900	467	122			42.0	0.94	0.22	0.020	21.8	29.0
Lower channel	585	345	235			41.6	0.93	0.22	0.019	9.7	9.0

NTU = nephelometric turbidity unit.

ıarate sample of fish randomly selected from : holding tank.

Frozen brine shrimp were fed to the fish in :eways in 1978 and in oval channels in 1978 d 1979. Oregon Moist Pellet of appropriate .e was fed to fish in raceways in 1979. Un-·essed fish took these foods readily. Food was ovided at a daily rate of 10–15% of body :ight, and was adjusted every 3–4 days to ac-ıunt for emigration and assumed weight gain. he ration was divided into three daily feed-gs. Food was dispensed to each raceway by ınd in 1978 and by automatic feeding in 1979. ɔr oval channels, brine shrimp were slowly dis-ibuted to the channel through a perforated ose in the substrate (Fig. 1). Food entering the channels peaked shortly after feeding, and decreased exponentially until the next feeding.

Experimental Procedures

At the start of each test, fish were counted into three containers: one for the turbid-water channel; one for the clear-water channel; and one for measurement of beginning lengths and weights. Fish were introduced into the channels in two ways: (1) placed in a screen cage open on the bottom and forced to go down into the gravel and emerge outside the box if the fish were near the size of emergence; and (2) poured into the head of raceway channels or middle of oval channels. Water in the turbid-water channel was usually turbid when fish were placed in the

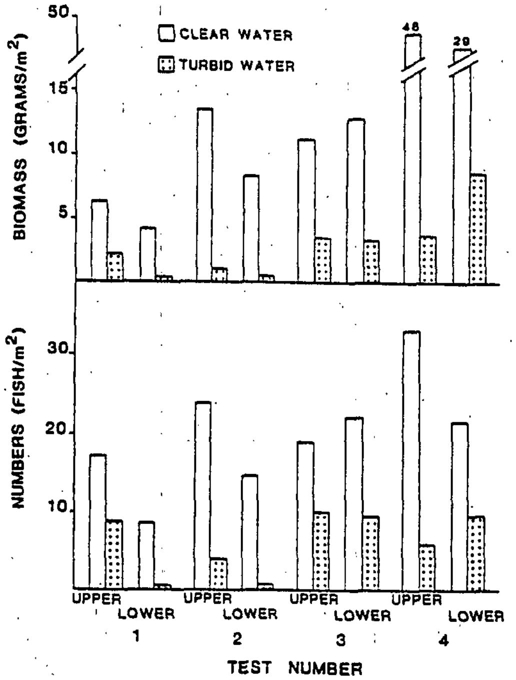


FIGURE 2.—*Densities at end of tests with steelheads in upper and lower raceway channels with clear and turbid water, 1979.*

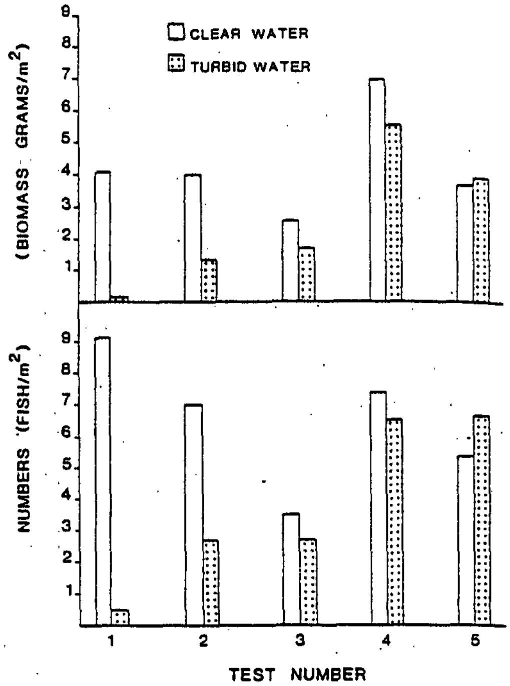


FIGURE 3.—*Densities at end of tests with coho salmon in oval channels with clear and turbid water, 1979.*

channels. Traps that fish could enter to leave the channels were not opened until 24–48 hours after fish were placed in the channel to provide time for the fish to acclimate to the channels. Additional small numbers of fish were added to each channel on the second and third day of tests to help insure the channels were fully seeded. At the end of each test, fish were removed from the channels first by electrofishing and then by killing any remaining fish with chlorine bleach. Fish were preserved in 10% neutral buffered formalin and later measured and weighed.

All fish could not be accounted for at the end of most tests, either as having left the channels through the traps or as having been recovered at the end of the test. The fate of the unrecovered fish is unknown, but we suspect that some died and settled into the gravel interstices. In any event, fish that took up residence in the channels and were recovered at the end of the test were the most important for evaluating the effects of turbidity on densities and growth.

Results

Steelhead

Oval Channels

In our first test in 1978 to determine the approximate carrying capacity of the channels with clear water, we released in each channel about 300 fish that averaged 29.7 and 30.2 mm total length, and 0.25 and 0.26 g. After 14 days, 32 and 27 fish remained in the channels (Table 1). Most fish that left the channel did so in the first 2–3 days; there was little or no emigration during the last 2–3 days. Densities at the end of the test were 4.5 and 5.3 fish/m^2, and 2.8 and 3.9 g/m^2. Fish in the channels at the end of the test grew an average of about 0.75 mm/day and 0.026 g/day, if they were representative of fish placed in the channel at the start.

We then conducted four tests to determine the range of turbidities we should use in growth tests. We placed 100–200 fish in each channel and then added the powdered clay to both channels to create turbidities that ranged from 57 to 265 NTUs (tests 2–5, Table 1). In tests 2–4

TABLE 3.—*Results of turbidity tests with coho salmon in two oval channels, 1979. Beginning mean weights and lengths are based on a separate sample of 25 fish taken at time fish were placed in channels.*

Test (duration) Turbidity (NTUs)[a]	Fish: Released	Fish: Entering trap	Fish: Removed at end of test	Mean size of fish released: Length (mm)	Mean size of fish released: Weight (g)	Mean size at end of test: Length (mm)	Mean size at end of test: Weight (g)	Mean daily length increase (mm)	Mean daily weight increase (g)	Density at end of test: Fish/m^2	Density at end of test: g/m^2
Test 1 (14 days)				33.4	0.34						
Clear water	130	70	55			38.6	0.46	0.37	0.007	9.2	4.2
Turbid water (86)	130	91	3			35.7	0.30	0.16	−0.005	0.5	0.2
Test 2 (13 days)				37.1	0.40						
Clear water	160	105	41			42.0	0.57	0.38	0.013	7.0	4.0
Turbid water (45)	160	136	16			40.6	0.49	0.27	0.007	2.7	1.3
Test 3 (11 days)				42.4	0.53						
Clear water	140	118	21			46.3	0.75	0.36	0.020	3.5	2.6
Turbid water (22)	120	104	16			44.1	0.65	0.16	0.011	2.7	1.7
Test 4 (14 days)				45.2	0.77						
Clear water	120	71	44			49.6	0.94	0.31	0.006	7.3	6.9
Turbid water (31)	120	73	39			48.5	0.87	0.24	0.011	6.5	5.6
Test 5 (15 days)				41.1	0.57						
Clear water	120	86	32			45.4	0.70	0.31	0.009	5.3	3.7
Turbid water (23)	120	67	40			42.0	0.58	0.13	0.000	6.7	3.9

[a] NTU = nephelometric turbidity unit.

with mean turbidities of 167 NTUs or higher, almost no fish could be found in the channels after 14 days. In test 2, with a mean turbidity of 143 NTUs in one channel, we removed 35 fish at the end of the test. We then tested much lower turbidities (57 and 77 NTUs) in test 5 and found that small fish could survive in those turbidities, and numbers near the carrying capacity (33 and 40 fish, 35 mm long) would stay in the channels. In all subsequent tests, mean turbidities were less than 86 NTUs.

We then conducted one additional test in 1978 with steelheads to compare growth of fish in turbid versus clean water (test 6, Table 1). Of the 110 fish (38.2 mm long, 0.44 g) released in each channel, 23 were removed from the one with clear water and 24 from the one with turbid water (80 NTUs). Density at the end of the 21-day test was near carrying capacity (3 g/m^2) in both channels and growth rates of the fish of the fish were not significantly different between channels.

In 1979, we conducted four turbidity-versus-growth tests with steelheads in the oval channels (tests 7–10, Table 1). In all four tests, the numbers of fish remaining in the channels at the end were less than half the carrying capacity, except for the turbid water channel in test 9. Because of the small number of fish at the end of the tests, comparisons of fish growth between clear and turbid water channels are of limited value. There is some evidence of slower growth of steelheads in turbid water versus clear water, but it is not conclusive.

Raceway Channels

Four tests of steelhead growth versus turbidity were conducted in the raceway channels in 1979 (Table 2). In all tests, more fish stayed in the clear-water channels than in those with turbid water (Fig. 2). The number and biomass of fish remaining in each channel somewhat depended on the number and size of fish released. In general, numbers of fish and biomass in either clear- or turbid-water channels at the end of the test were larger when larger numbers or larger-size fish were released.

Steelheads that stayed in the clear-water channels were consistently larger than fish in the turbid-water channels and they grew at fast-

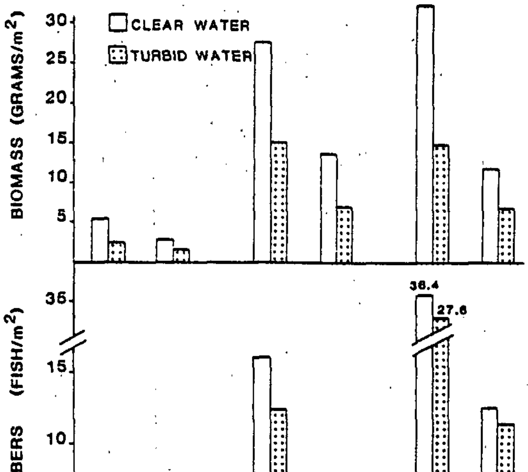


FIGURE 4.—*Densities at end of tests with coho salmon in upper and lower raceway channels with clear and turbid water, 1979.*

er daily rates of both weight and length (Table 2). Differences in growth and density between fish in clear and turbid water were statistically significant for the combined upper and lower channels: final weight ($F = 31.67$; $P = 0.003$); final length ($F = 36.64$; $P = 0.0002$); and mean daily length gain ($F = 46.61$; $P = 0.0001$).

Coho Salmon

Oval Channels

In four of the five tests of coho salmon growth versus turbidity in the oval channels, fewer fish had stayed in the turbid water channels by the end of each test than had stayed in the channels with clear water (Table 3; Fig. 3). Largest differences in ending densities occurred in tests 1 and 2 when the fish released were relatively small (33 and 37 mm mean length). In later tests, fish averaged 41 mm or more in length when released and differences in ending densities between clear and turbid water channels were not large. In all tests, ending densities in at least the clear-water channel were near carrying capacity.

Fish that stayed in the clear-water chann were significantly larger at the end of each te than fish in turbid water (Table 3) in both weigh ($F = 31.52$; $P = 0.005$) and length ($F = 35.0$ $P = 0.004$). Mean daily weight and length in creases of fish were significantly larger in th clear-water channels than in the turbid-wate channels (Table 3): weight increase, $F = 30.87$ $P = 0.005$; length increase, $F = 35.18$; P 0.004.

Raceway Channels

Fewer fry remained in raceway channels wit turbid water than in those with clear water a the end of all three tests with coho salmon (Ta ble 4; Fig. 4). Differences in fish numbers fo the combined upper and lower channels between clear and turbid water were not statistically significant ($F = 1.01$; $P = 0.35$), but differences in biomass were significant ($F = 7.21$; $P = 0.036$). As in raceway-channel tests with steelheads, ending densities of coho salmon were influenced some by the number and perhaps size of fish released: higher ending densities resulted from larger numbers released.

Coho salmon that stayed in clear water were consistently larger in weight and length than fish that stayed in turbid water channels (Table 4). Mean daily weight and length increases were up to six times larger for fish in clear water versus those in turbid water. Weights and lengths of clear- versus turbid-water fish at the end of the tests differed significantly ($F = 16.33$; $P = 0.006$; and $F = 19.91$; $P = 0.004$), as did mean daily length increase ($F = 38.54$; $P = 0.001$).

Discussion

In general, more fish stayed in channels with clear water than with turbid water, and weight and length of both steelheads and coho salmon increased faster in clear water. In most tests, there was a significant difference in growth rates between fish in clear versus turbid water. Fish reared in clear water were not always significantly larger than fish in turbid water, but were growing at faster rates. After longer periods of growth, greater divergences of weight and length between fish in clear versus turbid water presumably would have occurred.

Densities of fish in the clear-water channels, although not always statistically different, were consistently higher than those in the turbid-

TABLE 4.—*Results of turbidity tests with coho salmon in four raceway channels, 1979. Beginning mean weights and lengths are based on a separate sample of 25 fish taken at time fish were placed in channels.*

Test (duration) Turbidity (NTUs)[a]	Fish: Released	Fish: Entering trap	Fish: Removed at end of test	Mean size of fish released: Length (mm)	Mean size of fish released: Weight (g)	Mean size at end of test: Length (mm)	Mean size at end of test: Weight (g)	Mean daily length increase (mm)	Mean daily weight increase (g)	Density at end of test: Fish/m²	Density at end of test: g/m²
Test 1 (14 days)				35.1	0.45						
Clear water											
Upper channel	314	15	153			41.9	0.75	0.49	0.022	7.3	5.5
Lower channel	135	26	98			41.5	0.73	0.45	0.020	4.1	2.5
Turbid water (11–32)											
Upper channel	314	45	86			40.4	0.60	0.38	0.011	4.0	2.9
Lower channel	135	48	76			39.3	0.55	0.30	0.007	3.1	1.7
Test 2 (31 days)				38.2	0.52						
Clear water											
Upper channel	600		330			53.8	1.76	0.50	0.040	15.8	27.7
Lower channel	187	13	161			57.0	2.07	0.61	0.050	12.7	15.0
Turbid water (41)											
Upper channel	600	215	266			47.3	1.18	0.29	0.021	6.6	13.7
Lower channel	188	60	128			49.0	1.30	0.35	0.025	5.3	7.0
Test 3 (21 days)				37.2	0.45						
Clear water											
Upper channel	900	19	761			44.5	0.89	0.35	0.021	36.4	32.4
Lower channel	400	20	314			43.9	0.93	0.32	0.023	27.6	14.9
Turbid water (49)											
Upper channel	1,000	347	578			38.4	0.54	0.06	0.004	12.9	11.9
Lower channel	400	159	284			38.6	0.59	0.07	0.007	11.7	6.9

[a] NTU = nephelometric turbidity unit.

water channels (Figs. 2, 3, 4) and were somewhat smaller than those reported by Reiser and Bjornn (1979) for natural streams. Conditions in the turbid-water channels were less desirable or suitable for habitation than in the clear-water channels, perhaps because fish could not feed normally or suffered stresses resulting from the turbidity. Small fish (<40 mm) were less likely to stay in the turbid-water channels than larger fish.

Larger numbers of fish emigrated from the channel with turbid water than from the one with clear water during the first two diel cycles in each test. This early emigration by large numbers of fish is evidence that the turbidity was stressful to the fish. Some fish that still had a portion of yolk sac left the turbid water, indicating that inability to obtain sufficient food was not the principal reason for emigration.

Anadromous salmonids use many small west-coast streams with seasonally intermittent flow for spawning and early rearing. Summer-run steelheads in the Rogue River basin, Oregon, spawn primarily in streams that become intermittent or dry in summer (Everest 1973). Fall-run chinook salmon *Onchorhynchus tshawytscha* and coho salmon also spawn in small intermittent streams of the Rogue basin. Resident rainbow trout *Salmo gairdneri* in the Sagehen Creek basin, California, often spawned in an intermittent tributary (Erman and Hawthorne 1976). Young salmonids live in the intermittent streams for a few days to several weeks, after which they migrate downstream and enter larger streams where they must compete with other fish for food and space.

If fish in natural streams are subjected to turbidity soon after emergence, we would expect substantial emigration. Such downstream migration could reduce production in those tributaries if the emigrants did not secure suitable habitat in downstream areas. Fish rearing in chronically turbid intermittent streams eventually would be forced by declining space to emigrate to downstream waters or perish. Those that did emigrate after rearing in turbid water would be smaller than downstream cohorts reared in clear water and probably less able to compete for living space. Because the outcome of aggressive encounters usually is decided by size (Chapman 1962), survival to smolt for such emigrants would probably be reduced.

The higher rate of emigration by fish in turbid water is in contrast to the findings of Noggle (1978). He found a strong tendency for fish to stay in their initial territory when exposed for short periods to turbid water rather than leave, even when a less adverse condition (clear water) was accessible. Noggle's fish were larger than those in our tests and may have been better able to handle stress from turbid water.

In our study, gill-tissue damage was not readily observable in any of the fish examined until after 3 to 5 days of exposure to the test turbidities. Herbert and Merkens (1961) observed gill-epithelial thickening in six fish exposed for several weeks to 270 to 810 mg/liter diatomaceous earth, yet one fish surviving in 810 mg/liter had normal gills. Other studies cited by Noggle (1978) reported no damage to gills of fish exposed to high concentrations of the type of sediment used in our studies.

In our studies, as little as 25 NTUs of turbidity caused a reduction in fish growth. The slower growth, presumably from a reduced ability to feed, could be related to a mechanism more complex than inability to see prey (such as insufficient light). Brett and Groot (1963) reported that Pacific salmon could feed at light levels equivalent to $\frac{1}{300}$ of bright moonlight (0.001 lux), much darker than in our turbid-water channels. Quality of light may be a factor. Large amounts of suspended particles may intercept the wavelengths used by fish, thereby reducing their ability to see and secure food.

Acknowledgments

We acknowledge the assistance of the students, staff, and faculty of the Idaho Cooperative Fishery Research Unit, Moscow, and personnel of the Idaho Fish and Game Department. The United States Forest Service, Forest Science Laboratory, funded the study.

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