SUPERSATURATION OF NITROGEN IN THE COLUMBIA RIVER AND ITS EFFECT ON SALMON AND STEELHEAD TROUT

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ABSTRACT

The nitrogen gas regime in the Columbia River was studied in 1966 (from Grand Coulee Dam, Wash., to the estuary at Astoria, Oreg.) and in 1967 (from Priest Rapids Dam, Wash., to the estuary). Dissolved nitrogen was subject to considerable seasonal fluctuation and varied with flow of water over spillways of dams; it was normal (near 100-percent saturation) in the fall and winter when no water was spilled, and high (above 135-percent saturation) in the spring and summer when large volumes of water were spilled. Some saturation levels over large areas were high enough and lasted long enough to be potentially dangerous to salmon (*Oncorhynchus* spp.) and steelhead trout (*Salmo gairdneri*).

Supersaturation of nitrogen at Priest Rapids Dam lowered the tolerance of juvenile fish to temperature increases, and some showed symptoms of gas bubble disease. Field studies to determine the effects of high levels of dissolved nitrogen on adult salmon and steelhead trout did not provide conclusive results.

Observations in the spring of 1965 by the Washington State Department of Fisheries and the Bureau of Commercial Fisheries showed that saturation of dissolved nitrogen at some sites in the Columbia River was as high as 125 percent. Because levels of this magnitude had produced gas bubble disease in adult and juvenile salmon (Rucker and Hodgeboom, 1953; Harvey and Cooper, 1962; and Westgard, 1964), additional surveys were made in 1966–67 to attempt to determine whether high levels of dissolved nitrogen might be responsible for losses of adult salmon and poor production of young fish at spawning channels.

The first phase in the study of nitrogen and oxygen concentrations (February–November 1966) was primarily to determine the cause of supersaturation of dissolved nitrogen and to determine seasonal variations. Water samples were taken from 26 sites between Grand Coulee Dam, Wash., near the Canadian border, and Astoria, Oreg., at the mouth of the river. The second phase (March–October 1967) was to determine the effect of nitrogen supersaturation on adult and juvenile salmon. We suspected that gas bubble disease was one of the factors in losses of adult and juvenile chinook salmon (*O. tshawytscha*) migrating between dams. The studies in 1967 concentrated on obtaining field evidence of such losses.

This report discusses the amounts of dissolved nitrogen in 1966–67, the effect of dams and reservoirs on saturation, the seasonal variation and duration of supersaturation, and the effect of supersaturation of nitrogen on juvenile and adult salmon and steelhead trout (*Salmo gairdneri*) in the Columbia River.

METHODS

Descriptions of the sampling stations, analytical techniques, and other experimental procedures are given in this section.

SAMPLING STATIONS AND TECHNIQUE

Twenty-six principal sampling stations were established along the Columbia River between the forebay of Grand Coulee Dam and the estuary at Astoria (fig. 1). All stations except 13, 25, and 26 were either in midreservoir, about 500 m. upstream from the dam, or on the spillway side of the river, about 500 m. below. Samples of water were taken at the surface and at 10-m. depths at the forebay stations. The spillways discharge from the surface down to a maximum depth of about 10½ m., and

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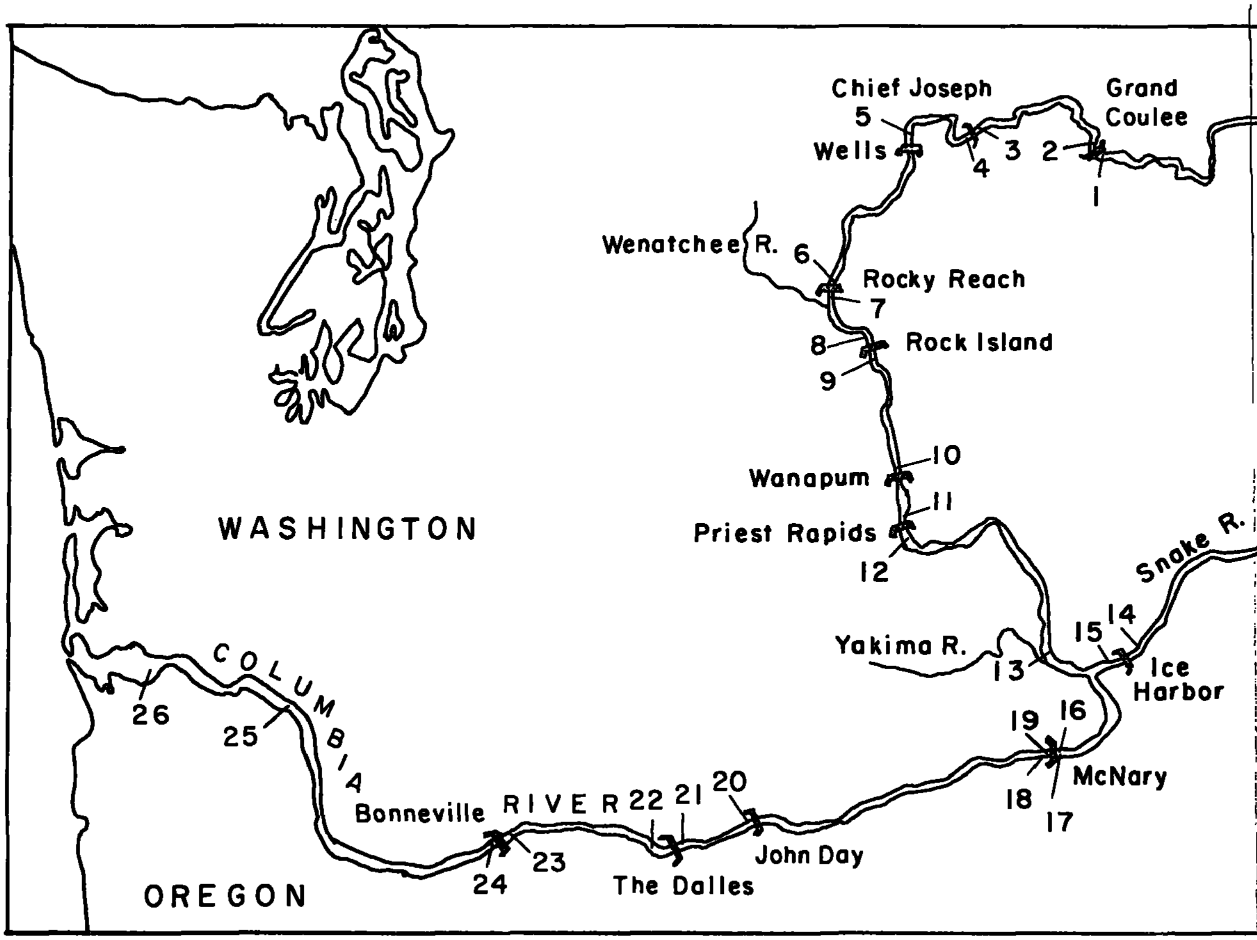

FIGURE 1.—Principal sampling stations on the Columbia and Snake Rivers.

the turbines withdraw water from about 8 m. down to 20 m. at all the dams downstream from Chief Joseph Dam. Maximum forebay depths at full pool do not exceed 45 m. Because of these facts and the fact that temperatures in the forebay of the reservoirs seldom varied more than 1° C. from the surface to the bottom, a sample at the surface and 10-m. depth was sufficient to represent the average forebay concentration and in turn represent the water passing through the turbines and spillways. Duplicate samples were collected at the surface at stations below the dams where high current velocities made it impossible to sample at depth. Because the amount of soluble nitrogen depends on water temperature,[1] the temperature of each sample was recorded before it was placed in an iced cooler for transport to the laboratory. The use of two aircraft made it possible to obtain all samples in 1 day; analysis was completed on the following day.

Water samples were obtained from additional stations when more information was needed for a specific dam or reservoir. For example, additional stations were established along the reservoirs behind McNary and Chief Joseph Dams to study changes in nitrogen content of water passing through these reservoirs. Additional stations were also sampled when the effect of a specific dam on saturation levels was examined. Table 1 gives a detailed description of the principal sampling stations and the dates when samples were obtained.

ANALYSIS

The amount of dissolved nitrogen in the sample was determined by a modification of the technique used by Swinnerton, Linnenbom, and Cheek (1962). A Fisher blood gas analyzer Model

[1] An atmospheric pressure of 760 mm. mercury was used in computing normal saturation (100 percent) for each sample.

TABLE 1.—*Locations and dates of sampling in the Columbia and Snake Rivers; sampling sites are shown by number in figure 1*

Station location and number		Dates sampled																				
		1966											1967									
		Feb. 9	Mar. 7	Apr. 6	Apr. 18	May 9	June 6	July 11	Aug. 1	Sept. 6	Oct. 2	Nov. 7	Apr. 3	May 1	May 15	June 6	June 27	July 5	July 19	Aug. 2	Aug. 23	Sept. 5	Oct. 3
Number	*Station*																						
1	Forebay—Grand Coulee Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
2	Tailrace—Grand Coulee Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
3	Forebay—Chief Joseph Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
4	Tailrace—Chief Joseph Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
5	Wells damsite	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
6	Forebay—Rocky Reach Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
7	Tailrace—Rocky Reach Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
8	Forebay—Rock Island Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
9	Tailrace—Rock Island Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
10	Forebay—Wanapum Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...	...
11	Forebay—Priest Rapids Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	X	X	X	X	...	X	...
12	Tailrace—Priest Rapids Dam.	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	X	X	X	X	...	...	...
13	Columbia River at Richland, Wash.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
14	Forebay—Ice Harbor Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	...	X	...	X	X
15	Tailrace—Ice Harbor Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...
16	Forebay—McNary Dam (north side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
17	Forebay—McNary Dam (south side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
18	Tailrace—McNary Dam (south side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
19	Tailrace—McNary Dam (north side).	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	John Day damsite	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
21	Forebay—The Dalles Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
22	Tailrace—The Dalles Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
23	Forebay—Bonneville Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	...
24	Tailrace—Bonneville Dam.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	...
25	Columbia River at Longview, Wash.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
26	Columbia River estuary Astoria, Oreg.	X	X	X	X	X	X	X	X	X	X	X	X	...	...	...	...	...	...	...	...	...	...

6–390V2[2] was substituted for their Model 25, and the length of the extraction chamber was increased to 150 mm. Model 6–390V2 is more sensitive than Model 25, and the longer extraction chamber allowed analysis of larger samples.

Saturation values quoted in this report are correct to within ±2 percent. Limitations in the accuracy of the method and the uncertainty of the theoretical solubilities of nitrogen precluded more precise interpretation.

[2] Trade names referred to in this publication do not imply endorsement of commercial products by the Bureau of Commercial Fisheries.

EFFECT OF DAMS AND RESERVOIRS ON SATURATION OF DISSOLVED NITROGEN

Major causes of supersaturation of water with gases are heavy concentrations of algae (Woodbury, 1942), warming of water without adequate circulation and exposure to the atmosphere for equilibration, and falling of water into an enclosed plunge basin (Harvey and Cooper, 1962). Algae concentrations like those described by Woodbury are not found in the Columbia River and the river is not warmed sufficiently at any location to account for the high concentrations previously recorded. Spillways at dams create conditions similar to those described by Harvey and Cooper and were suspected to be the major cause of supersaturation; during periods of high flow, large volumes of water plunge from spillways at all the dams on the Columbia River into various types of basins.

OBSERVATIONS AT DAMS

Samples analyzed at individual dams to determine the effect of turbines and spillways on dissolved nitrogen indicated that supersaturation in the Columbia River is caused primarily by spillways. This was clearly demonstrated during tests at Bonneville Dam in March 1966 when the Corps of Engineers spilled large volumes of water at a time when spilling normally does not occur. Variables, such as spilling at upstream dams and rapid temperature increases, were eliminated; the only factor which remained that could create supersaturation was the spilling of the water. The concentration of dissolved nitrogen at Bonneville Dam before and during these spillway tests is shown in figure 2. Two replicates of samples were taken before spill and three replicates after spill at each location. Maximum variance in analysis at each location before spill was 4 percent; after spill, 6 percent. Concentrations in the forebay and below the turbines and spillway before the spill tests were near normal saturation (98–102 percent). During the spill tests, concentrations below the spill increased to 125-percent saturation, whereas concentrations in the forebay and below the turbines remained near 100 percent.

Nitrogen levels at other dams (table 2) indicated that each dam has different, characteristic effects on nitrogen saturation. The spillways at Bonneville, Grand Coulee, and Ice Harbor Dams increased the concentration of nitrogen, but the amount of the increase differed. By contrast, the spillway at Priest Rapids decreased the concentration when the water was supersaturated above the dam. Differences in the structural arrangement of the dams, shape of the spillways, and depth of tailwater are factors which could explain the differences.

EQUILIBRATION IN RESERVOIRS

Sampling throughout the length of reservoirs above Chief Joseph and McNary Dams showed that water supersaturated with dissolved nitrogen does not equilibrate during transit. In McNary Reservoir on June 8, the saturation of nitrogen that entered the reservoir from the Columbia River averaged 127 percent; samples collected in the forebay of McNary Dam on the same day averaged 127 percent. Evidently, lack of circulation and warming of the surface water in the forebay tended to maintain the saturation level.

TABLE 2.—*Average nitrogen concentrations (percentage saturation) in the Columbia River of samples taken at specific dams to determine effect of dams on water passing through turbines and over spillways (spring 1966)*

Location and date	Forebay above spill	Tail-water below spill	Forebay above turbines	Tail-water below turbines	Samples	Spill volume
	Percent	*Percent*	*Percent*	*Percent*	*Number*	*100 c.m.s.*
Bonneville:						
Mar. 10 and 11	102	125	94	98	8	28.3–42.5
The Dalles:						
Feb. 27–Mar. 2	103	104	102	97	12	1–33.7
Ice Harbor:						
May 16 and 18	109	118	107	105	8	.5–0.8
Priest Rapids:						
May 25 and 31	131	114	121	--------	8	1.9–2.4
Grand Coulee:						
Apr. 27	105	129	105	105	4	.7

SEASONAL AND DAILY VARIATIONS IN SATURATION OF DISSOLVED NITROGEN

As expected, variations of dissolved nitrogen concentrations from Grand Coulee Dam to the estuary depended largely on the volume of water released over the spillways. Nitrogen saturation in February, March, and April of 1966 was below 110 percent except below dams where intermittent spilling occurred. On February 9, when no dams were spilling (table 3), all samples had saturation below 105 percent (fig. 3). The concentrations in March were nearly the same except below the Bonneville spillway where spilling was minimal. Saturation of dissolved nitrogen remained below 110 percent through April except in areas of spilling. Streams began to rise in April, and spill releases became regular at all dams by early May. Surface concentrations of nitrogen were over 110 percent at all stations except in the forebay of Grand Coulee and The Dalles Dams. The highest concentration in May (132 percent) was downstream from the spillway at Bonneville Dam. Temperature on May 9 ranged from a low of 8.5° C. (47.3° F.) in the forebay of Chief Joseph Dam to a high of 15.3° C. (59.5° F.) in the forebay of Grand Coulee Dam.

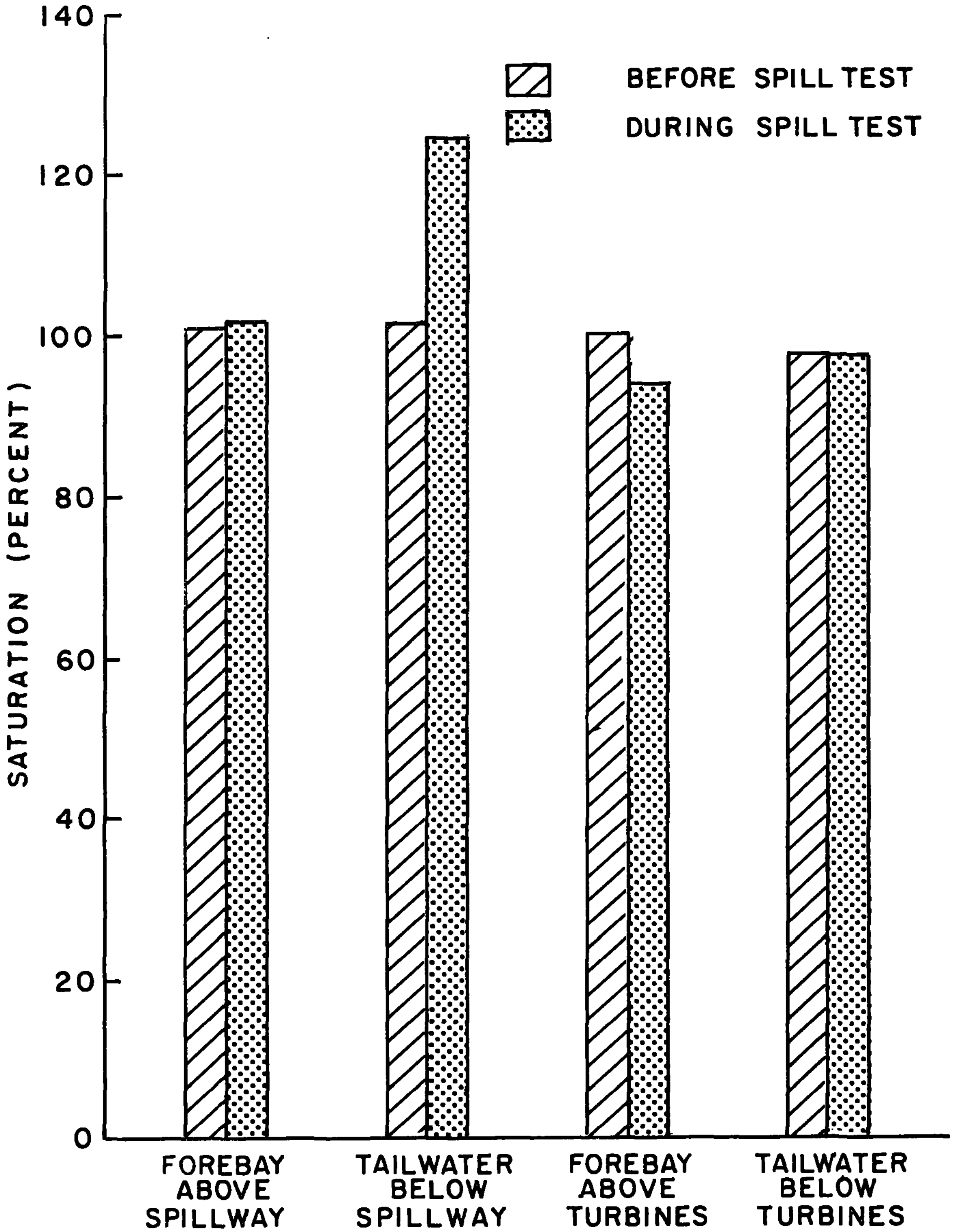

FIGURE 2.—Percentage saturation of dissolved nitrogen in 32 samples taken near Bonneville Dam before and during spill tests, March 3–11, 1966.

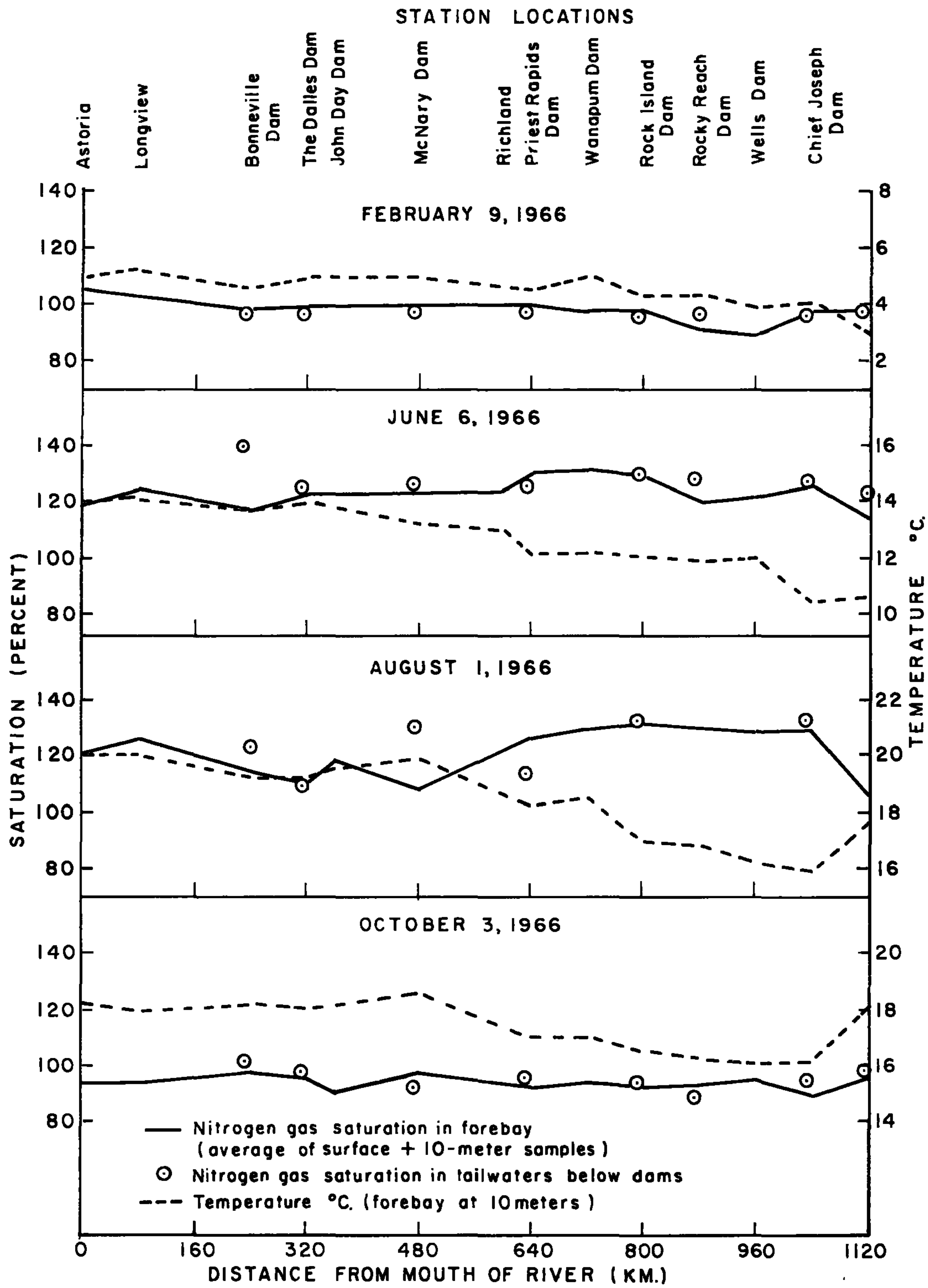

FIGURE 3.—Saturation of dissolved nitrogen and temperature of samples in Columbia River from Astoria to Grand Coulee Dam, February to October 1966.

TABLE 3.—*Mean daily spill (S.) and total flow (T.), in 100 c.m.s. (hundreds of cubic meters per second), at different Columbia River dams, February–November 1966*

Dam	Feb. 9		Mar. 7		Apr. 6		May 9		June 6		July 1		Aug. 1		Sept. 6		Oct. 3		Nov. 7	
	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.	S.	T.
										100 c.m.s.										
Grand Coulee	0.0	21.8	0.0	21.9	0.0	17.5	19.4	47.2	55.1	74.7	49.7	66.3	22.4	42.9	0.0	19.5	0.0	21.0	0.0	18.4
Chief Joseph	.0	23.2	.0	26.1	.0	15.1	28.8	47.5	60.3	77.9	48.1	71.1	20.7	41.4	.0	22.6	.0	20.6	.0	16.5
Rocky Reach	.0	23.7	.0	22.4	.0	16.5	------	52.0	------	78.1	------	68.5	------	43.6	.0	22.0	.0	20.1	.0	17.5
Rock Island	.0	24.3	.0	23.2	.0	17.4	------	57.7	------	83.5	------	73.3	------	45.4	.0	22.3	.0	20.5	.0	17.5
Wanapum	.0	24.7	.0	27.1	.0	19.4	17.1	54.3	46.0	80.8	31.9	69.2	1.9	44.8	.0	23.1	.0	23.5	.0	22.1
Priest Rapids	.0	25.4	.0	26.9	.0	19.4	21.9	56.2	46.8	81.4	36.3	70.3	36.2	35.7	.0	23.2	.0	23.6	.0	21.5
Ice Harbor	.0	7.1	.0	19.3	.0	19.3	19.3	30.9	9.7	21.0	.0	7.2	.0	6.1	.0	6.2	.0	4.5	.0	6.1
McNary	.0	31.7	.0	26.4	.0	42.8	50.7	91.4	56.7	99.4	41.7	79.1	11.1	54.1	.2	24.6	.0	25.3	.0	25.7
The Dalles	.0	33.0	.0	27.1	.0	46.4	43.4	84.1	60.3	101.0	39.3	80.3	11.5	57.6	.0	26.7	.0	25.3	.0	26.2
Bonneville	.0	33.7	.0	24.3	.0	44.9	59.6	86.5	67.8	99.6	47.3	80.1	23.8	56.6	.0	27.8	.7	26.1	.0	26.6

The highest nitrogen saturation during 1966 occurred in June. Concentrations ranged from 112 to 140 percent; most of the samples were above 120 percent (fig. 3). These values remained high through August between Grand Coulee and Priest Rapids Dams. On July 11 and August 1, however, the river equilibrated rapidly between Priest Rapids and McNary Dams. Concentrations in the forebays dropped from an average of 132 percent at Priest Rapids Dam to an average of 109 percent at McNary Dam. Spilling at Bonneville Dam then increased the saturation to above 120 percent downstream from Bonneville. The rapid equilibration of gas content between Priest Rapids and McNary Dams during July and August was probably caused by the increased circulation of water in the unimpounded river area below Priest Rapids and the lower total flow and spill volumes at Priest Rapids and Ice Harbor Dams (table 3).

In September, Columbia River flows had decreased further and spilling had almost ceased at all dams; this change precipitated a marked reduction in the saturation of nitrogen at all stations—only five samples were above 110 percent. Saturation continued to decrease in October and was well below 110 percent—ranging from 88.4 percent at Rocky Reach Dam to 100.6 percent at Grand Coulee Dam. Water temperatures in October ranged from 16.1° to 18.6° C. (60.8–65.5° F.), and the average temperature was about 1° C. lower than in September. The lack of spilling and lower water temperatures accounted for the decrease in saturation from August to September.

In the last survey during 1966, on November 7, the saturation was not significantly different from that in October 1966 (or November 1965).

DIURNAL VARIATIONS

During a 24-hour period (June 30 and July 1, 1966) of moderately high saturation in the forebay of The Dalles Dam, nitrogen concentrations varied only 0.6 p.p.m. from a maximum of 18.6 p.p.m. (114 percent saturation). Spill volumes at The Dalles Dam were nearly constant for the 24-hour period.

SEASONAL VARIATIONS IN THE SNAKE RIVER

Samples from the tailrace below the spillway of Ice Harbor Dam in the Snake River (station 15) indicated a seasonal variation in amount of nitrogen similar to that in the Columbia River; i.e., normal saturation before spill releases increased saturation as spill releases increased and decreased saturation as spill releases subsided. The timing of the cycle differed from that in the Columbia River, as spilling at Ice Harbor Dam usually began in late April, peaked about mid-May, and ended by mid-June. Thus, the net effect of the Snake River discharge on saturation in the Columbia River was to increase the amount of nitrogen in late April and May and decrease it in June, July, and August.

COMPARISION OF 1966 AND 1967

Saturation of dissolved nitrogen in 1967 followed the same general seasonal changes as in 1966. Values were normal in winter and early spring before the dams began spilling, but rose as spilling increased. Levels again were highest in June and July when the largest volume of water passed through the spillways. When spilling ceased and cooling of the river began in September and October, saturation decreased sharply (fig. 4).

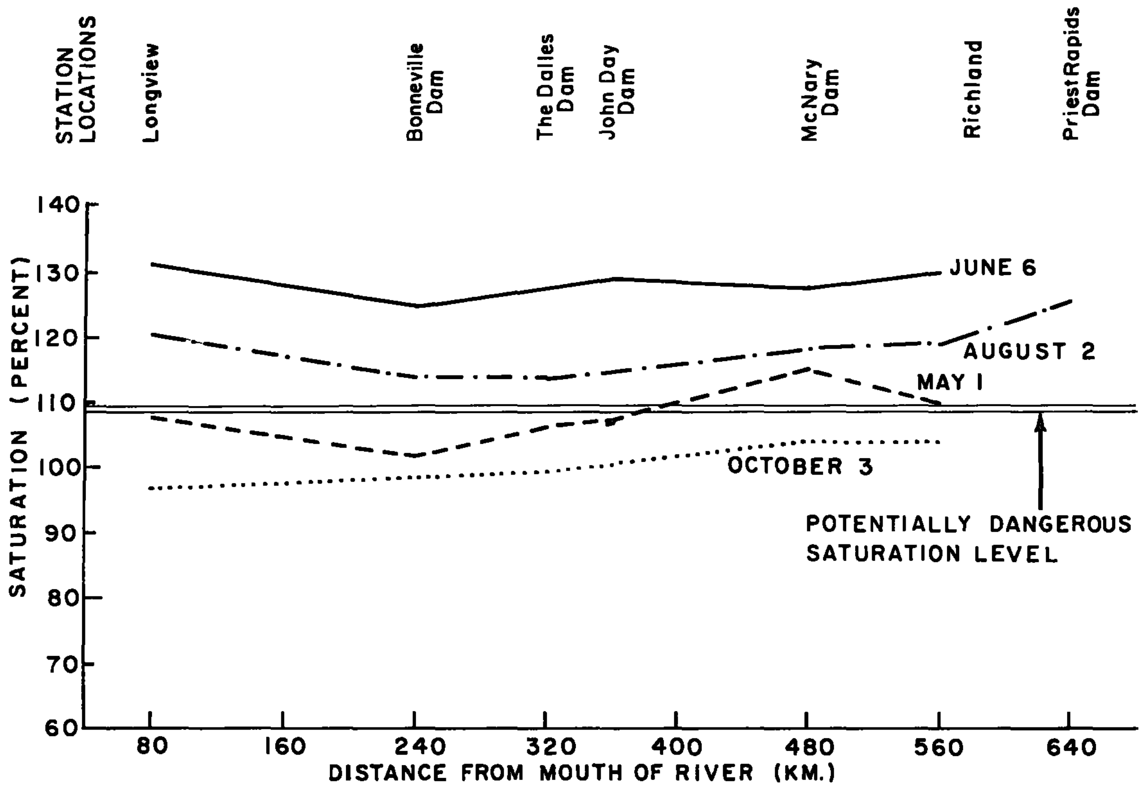

FIGURE 4.—Saturation values of dissolved nitrogen in samples of Columbia River water taken from Longview, Wash., to Priest Rapids Dam, May 1, June 6, August 2, and October 3, 1967. (Values shown are the averages of the surface and 10-m. sample at each location.)

Saturation in May 1967 (102–115 percent) was considerably lower than in May 1966 (110–133 percent) because spillway releases in 1967 were not significant on the main Columbia until late May. By mid-June 1967, however, extremely high spillway releases brought even higher saturations than were recorded in 1966.

In 1966–67 the saturation of dissolved nitrogen over a large area of the river was sufficiently high and of sufficient duration (middle to late May through mid-August) to be a potential danger to migrating juvenile and adult salmon and trout. Experiments by Westgard (1964) showed that adult chinook salmon held in water with concentrations of dissolved nitrogen at 116 percent saturation developed definite symptoms of gas bubble disease. Harvey and Smith (1962) indicated that saturation as low as 108 percent produced gas bubble disease in fingerlings at Cultus Lake Trout Hatchery. These values were much lower than those recorded in the Columbia River. The fish were held in shallow ponds or raceways, however, whereas fish in the Columbia River are usually able to move to greater (compensating) depths, except when they are ascending fishways. The ability of fish to seek compensating depths must be taken into account in the assessment of the effect of high saturation of nitrogen in the Columbia River.

EFFECT OF SUPERSATURATION OF DISSOLVED NITROGEN ON SALMON IN THE COLUMBIA RIVER

Studies of supersaturation of nitrogen in 1967 were made in conjunction with tagging studies designed to determine the cause of loss of adult fish during their migration from Bonneville to Ice Harbor and Priest Rapids Dams.[3] The primary purpose in 1967 was to determine the effect of dissolved nitrogen on juvenile and adult salmon and steelhead known to be in the river when concentrations of dissolved nitrogen were high.

[3] Tagging study in progress by Bureau of Commercial Fisheries, Seattle, Wash.—James H. Johnson, Program Leader.

JUVENILE SALMON

Examination of juvenile chinook salmon that suffered excessive mortality in holding tanks (used for marking fish) at Priest Rapids Dam in 1966 revealed that most fish had symptoms of gas bubble disease. Although the fish otherwise appeared to be sound, they were definitely distressed and, if held, eventually died from gas embolism. Dissolved nitrogen concentrations at Priest Rapids Dam ranged from 114 to 133.9 percent saturation. Temperature in the gatewells of the dam from which fish were collected ranged from 13.9° C. (57° F.) on July 7 to 17.8° C. (64.0° F.) on August 31 when operations ceased. The water temperature in the holding tanks usually rose about 1° to 2° C. before marking began. This slight increase was sufficient to liberate enough gas from the blood of the fish to cause embolism and death. The symptoms of gas bubble disease and distress were eliminated if these fish were held in water slightly cooler than that in the river where they were collected. Usually a decrease of 1° or 2° C. was sufficient to reduce the mortality.

Apparently, juvenile chinook salmon, equilibrated to supersaturation of nitrogen in this temperature range, have considerably less tolerance to increases in temperature than fish that are equilibrated to normal saturation. Brett (1952) in his studies of the tolerance range of juvenile salmon to temperature changes showed that spring chinook salmon acclimated to 10° C. (50° F.) could tolerate temperatures up to 24.5° C. (76.1° F.) before mortalities began. The fish at Priest Rapids Dam, which were acclimated to higher temperatures (13.9–17.8° C.), could not tolerate increases of 1° to 2° C.

It was apparent from observations at Priest Rapids Dam that juvenile migrants were in a precarious situation in July and August. If they did not remain at sufficient depth to compensate for the supersaturation of dissolved nitrogen, they died of gas bubble disease. Their tolerance to temperature increases was also lowered; conceivably sudden temperature increases of only a few degrees centigrade would have caused mortality.

We conducted an experiment in the forebay of Priest Rapids Dam to determine the depth at which juvenile fish must remain to avoid gas bubble disease when subjected to supersaturation of nitrogen. Juvenile coho (*O. kisutch*) and chinook salmon were held in pens submerged at different depths in the forebay and then observed by SCUBA divers at various intervals for symptoms of gas bubble disease. Three tests from 200–280 hours' duration were conducted from May 28 to August 14, 1967, a period when saturation of dissolved nitrogen changed from a high of 143 percent in late May and June to 118 percent in August. Hatchery-reared coho salmon were used in tests 1 and 2 and wild chinook in test 3. One hundred fish were placed in each test cage and in a control cage held in river water of normal saturation at the dam. The first observation was made about 12 hours after placing the cages at the selected depths in the forebay. Other observations were made at 24-hour intervals for the first 4 days; the time between observations was increased thereafter, depending on rate of mortality. Dead fish were brought to the surface by divers and examined for symptoms of gas bubble disease. Neither test nor control fish were fed during the tests. In one test 100 percent of the coho salmon in a surface pen and 70 percent in a pen lowered to a depth of 2 to 3 m. died from gas bubble disease (fig. 5). Three percent was the maximum mortality for control fish held during the test. The experiment showed that at 130 to 140 percent saturation fish must remain below 2.5 m. if they are to be free of symptoms of gas bubble disease. From

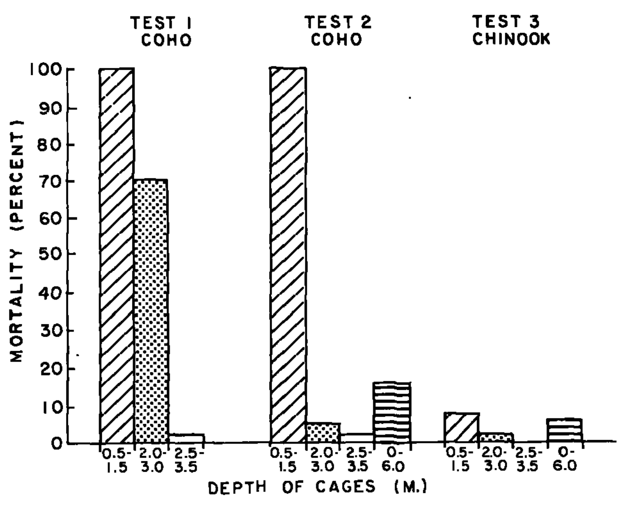

FIGURE 5.—Percentage mortality caused by gas bubble disease during holding experiment in forebay of Priest Rapids Dam May 28 to August 14, 1967. Saturation of dissolved nitrogen ranged from 143 percent in test 1 to 118 percent in test 3: fish were held about 200 hours in tests 1 and 2,280 hours in test 3.

6 to 16 percent of the coho and chinook salmon died in a pen which allowed the fish to seek any depth from the surface to 6 m., which suggested that some mortality may also have occurred to naturally migrating fingerlings even though they could move to any depth.

These field observations of juvenile migrants, though limited, indicate that naturally migrating juvenile fish in the Priest Rapids Dam area are under stress from supersaturation of dissolved nitrogen; it is highly probable that a significant percentage of the fish is lost. The Hanford area of the river downstream from Priest Rapids is of particular concern. Juvenile and adult salmon already under stress must pass areas where thermal reactors emit large volumes of water with temperatures 10° to 15° C. higher than the river temperatures. Obviously, fish under stress from supersaturation of gases have less tolerance to rapid temperature increases, and losses of fish which inadvertently enter the thermal plumes are inevitably high. Further investigation seems imperative on the effect of supersaturation of dissolved nitrogen on the tolerance of salmon to temperature increases.

ADULT SALMON AND STEELHEAD TROUT

About 2,300 adult chinook salmon, 1,600 steelhead trout (*Salmo gairdneri*), and 1,000 sockeye salmon (*Oncorhynchus nerka*) were examined at Bonneville and McNary Dams from mid-April through mid-October 1967 for external symptoms of gas bubble disease. The external symptoms that were used to indicate gas bubble disease were (1) gas bubbles under skin, in roof of mouth, and in fin membranes and (2) hemorrhaging inside the eye and the associated "pop eye" condition of the eyeball. Nitrogen saturation was measured at both dams so that the incidence of disease symptoms could be correlated with the saturation of nitrogen.

Examination of the adult salmon and steelhead trout began on April 11 when saturation was about 106 percent and continued until May 25 when saturation was near 120 percent. Because nitrogen saturation did not exceed 110 percent until May 10, little incidence of gas bubble disease was expected; 1 of 125 steelhead trout examined showed symptoms of the disease (on May 25).

Observations of adult fish at McNary Dam began on June 23 and ended October 11. Nitrogen saturation ranged from 131 percent in June to 104 percent in October. Saturation was high (above 120 percent) from June 23 to July 19 but began to drop sharply after July 19; by August 22, values were below 110 percent. In July, symptoms of gas bubble disease were noted in 10 of 1,000 sockeye salmon, but none were observed in 1,762 chinook salmon and 1,461 steelhead trout. Apparently, chinook salmon and steelhead trout in this area either compensated for the high saturation by remaining at a sufficient depth or the symptoms of the disease had not progressed sufficiently to be evident.

Surveys for carcasses of adult fish were made from April to October during each flight made to obtain water samples. Four additional aerial surveys for carcasses were made during June and July when saturation was highest. Carcasses of eight dead salmon (and a few unidentified fish) were observed; however, it could not be positively verified that any of these fish had died from gas bubble disease. Generally, the fish were too decomposed for determination of cause of death.

Steelhead trout and chinook salmon were observed (June 15 to September 19) congregating in the Columbia River at its confluence with the Snake River. Saturation of dissolved nitrogen in the Columbia ranged from 110 to 130 percent, and temperatures in the Snake River were as much as 5.7° C. (10.3° F.) higher than in the Columbia (table 4). Fish equilibrated to supersaturation of dissolved nitrogen in the Columbia could have died from gas embolism if they had entered the Snake River at this time. A concentrated search on the surface by boat and on the bottom with SCUBA did not yield carcasses of any salmon whose death

TABLE 4.—*Temperature (° C.) and percentage saturation of dissolved nitrogen in the Columbia and Snake Rivers at the mouth of the Snake River—June 6 to Sept. 5, 1967*

Date	Columbia River at mouth of Snake River		Snake River at mouth	
	Temperature	Saturation of dissolved nitrogen	Temperature	Saturation of dissolved nitrogen
	° C.	*Percent*	*° C.*	*Percent*
June 6	13.2	130	12.2	126
June 27	14.2	129	16.3	123
July 5	16.6	129	19.4	113
July 19	17.0	126	22.2	----------
July 27	18.4	120	23.0	109
Aug. 2	19.1	119	23.7	111
Aug. 9	19.3	118	25.0	108
Aug. 15	21.0	118	24.7	106
Aug. 30	20.3	118	23.5	103
Sept. 5	21.2	110	23.3	105

could be attributed to gas bubble disease or gas embolism. A study of the movement of these fish indicated that many did not reach Ice Harbor Dam.[4] The destination or fate of these fish was not determined.

We have no positive evidence to indicate that the high nitrogen saturation in the Columbia River in 1967 caused serious mortality of adult salmon, but the possibility cannot be discounted. From the surveys and searches made in 1967 it was obvious that it would be difficult to detect a continuous low rate of mortality in a river the size of the Columbia even with continuous surveillance. Various reports of mortality were received from local residents, but again it could not be established that fish had died from gas bubble disease.

SUMMARY AND CONCLUSIONS

A seasonal cycle of supersaturation of dissolved nitrogen occurs each year in the Columbia River. Degree of supersaturation varies with flow of water over spillways of dams. Levels are normal (near 100-percent saturation) in the fall and winter when little or no spilling takes place and high (above 120 percent) in the spring and summer when large volumes of water are being spilled. Water plunging over spillways is the primary cause of supersaturation in the Columbia River.

Water supersaturated with nitrogen does not equilibrate rapidly in reservoirs. Lack of circulation and increases in surface water temperature tend to slow the rate of equilibration. Saturation of dissolved nitrogen in the Columbia River is sufficiently high and occurs over a large area over a sufficiently long time to be potentially dangerous to salmon and steelhead trout. Observations of juvenile salmon at Priest Rapids Dam indicate that supersaturation of nitrogen offers a definite problem; further study is needed to determine its extent.

Field observations to determine the effect of high levels of dissolved nitrogen on adult salmon and steelhead trout were not conclusive. Some sockeye salmon and steelhead trout were observed with symptoms of gas bubble disease, but no chinook salmon had symptoms. A potential problem exists for adult salmon and trout migrating from the Columbia River into the Snake River in July and August. Fish equilibrated to supersaturation of nitrogen from the Columbia River encounter an increase of 5° to 6° C. in temperature on entering the Snake River. The tolerance of the salmon to this temperature change under those conditions is unknown.

[4] Percentage of tag returns from fish subjected to these conditions was about 50 percent lower than returns from other groups passing over Ice Harbor Dam. (Verbal communication, Gerald Monan, BCF Biological Laboratory, Seattle, Wash.)

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LITERATURE CITED

BRETT, J. R.
1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J. Fish. Res. Bd. Can. 9: 265–323.

HARVEY, H. H., and A. C. COOPER.
1962. Origin and treatment of a supersaturated river water. Int. Pac. Salmon Fish. Comm., Progr. Rep. 9, 19 pp. [Processed.]

HARVEY, H. H., and S. B. SMITH.
1962. Supersaturation of the water supply and occurrence of gas bubble disease at Cultus Lake trout hatchery. Can. Fish Cult. 30: 39–47.

RUCKER, R. R., and K. HODGEBOOM.
1953. Observations on gas-bubble disease of fish. Progr. Fish-Cult. 15: 24–26.

SWINNERTON, J. W., V. J. LINNENBOM, and C. H. CHEEK.
1962. Determination of dissolved gases in aqueous solutions by gas chromatography. Anal. Chem. 34: 483–485.

WESTGARD, RICHARD L.
1964. Physical and biological aspects of gas-bubble disease in impounded adult chinook salmon at McNary spawning channel. Trans. Amer. Fish. Soc. 93: 306–309.

WOODBURY, LOWELL A.
1942. A sudden mortality of fishes accompanying a supersaturation of oxygen in Lake Waubesa, Wisconsin. Trans. Amer. Fish. Soc. 71: 112–117.

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