MFR PAPER 1191

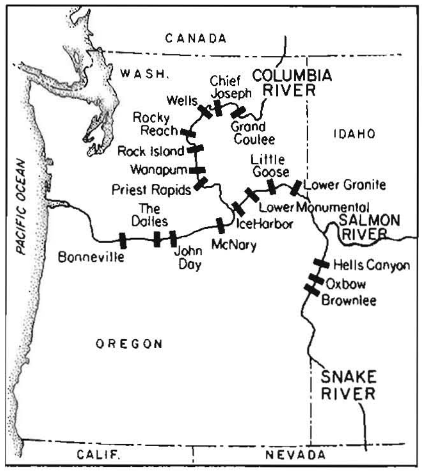


Figure 1.—Main stem dams in the Columbia River Basin.

Effect of Atmospheric Gas Supersaturation on Salmon and Steelhead Trout of the Snake and Columbia Rivers

WESLEY J. EBEL and HOWARD L. RAYMOND

ABSTRACT—Laboratory and field research data defining the effects of supersaturation of atmospheric gas on fish (primarily salmonids) in the Columbia River are summarized. Recent bioassay information regarding effects of various levels of supersaturation on several species of salmonids are compared with observations obtained in the river. The severity of the effect of supersaturation was dependent on level of supersaturation, the duration of exposure, water temperature, general physical condition of the fish, and the swimming depth maintained by the fish. Mortality caused by supersaturation was estimated for each of several years from 1966-74.

INTRODUCTION

Dams constructed on the Columbia and Snake Rivers in the past decade have impounded most of the free flowing sections of these rivers and created a water condition that in high-flow years is deadly to valuable stocks of anadromous Pacific salmon, *Oncorhynchus* spp., and steelhead trout, *Salmo gairdneri*. With high spills, the water becomes supersaturated with atmospheric gases to a level that is lethal to fish. In response to this problem, a major research effort is in progress which seeks to define the effects of supersaturation on fish and to develop methods of reducing supersaturation caused by dams. This report summarizes the present status of the research and the relation of our current information to the anadromous resources of the Columbia River.

Wesley J. Ebel and Howard L. Raymond are with the Northwest Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. East, Seattle, WA 98112.

Salmon and steelhead resources of the Columbia River have in the past produced as much as 50 million pounds of fish in one year for consumption. Today, production is estimated at between 25 and 30 million pounds. Even in today's depressed state, the contribution of the Columbia River resources to our commercial and recreational fisheries is of a magnitude far greater than most people realize.

Columbia River salmon and steelhead represent an annual value of $22.5 million to commercial fishermen, and nearly $77.2 million at the retail level. An average of 42 percent of the chinook salmon, *O. tshawytscha*, and 73 percent of the steelhead trout taken annually by the United States commercial fisheries are of Columbia River origin.

The great majority of Columbia River fish are affected by the huge dams built for hydroelectric power, navigation, irrigation, and flood control. The upper river runs, because they must pass through a long sequence of dams (Fig. 1), are most severely affected. This review addresses itself to the salmon and steelhead trout runs of the Snake River where we have our most complete information, but it is logical that the conclusions apply as well to the stocks of the upper Columbia River and to a lesser degree, to the runs entering the Columbia River below the Snake River.

SUPERSATURATION OF NITROGEN: ITS SOURCE AND ITS EFFECT ON FISH

Supersaturation of nitrogen (atmospheric gas) was first recognized as a potential problem to anadromous fish in the Columbia River in 1965 when levels as high as 125 percent of saturation were recorded. A comprehensive study (Ebel, 1969) of dissolved gas levels done in 1966-1967 throughout the Columbia from Grand Coulee Dam to the estuary at Astoria, Oreg. substantiated that high levels of dissolved gases occurred throughout the study area (Fig. 2) during the spring and early summer when high flows occur. The study also showed that water plunging over spillways was the main cause of supersaturation and that little equilibration occurred in the reservoirs associated with the dams.

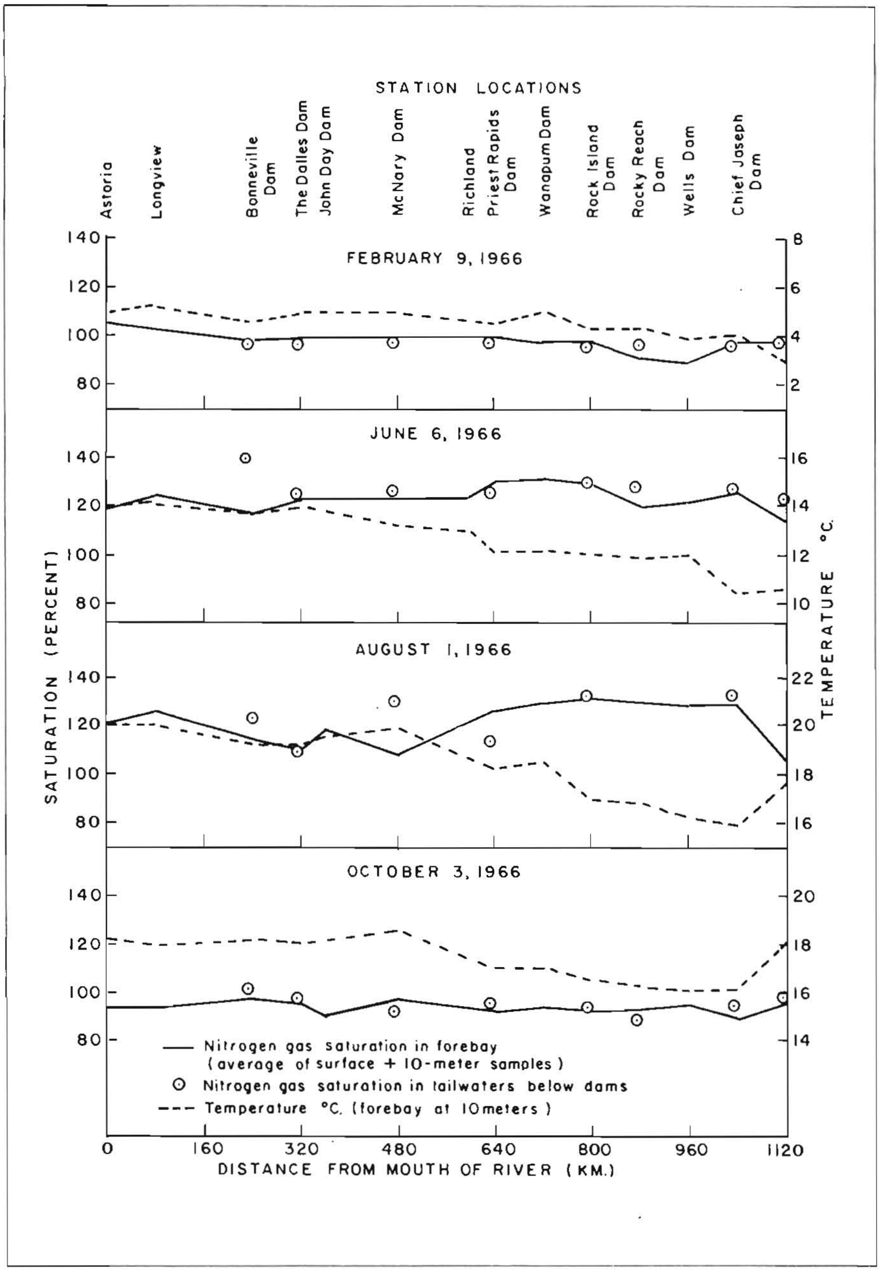


Figure 2.—Saturation of dissolved nitrogen and temperature of samples in Columbia River from Astoria to Grand Coulee Dam, February to October 1966. (Source: Ebel, 1969.)

Subsequent studies conducted by Roesner and Norton [1] (1971) and Meekin and Allen (1974) substantiated the earlier data of Ebel. Sufficient data are now available to establish air entrainment coefficients and rating curves for most of the dams on the Columbia and Snake Rivers; reasonably accurate predictions of the level of supersaturation that might occur downstream from a given dam during a specified flow are now possible. Thus, the mechanisms involved in creating supersaturation in the Columbia and Snake Rivers are at this time well understood.

A substantial impact from supersaturation of N_2 on fish populations, however, was not documented until John Day Dam was placed in operation in 1968. During the spring of that year heavy spillway discharge at the dam caused abnormally high (123-143 percent) supersaturation downstream

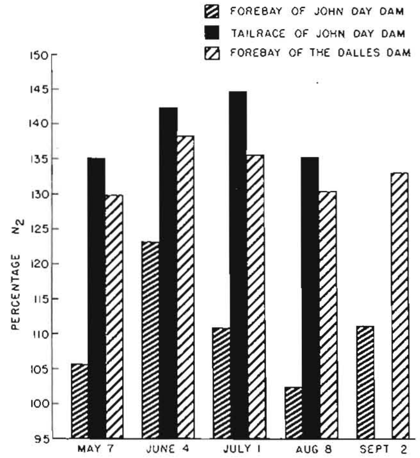


Figure 3.—Comparison of percentage saturation of dissolved nitrogen in forebay of John Day Dam with tailrace of John Day Dam and The Dalles Dam forebay, May-September 1968. (Source: Beiningen and Ebel, 1970.)

(Fig. 3) and substantial mortalities of both adult and juvenile salmonids were recorded (Beiningen and Ebel, 1970). Continued evidence that a substantial problem for both juvenile and adult salmon and steelhead existed in the Columbia drainage (Ebel, 1971; Raymond[2]) prompted a large scale research effort to 1) measure the effects of supersaturation of dissolved gases on fish and 2) develop methods of reducing levels of supersaturation caused by dams. This report summarizes most of the recent research on effects of supersaturation of dissolved gases on fish.

Effects of Supersaturation on Juvenile Salmonids

Supersaturation of atmospheric gas (mainly nitrogen) in waters of the Columbia and Snake Rivers was well documented by 1970 as a serious problem to valuable stocks of salmon and steelhead. There was sufficient evidence that gas bubble disease resultling from this supersaturation caused both direct and indirect mortalities. However, precise data on tolerance of various species of salmonids to various levels of supersaturation of atmospheric gases was unknown.

Several investigators recorded the

[1]Roesner, L. A., and W. R. Norton. 1971. A nitrogen gas (N_2) model for the lower Columbia River. Water Resources Engineers, Inc., Walnut Creek, Calif., Final Rep. to Portland Dist., U.S. Army Corps of Engineers, 88 p.

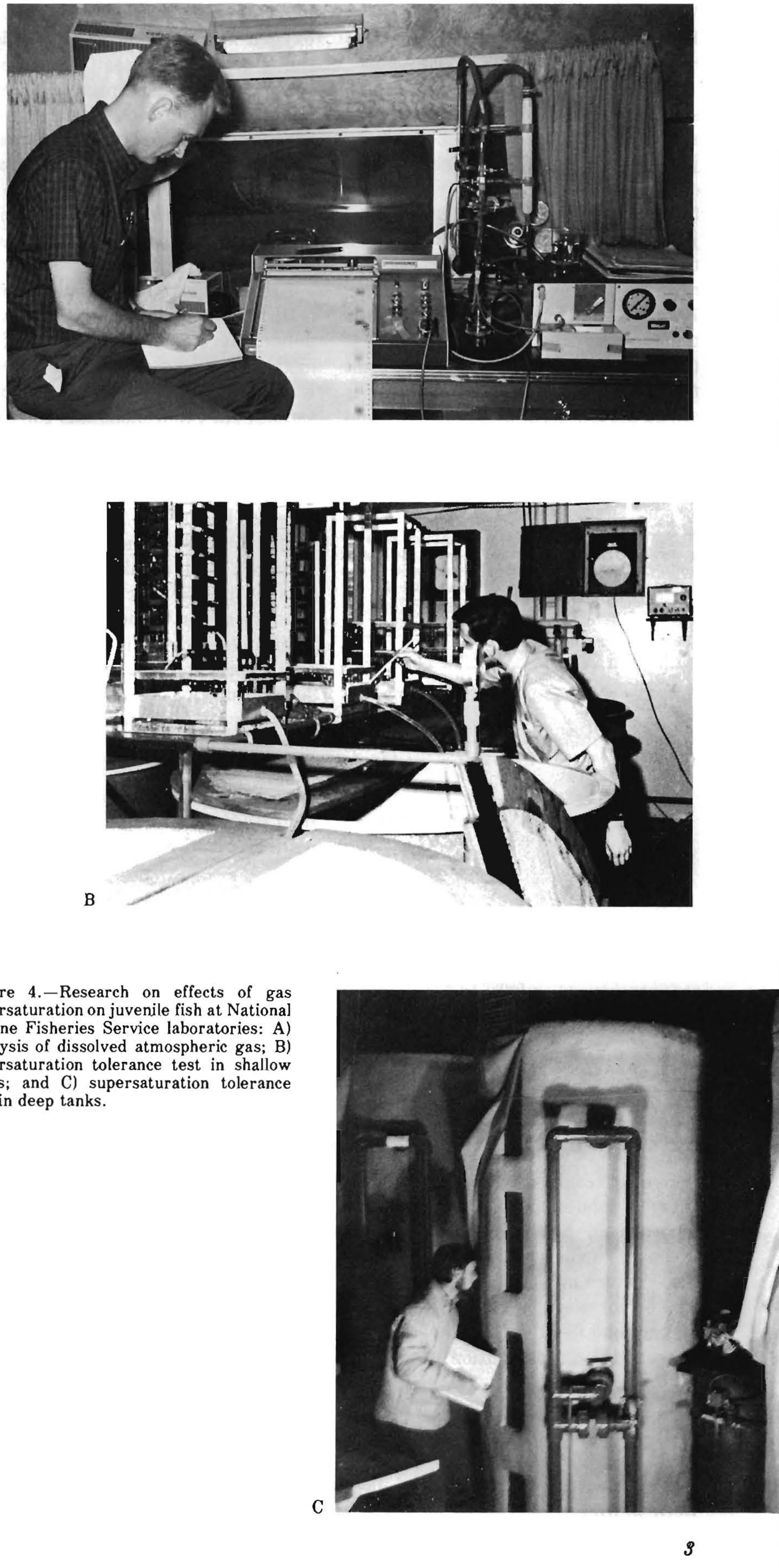
[2]Raymond, Howard L. 1970. A summary of the 1969 and 1970 out-migration of juvenile chinook salmon and steelhead trout from the Snake River. Bur. Commer. Fish. Biol. Lab., Seattle, Wash., Progress Rep. 11 p. Processed.

lowest level observed during various experiments where mortalities occurred from gas bubble disease; however, very little attention was given to determining precise tolerance levels or effect of sublethal exposure on performance. Harvey and Cooper[3] (1962) indicated 108-110 percent saturation produced gas bubble disease and subsequent mortalities in sockeye salmon alevins, *O. nerka*; Rucker and Tuttle (1948) indicated a level somewhere between 110 percent and 115 percent as being the critical range for trout. Shirahata (1966) conducted the most comprehensive study to date on the effects of various levels of nitrogen gas on rainbow trout (rainbow trout is the resident freshwater form of *S. gairdneri*, whereas the steelhead trout is the anadromous form of the species) from hatching to the swim-up stage, but such detail is lacking for other species of salmonids. In many experiments on gas bubble disease, either the water temperatures, nitrogen gas concentrations, or life stages of the test fish were omitted from the record, thus making the results incomplete for critical applications. The extent of the costs involved in alleviating the supersaturation problem in the Columbia and Snake Rivers will depend on the degree of protection required to afford a safe environment for the aquatic biota. It was imperative, therefore, that regulatory and corrective measures established to govern the level of saturation be based upon a thorough understanding of the effects of dissolved gases on aquatic organisms.

Presently available laboratory and field research data defining the effects of supersaturation on juvenile salmonids and some nonsalmonids present in the Columbia drainage are summarized here.

Laboratory Studies

Research (Fig. 4) was undertaken to define the effects of various levels of dissolved gases on several species of fish (primarily juvenile salmonids) by the National Marine Fisheries Service (NMFS), Bureau of Sport Fisheries and



A

B

C

Figure 4.—Research on effects of gas supersaturation on juvenile fish at National Marine Fisheries Service laboratories: A) Analysis of dissolved atmospheric gas; B) supersaturation tolerance test in shallow tanks; and C) supersaturation tolerance test in deep tanks.

[3] Harvey, H. H. and A. C. Cooper. 1962. Origin and treatment of a supersaturated river water. Int. Pacific Salmon Fish Comm. Prog. Rep. 9. 19 p.

Wildlife (BSFW)[4], Battelle Northwest Laboratories (BNW), and the Environmental Protection Agency (EPA).

NMFS centered their research on smolting size juvenile spring chinook and steelhead, fall chinook fry, and juvenile and adult squawfish, *Ptychocheilus oregonensis*. Dawley and Ebel (in press) found that exposure of juvenile spring chinook and steelhead to 120 percent saturation for 1.5 days resulted in over 50 percent mortality; 100 percent mortality occurred in less than 3 days. They also determined that the threshold level where significant mortalities begin occurring (Table 1) is at 115 percent saturation nitrogen and argon (111 percent total gas saturation).

Table 1.—Mean values of lethal exposure time for juvenile steelhead and spring chinook acclimated to 15°C and then subjected to various levels of gas saturation[1] from 100 to 125% in shallow (25 cm depth) tanks. (From Dawley and Ebel, 1975.)

Percent mortality	Percent saturation (N_2 + Ar)	Hours exposure: Steelhead	Hours exposure: Chinook
10	125	10.3	10.6
50		14.2	13.6
100		[2]23.0	[2]32.1
10	120	26.0	19.3
50		33.3	26.9
100		[2]40.0	[2]55.0
10	115	[2]258.0	7% mortality in 792 h
50		[2]486.0	Not reached
100		Not reached	Not reached
	110, 105, 100	Mortality of 5% or less recorded for either steelhead or chinook after 35 days at these concentrations. Gas bubble disease was not apparent cause of deaths.	

[1] Percentage saturation of nitrogen and argon was set as indicated in the table (±2%). Oxygen concentrations ranged between 87 and 98% saturation in tanks set at 100-110% nitrogen plus argon saturation; in tanks set at 115-125% nitrogen saturation, O_2 levels ranged between 98 and 115%.

[2] Exposure times indicated for test replicates of section A only. Mortality in section B had not reached indicated level at termination of test.

Similar results on mortality rates of juvenile coho salmon, *O. kisutch*, were obtained in bioassays conducted by Nebeker[5] and Rucker (1975). Rucker also determined that smaller coho (3.8-6 cm) were more resistant than larger coho (8-10 cm) at the same gas concentration. In addition, he determined the effect of individual ratios of oxygen and nitrogen and established that a drastic decrease in lethal effect occurred when the nitrogen content fell below 109 percent saturation even though total gas saturation remained at 119 percent saturation, indicating the importance of determining the concentration of the individual components (O_2 and N_2) of the atmospheric supersaturation.

An additional study was done by NMFS in 1974 to more accurately define the benefit that stocks of fish might receive by sounding into deeper water levels (hydrostatic compensation). An experiment was conducted where juvenile fall chinook salmon and steelhead mortality rates could be compared when they were exposed to various levels of N_2 in deep and shallow tanks. This study (Dawley, Schiewe, and Monk, 1976) showed that by providing chinook and steelhead the option to sound in deep tanks, their ability to survive was increased, particularly at the lower levels of supersaturation. However, substantial mortality still occurred in fish tested in deep tanks when the concentrations exceeded 120 percent (Fig. 5). It is apparent from this study and similar field studies that depth of migration or hydrostatic pressure must be considered when estimating probable loss from N_2 for fish populations migrating in the Columbia or Snake River. Calculations of estimated mortality discussed later in this report take this into consideration.

Sublethal Exposure

Experiments were conducted by Schiewe (1974), Weber and Schiewe (1976), and Newcomb (1975) to determine the effect of sublethal exposure of juvenile steelhead and chinook to supersaturated water. Effect of sublethal exposure on swimming performance, growth, lateral line function, and blood chemistry was measured. These experiments showed that swimming performance of chinook and lateral line function of steelhead were adversely affected by sublethal exposure to various levels of supersaturated atmospheric gas. Blood chemistry measurements showed altered characteristics in albumen, calcium, phosphates, potassium, and chloride levels after exposure to supersaturated water. These data suggest that survival of juvenile populations stressed to a sublethal level by exposure to supersaturated water would be lower than normal, particularly in a river environment like the Columbia where numerous hazards are encountered.

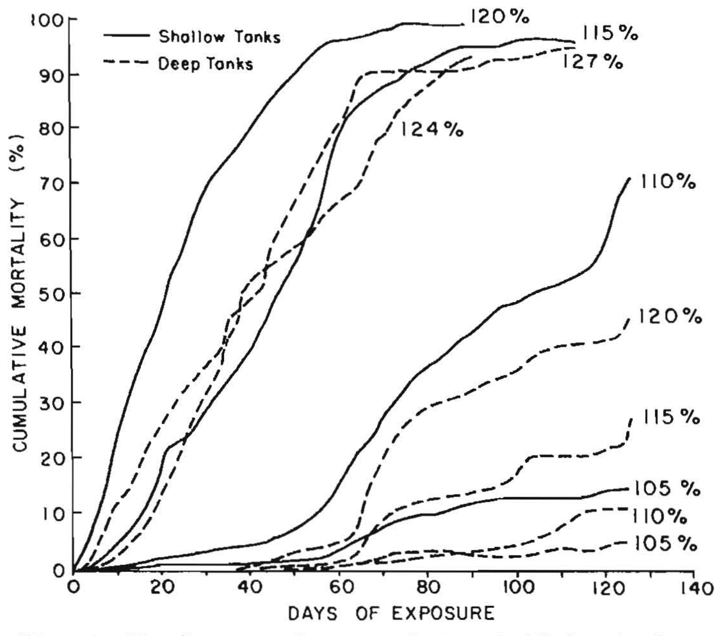


Figure 5.—Mortality versus time curves for juvenile fall chinook salmon exposed to various concentrations of dissolved atmospheric gas (percent of saturation TDG) in shallow (0.25 m) and deep water (2.5 m) tanks at 10°C. (Source: Dawley et al., 1976.)

[4] This agency is now the U.S. Fish and Wildlife Service (FWS).

[5] Nebeker, Alan V. 1973. Effect of nitrogen (air) supersaturation on Columbia River fishes. Environ. Prot. Agency, Western Fish Toxicol. Sta., Corvallis, Oreg. Annu. Prog. Rep. 1973, ROAP 21 AKG.

Field Studies

Numerous field studies have been conducted by state, federal, and private fishery research groups to obtain information on effect of supersaturation of atmospheric gas on juvenile salmonids in the Columbia and Snake Rivers. Live cage, migration rate, timing, and survival studies were of particular significance because they have been done over a range of river conditions for several consecutive years. Incidence of symptoms of gas bubble disease in juvenile migrants arriving at Ice Harbor and The Dalles Dams was also determined for several years. Data are therefore available from studies done during periods of low, intermediate, and high levels of supersaturation.

Live Cage Studies. The first live cage studies conducted in the middle Columbia River (Ebel, 1969) indicated that 6-16 percent mortality occurred in populations of juvenile coho and chinook held in a deep (surface to 6 m) cage when concentrations of N_2 ranged from 118 to 143 percent. Mortality ranged from 10 to 100 percent in fish held in shallow cages (surface to 1 m deep). Similar tests done in the lower Columbia River (The Dalles forebay) by Beiningen[6] and Ebel in 1969 resulted in a mortality range for juvenile fall chinook of 25-30 percent in the deep cage and 95-100 percent in shallow cages. At this time N_2 concentrations ranged from 126 to 145 percent of saturation. Another live cage test done later by Ebel (1971) in the forebay of Ice Harbor Dam on the Snake River resulted in a range of mortality from 45 to 68 percent in the deep cage where fish could sound to 4.5 m. In these tests both hatchery and wild stocks of juvenile spring and fall chinook were used as test animals. Nitrogen concentrations ranged from 127 to 134 percent of saturation.

Finally, a similar live cage test was again conducted in the Wanapum area of the Columbia in 1974 by Weitkamp[7]. No mortality occurred in his deep cage, but nitrogen levels never exceeded 126 percent during these tests.

It is obvious from these live cage studies that various levels of mortality occur depending on the location, level of nitrogen supersaturation, and stock of fish used. Of particular significance, however, is the fact that substantial mortalities occurred even in the deep cages, which allowed fish to sound when concentrations exceeded 125 percent saturation. Nearly 100 percent mortality occurred in surface cages used in all the tests.

Similar studies were conducted by Blahm, McConnell, and Snyder[8], 1973. In these studies, ambient Columbia River water was pumped into 1-m and 3-m deep tanks, and mortality was recorded as dissolved gas concentrations in the river changed from a low of about 106 percent in April to a high of 130 percent in June. Substantial mortality of both juvenile chinook and coho salmon occurred in the shallow (1-m) tank; in the deep (3-m) tank, mortality did not begin until dissolved nitrogen concentrations approached 125 percent near the termination of the test in June. Nitrogen concentrations did not exceed 125 percent saturation except for about one day at the termination of the test. These data substantiate other laboratory and field data where high

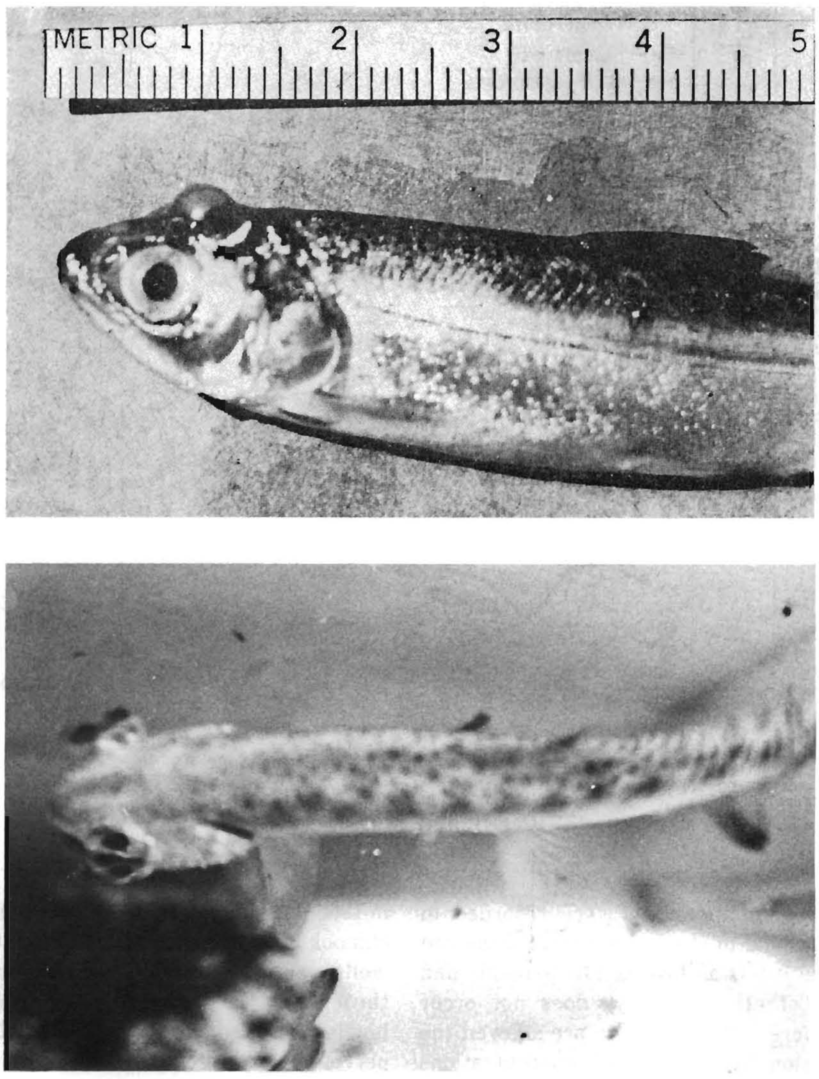


Figure 6.—Gas bubble disease symptoms observed on juvenile fish sampled at The Dalles Dam. Above, gas blister on juvenile coho salmon (photo from Beiningen and Ebel, 1970). Below, bilateral exophthalmia on juvenile chinook salmon.

[6]Kirk T. Beiningen, presently employed by the Oregon Dept. of Fish and Wildlife, Clackamas, Oreg.

[7]Donald E. Weitkamp, Parametrix Inc., Seattle, Wash. Unpubl. data.

[8]Blahm, Ted H., Robert J. McConnell, and George R. Snyder. 1973. Effect of gas supersaturated Columbia River water on survival of juvenile salmonids April-June 1972. Natl. Mar. Fish. Serv., NOAA, Prescott, Oreg. Final Rep., Pt. I. 61 p. Processed.

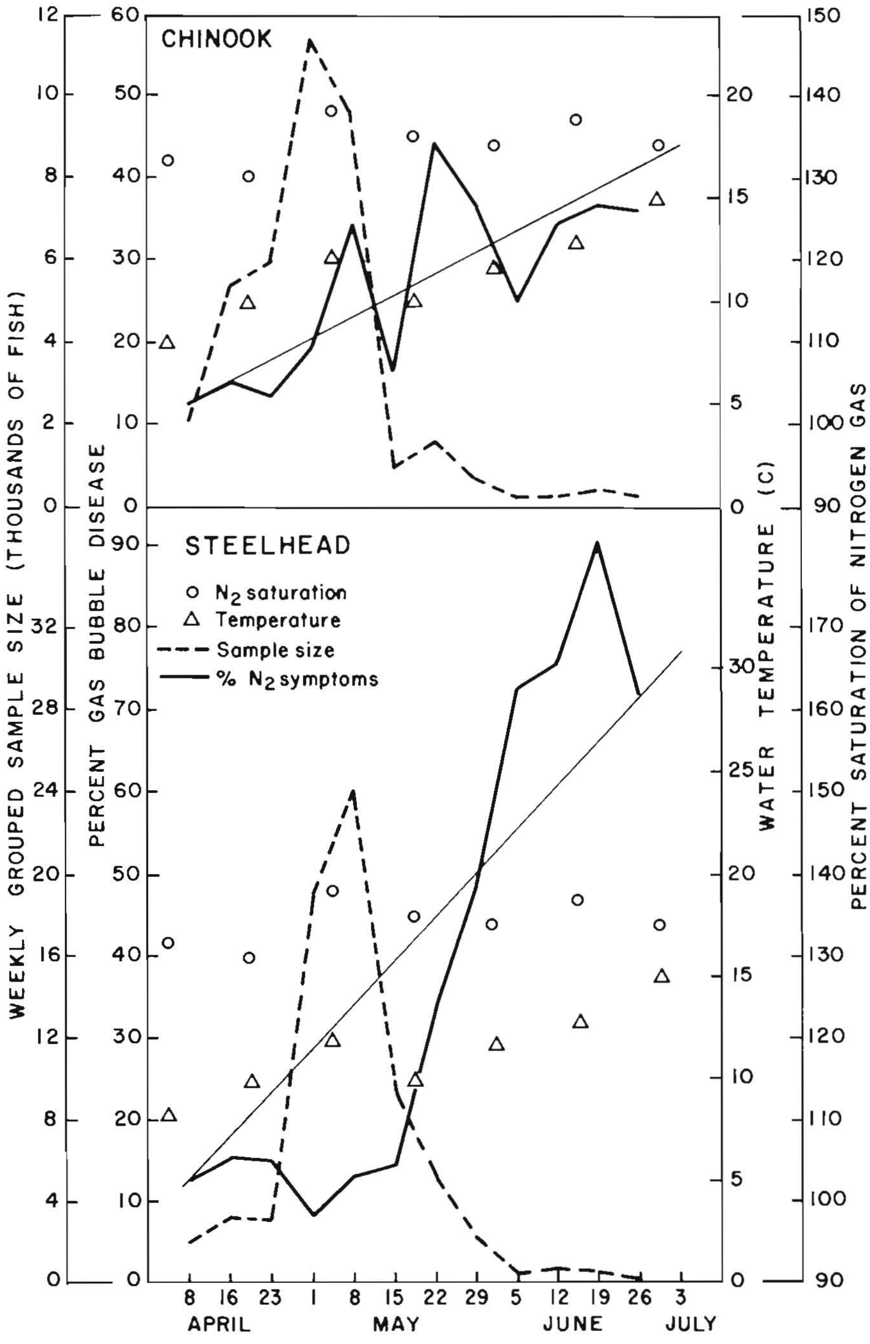


Figure 7.—Percentage gas bubble disease symptoms in juvenile steelhead and chinook in relation to nitrogen concentrations and temperature of tailrace water samples at Lower Monumental Dam. Sample size reflecting the magnitude of the migrating populations is also shown. (Source: Ebel et al., 1971, footnote 12.)

levels of mortality were recorded in fish held in shallow water at dissolved gas levels as low as 115 percent, and substantial mortality does not occur where juvenile salmon are allowed the option to sound until concentrations exceed 120-125 percent of saturation.

Observations of gas bubble disease symptoms in juvenile migrants (Fig. 6) in the Columbia River were first noted in 1966 (Ebel, 1969) from samples of fall chinook and coho netted from gatewells. These symptoms persisted throughout July and August when levels of nitrogen as high as 137 percent were recorded. Subsequent observations of symptoms were made from samples taken in gatewells at The Dalles Dam in 1968 and at Ice Harbor Dam each year since 1969 (Ebel, 1971; Ebel, Krcma, and Raymond[9]; Ebel, Raymond et al.[10,11]. These data generally show that during periods when nitrogen levels are high the incidence of symptoms is also high, particularly on the later migrants (Fig. 7). Incidence of symptoms cannot be directly transferred into percentage mortality, but we believe they are an indication of the degree of stress a population is suffering from exposure to supersaturation of atmospheric gas. For example, in 1970 the incidence of symptoms of gas bubble disease on chinook migrants examined at Ice Harbor Dam ranged from 25 to 45 percent; the survival of chinook (Raymond[12], footnote 2) passing from the Salmon River to Ice Harbor Dam was estimated to be 30 percent. In 1971, incidence of gas bubble disease ranged from 10 to 32 percent during the main portion of the migration; survival was estimated at 50 percent.

Relationship Between Survival Estimates (Juvenile Chinook and Steelhead) and Supersaturation of Atmospheric Gases. Research on the migrations of juvenile salmonids from the Salmon River (the main spawning tributary of the Snake River) as far downstream as The Dalles Dam has

[9]Ebel, Wesley J., Richard F. Krcma, and Howard L. Raymond. 1973. Evaluation of fish protective facilities at Little Goose Dam and review of other studies relating to protection of other salmonids in the Columbia and Snake Rivers, 1973. Northwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, Wash., Prog. Rep. to U.S. Army Corps of Engineers, contract no. DACW68-71-0093, 62 p. Processed.

[10]Ebel, Wesley J., Howard L. Raymond, Clifford W. Long, Willman M. Marquette, Richard Krcma, and Donn Park. 1971. Progress report on fish-protective facilities at Little Goose Dam and summaries of other studies relating to the various measures taken by the Corps of Engineers to reduce losses of salmon and steelhead in the Columbia and Snake Rivers. Northwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, Wash. Prog. Rep. to U.S. Army Corps of Engineers, contract no. DACW68-71-C-0093, 58 p. Processed.

[11]Ebel, Wesley J., Howard L. Raymond, Clifford W. Long, Willman M. Marquette, Richard Krcma, and Donn Park. 1973. Evaluation of fish protective facilities at Little Goose Dam and review of other studies relating to protection of juvenile salmonids in Columbia and Snake Rivers, 1972. Northwest Fish. Cent., Natl. Mar. Fish. Serv., (NOAA), Seattle, Wash. Prog. Rep. to U.S. Army Corps of Engineers, contract no. DACW68-71-0093, 83 p. Processed.

[12]Raymond, Howard L. 1974. Snake River runs of salmon and steelhead trout: trends in abundance of adults and downstream survival of juveniles. Northwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, Wash., 12 p. Processed.

been conducted since 1966. The object of the research has been to measure the effects of new dams and impoundments on juvenile timing, migration rate, and survival. A general decline in survival of downstream migrants has occurred since 1967. This decline is attributed to four main factors: passage through turbines, delays in migration, predation, and supersaturation of nitrogen.

In this section of the report, losses or decrease in survival of juvenile salmonid populations attributable to excessive exposure to supersaturation of atmospheric gases (N_2) will be defined. The results obtained from data collected in 1966-67 provided a basis for comparing migrations after John Day (1968), Lower Monumental (1969), and Little Goose Dams (1970) were completed. Details of methods, experimental design, and statistical calculations are contained in annual progress reports (Raymond[13,14], footnote 2, and 1968; Park and Bentley[15]). Fish at each of the sampling sites from the Salmon River to The Dalles Dam were given separate marks to identify the sampling site and the time of release. Subsequent recovery of these marked fish (Fig. 8) at dams provided the necessary data for the measurement of survival. Juvenile chinook salmon and steelhead trout, which represent 95 percent of the outmigration from the Snake River, were the primary species studied.

Migration Rate. Travel time or migration rate is related to river velocity; i.e., the higher the water velocity the higher the rate of fish migration. Raymond (1968 and 1969) determined that juvenile chinook moved only one-third as fast through McNary and John Day reservoirs as through free-flowing stretches of river. Calculations made for impoundments in the Snake River indicated similar delays. Migration rates of both chinook and steelhead are similar. These are shown (Table 2) for low, moderate, and high river flows through both free-flowing and impounded sections of the Snake and Columbia Rivers. These data become particularly important when estimating the length of time fish are exposed to supersaturation of atmospheric gas.

Timing of Peak Migration. Peak migrations generally occur between

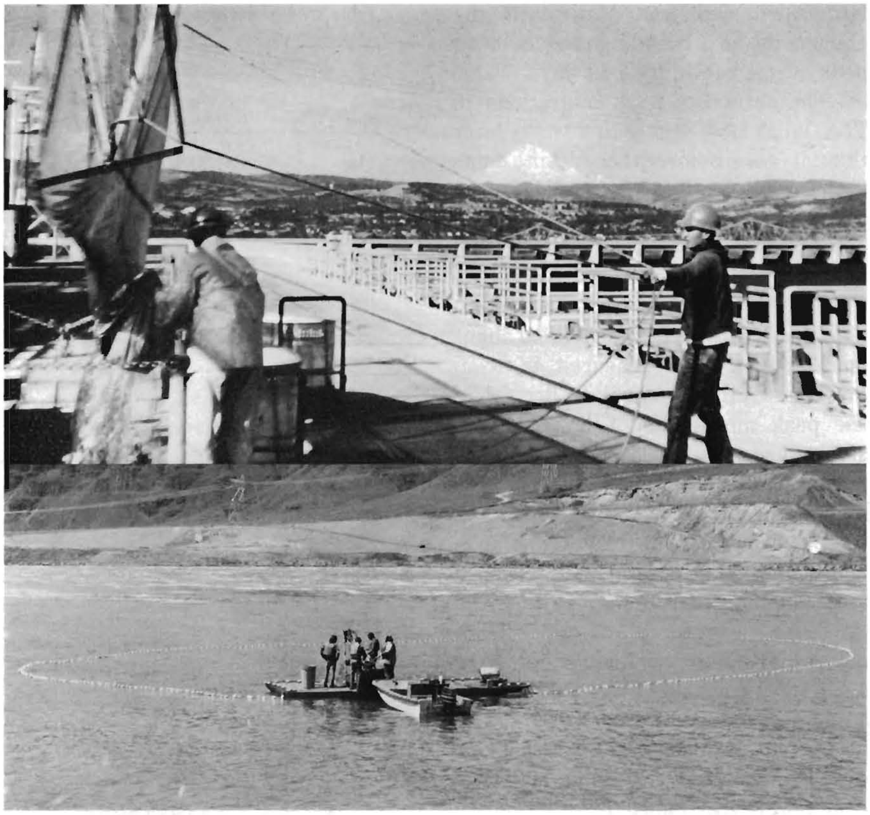


Figure 8.—Above, sampling for juvenile migrants at the turbine intake gatewell of a dam with a specially designed dip net. Below, purse seining for juvenile migrants near Little Goose Dam.

Table 2.—Travel time[1] estimates in days for Snake River juvenile chinook and steelhead trout to travel from the Salmon River to the estuary.

Section of river	Flow: Low[2]	Moderate[3]	High[4]
Salmon River to Lewiston (115 miles) free-flowing	8	5	3
Lewiston to Lower Granite Dam (35 miles) impounded	7	4	2
Lower Granite to Little Goose Dam (40 miles) impounded	8	5	3
Little Goose to Ice Harbor Dam (63 miles) impounded	13	8	4
Total Snake River	36	22	12
Ice Harbor to The Dalles Dam (143 miles) impounded	29	18	10
The Dalles Dam to the Estuary (192 miles) like free flowing	13	8	6
Total Columbia River 335 miles	42	26	16
Grand total	78	48	28

[1]Travel time based on the following migration rates. Free-flowing: Low, 15 m/day; moderate, 25 m/day; high, 34 m/day. Impounded: Low, 5 m/day; moderate, 8 m/day; high, 15 m/day.
[2]Snake River, 30-50,000 cfs; Columbia River, 150-180,000 cfs.
[3]Snake River, 80-100,000 cfs; Columbia River, 200-300,000 cfs.
[4]Snake River, 120-180,000 cfs; Columbia River, 350-500,000 cfs.

[13]Raymond, Howard L. 1967. A summary of the 1966 outmigration of juvenile salmonids in the Columbia Basin. Bur. Commer. Fish., Biol. Lab., Seattle, Wash., 20 p. Processed.

[14]Raymond, Howard L. 1968. A summary of the 1968 outmigration of juvenile salmon and steelhead trout from the Snake River. Bur. Commer. Fish., Biol. Lab., Seattle, Wash., 12 p. Processed.

[15]Park, Donn L., and Wallace W. Bentley. 1968. A summary of the 1967 outmigration of juvenile salmonids in the Columbia Basin. Bur. Commer. Fish., Biol. Lab., Seattle, Wash., 14 p. Processed.

late April and late May with the chinook peaks preceeding the steelhead peak outmigration by 3-14 days (Table 3). The arrival of peak migrations to The Dalles Dam is now 10-20 days later than it was before the recent dams (John Day, Little Goose, and Lower Monumental) impounded large stretches of the river. This later arrival of peak migrations is caused by a reduction in the migration rate in the impounded stretches of the river to about one-third of that measured in free-flowing stretches. The late arrival of the peak migrations of Snake River stocks has resulted in increased exposure to supersaturation during some high flow years. In years prior to 1968, the peak migration of juvenile chinook from the Snake River usually entered the Columbia River before flows in the Columbia had peaked and hence were not subjected to the highest levels of supersaturation in the Columbia. With a 10-day later arrival they often become subjected to the highest levels of supersaturation in both rivers. Recent differences (since 1970) in timing between years and between species are attributable to annual variability in water temperature, stream flow, and—particularly in the case of steelhead smolts—time of release from hatcheries.

Survival Estimates. Survival of juvenile populations of chinook and steelhead from the Salmon River to Ice Harbor Dam was about equal and was estimated to be about 90 percent (Fig. 9) in the years prior to 1968. Survival between Ice Harbor and The Dalles

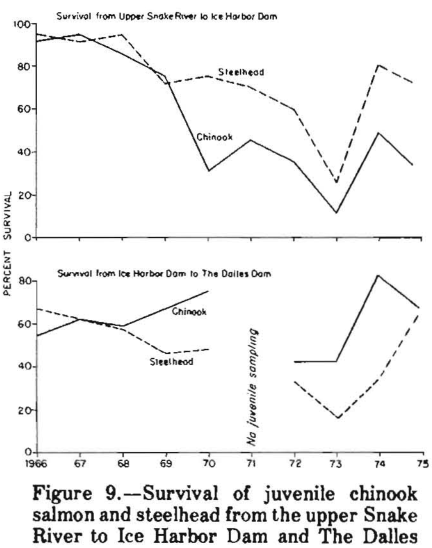


Figure 9.—Survival of juvenile chinook salmon and steelhead from the upper Snake River to Ice Harbor Dam and The Dalles Dam.

Table 3.—Comparison of timing of the migration peak of juvenile chinook salmon and steelhead trout at Ice Harbor Dam on the Snake River 1966-74.

	Chinook		Steelhead		
Year	Peak of migration	River flow at peak	Peak of migration	River flow at peak	Timing difference in days
1966	5/ 4	65,000	5/11	108,000	7
1967	5/10	93,000	5/22	148,000	12
1968	5/10	53,000	5/21	90,000	11
1969	4/28	107,000	5/12	165,000	14
1970	5/13	88,000	5/25	175,000	12
1971	5/4	188,000	5/8	204,000	4
1972	5/12	122,000	5/22	186,000	10
1973	5/21	87,000	5/24	78,000	3
1974	5/6	157,000	5/13	140,000	7

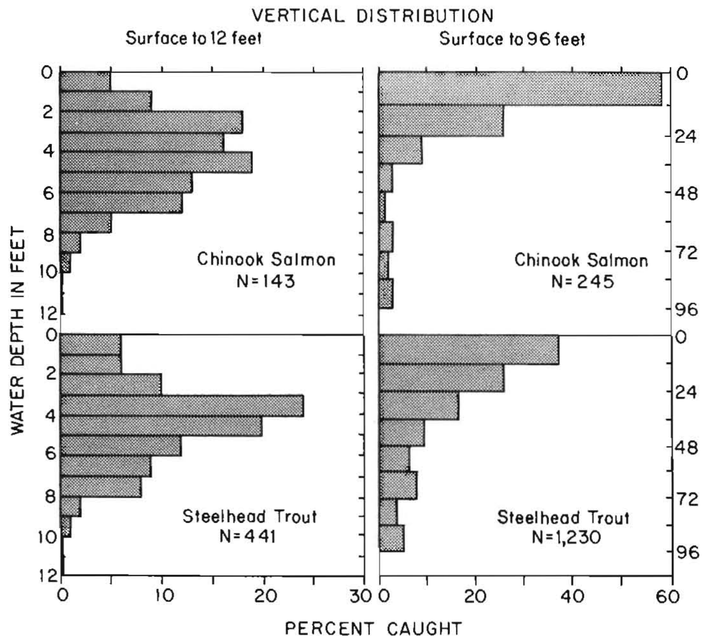


Figure 10.—Vertical distribution of juvenile chinook salmon and steelhead caught in the forebay of Lower Monumental Dam, 1973. (Source: Ebel et al., footnote 13.)

dams was reduced to about 60 percent during the years prior to 1968, largely we believe, because of fish passage through the turbines of Ice Harbor and McNary Dams (N_2 levels were not critical through this stretch of river until 1969). After 1968, survival rate of the two species declined and was no longer equal. The data indicate that the decline in survival of both species during high-flow years can be attributed primarily to increased exposure to supersaturated water. Knowledge of the timing and migration rate, depth distribution (Fig. 10), and dissolved gas concentrations makes it possible to estimate the percentage loss that can be attributed to exposure to supersaturation. Figure 11 provides a pictorial representation of the relationship between surface supersaturation, exposure time, depth of fish, and hydrostatic compensations. Table 4 provides an example of the method used to calculate the percentage loss of chinook attributable to exposure to supersaturation of atmospheric gas (nitrogen) in 1970. Similar calculations were used to estimate losses attributable to supersaturation in other years.

Survival estimates from the upper Snake River to The Dalles Dam for juvenile populations of chinook and steelhead migrating down the Snake and Columbia Rivers are shown in Figure 12. Survival differences noted between the Snake River stretch of the migration and the Columbia River stretch between Ice Harbor and The Dalles Dams are indicated in Figure 8. Both figures are referred to frequently throughout this section.

Survival of both chinook and steelhead smolts during migration down the Snake River to Ice Harbor Dam declined from over 90 percent through 1968 to about 70-75 percent in 1969. It is believed that N_2 levels above 130 percent, appearing for the first time in the Snake River after completion of the Lower Monumental Dam, were largely responsible for the decline. Survival of chinook smolts from Ice Harbor Dam to The Dalles Dam in 1969 were slightly higher than in the previous years (67 percent). Conversely, steelhead survival through this stretch of river dropped significantly to 46 percent. The lower steelhead survival was attributed to increased exposure to higher N_2 supersaturation in the Columbia River. Most of the chinook migrated downstream in April and early May when flows were 80-100,000 cfs in the Snake River and about 300,000 cfs in the Columbia River. Steelhead migrations were nearly 2 weeks later when flows exceeded 166,000 cfs in the Snake and 440,000 cfs in the Columbia River. Thus, even though a larger portion of the steelhead migrated deeper they were exposed longer to a higher level of supersaturation and consequently suffered a higher mortality than the chinook in this stretch of the river in 1969.

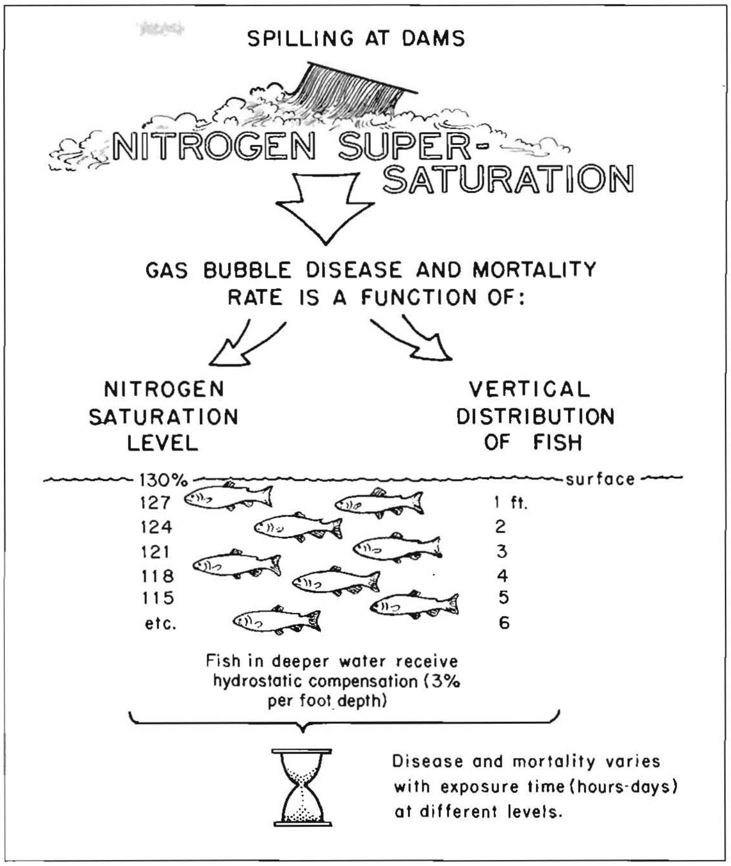


Figure 11.—Generalized representation of cause and effect relationship in gas supersaturation-gas bubble disease-fish mortality.

Estimated survival of juvenile chinook and steelhead from the upper Snake River to The Dalles Dam in 1970 was 24 and 40 percent, respectively. However, with respect to area of loss, survival of juvenile chinook and steelhead was markedly different in 1970 for the two species. Most chinook mortalities occurred in the Snake River while most of the steelhead did not succumb until reaching the Columbia River. Differences can be related to length of exposure and differences in depth (vertical) distribution and tolerance to N_2 supersaturation. Most chinook migrated during Snake River flows of 50-100,000 cfs during the first 20 days in May. Travel time was 8-13 days from Little Goose to Ice Harbor Dam, and N_2 levels exceeded 130 percent saturation. Survival of chinook smolts to Ice Harbor Dam was 32 percent.

Table 4.—Estimated mortality of juvenile chinook salmon from exposure to supersaturated atmospheric gas in the Snake River, 1970 (from Ebel, 1971).

Percentage migration	Depth distribution (feet)	Gas level (% sat.)	Depth[2] compensated level (% sat.)	Exposure[3] time (days)	Percentage[4] mortality	Total mortality of group (%)	Portion[5] of total migration
34	0-5	135	120	3	100	34.0	
11	5-7	135	114	3	0	0.0	
					Subtotal	34.0	⅓
34	0-5	135	120	14+	100	34.0	
11	5-7	135	114	14+	30	3.3	
					Subtotal	37.3	⅔

Summary of estimates:

One-third of migration, 34.0% loss
Two-thirds of migration, 37.3% loss

Weighted average, 35.2% total estimated mortality

[1]Determined from depth distribution study.
[2]Computed from prevailing gas concentration minus hydrostatic pressure compensation as determined by average depth of migrants.
[3]Determined from migration rate and timing data. The first one-third of the migration was subjected to 3 days exposure to levels of 135% or greater; the remaining two-thirds of the migration was subjected to 135% or greater for 14 days.
[4]Percentage mortality as determined from exposure time and bioassay research.
[5]Portion of migration subjected to this loss as determined by timing of migration.

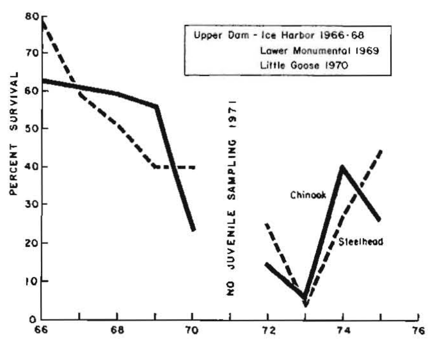


Figure 12.—Survival of Snake River juvenile chinook salmon and steelhead from the upper dam down to The Dalles Dam, 1966-74. (Source: Raymond, 1974, footnote 14.)

Data by Ebel (1971) indicate that losses from nitrogen are directly related to exposure time. He found that fish held in surface cages all died within 48 hours; 50 percent of the fish held in a 0-4.5 m volitional cage, where fish were allowed to seek their own depth, died in 7 days (127-134 percent saturation). If chinook were traveling near the water surface as indicated from depth distribution studies (Smith, 1974) and were exposed to high nitrogen from 10 days to 2 weeks as indicated by the data on timing of migration, most of the 68 percent mortality measured could be attributed to gas bubble disease caused by prolonged exposure to high levels of supersaturated nitrogen as fish migrated down the Snake River to Ice Harbor Dam. In contrast to high losses in the Snake River, mortality of chinook between Ice Harbor and The Dalles Dams was only 25 percent; most of this was believed to have been turbine related. There was little spilling at Columbia River dams during this period which resulted in relatively low levels of supersaturation in the Columbia River during the chinook outmigration.

On the other hand steelhead smolts migrated between 15 May and 5 June; this was 2 weeks later than chinook and in river flows of 160-200,000 cfs in the Snake River and 350-400,000 cfs in the Columbia River. During their migration, N_2 levels increased to over 140 percent in the Snake River and 127-139 percent in the Columbia River. With the higher flows, travel time was much faster—4 days in the Snake River and 10 days in the Columbia River. Estimated survival was 75 percent down the Snake River, sharply declining to 48 percent in the Columbia River. Although gas concentrations were higher in the Snake River during this period, exposure time (4 days) was short; and since a larger portion of the steelhead migrate at deeper levels, the loss to Ice Harbor Dam was only 25 percent. However, a 10-day additional exposure in the Columbia River from Ice Harbor to The Dalles Dam in supersaturated water was sufficient to cause an additional 52 percent loss, resulting in a 60 percent total loss.

Measurements of survival of juvenile chinook and steelhead to The Dalles Dam were not conducted in 1971 because sampling of juvenile populations for marks was discontinued that year. Measurements of survival from the Salmon River to Ice Harbor Dam indicated that survival of chinook was 45 percent and steelhead, 70 percent. The Snake River flow was extremely high in 1971 (180-200,000 cfs during the peak of the migration of both steelhead and chinook), and the majority of the mortality was attributed to exposure of the populations to supersaturation of nitrogen gas. The relationship between time (exposure), supersaturation of nitrogen, and survival is shown in Table 5. Slower moving fish migrating during the lower flows in 1970-71 survived at a lower rate (25-37 percent) than those traveling at a faster rate during higher flows (50-52 percent). The table also indicates that a flow control effort for 3 days between 21 April and 30 April, which reduced dissolved gas concentrations to 109 percent for about 3 days, increased survival from 25 to 37 percent.

Table 5.—Relationship between travel time, supersaturation of nitrogen, and survival of juvenile chinook salmon from the Salmon River to Ice Harbor Dam 1970-71.

Year	Travel time (days)	Period of migration	Nitrogen[1] % saturation	Percent survival
1970	25	4/19-5/13	130	25
	12	5/14-5/31	136	50
1971	26	4/7 -5/31	[2]109-131	37
	13	5/4 -5/19	135	50

[1] N_2 levels—Lower Monumental Dam Forebay.
[2] N_2 109 percent during flow control period 4/27-29.

Survival of Snake River juvenile chinook and steelhead populations to The Dalles Dam in 1972 was 15-25 percent, respectively. Survival to Ice Harbor Dam in the Snake River was 35-60 percent, respectively. We believe differences in timing between chinook and steelhead in 1972 accounts for the higher survival calculated for steelhead down the Snake River. Slotted bulkheads installed in skeleton bays to reduce N_2 in the river caused significant losses to juveniles (Long and Ossiander[16]). Most of the chinook migrated when the bulkheads were in place, whereas, the peak steelhead migration occurred 10 days later—after many of the bulkheads had been removed. After removal of the bulkheads, N_2 levels exceeded 130 percent through most stretches of the Snake and Columbia Rivers. A total of 14 days exposure (based on migration rate) to nitrogen levels of this magnitude would have caused at least 36 percent of the 75 percent loss of steelhead measured from Little Goose to The Dalles Dam in 1972.

[16] Long, Clifford W., and Frank J. Ossiander. 1974. Survival of coho salmon fingerlings passed through a perforated bulkhead in an empty turbine bay and through flow deflectors (with and without dentates) on spillway at Lower Monumental Dam, Snake River April-May 1973. Northwest Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, Wash., Rep. to U.S. Army Corps of Engineers, contract no. DACW68-72-C-0101, 20 p. Processed.

Catastrophic losses in 1973 were primarily turbine-predator related and resulted from passage of nearly the entire juvenile migration through the powerhouses of dams. Net survival to The Dalles Dam was only 4-5 percent for both species. Supersaturation of nitrogen was not a factor in 1973 because there was little or no spilling at most dams.

Downstream survival of chinook and steelhead in 1974 to The Dalles Dam increased from the low of 4-5 percent in 1973 to 40 percent for chinook and 27 percent for steelhead. Nearly two-thirds of the 60 percent loss for chinook in 1974 was attributed to exposure to supersaturation of atmospheric gas. The major factor causing the loss of steelhead in 1974 cannot be estimated because of a disease problem[17] in stocks of steelhead released from Dworshak Hatchery, which now accounts for 50-75 percent of the juvenile steelhead migrating down the Snake River. A combination of loss from exposure to supersaturated atmospheric gases and disease no doubt occurred.

Estimated survival of juvenile steelhead and chinook from Lower Granite Dam to The Dalles Dam in 1975 was 42 and 25 percent, respectively. Steelhead survival was the highest measured since 1969. The lower survival of chinook was attributed to dominance (60 percent) of the 1975 outmigration by hatchery fish (mostly Rapid River) which survived at a much lower rate (17 percent) than native stocks (38 percent). In previous years less than 30 percent of the outmigration were of hatchery origin and their impact on overall survival was not significant. The 38 percent survival of native

[17] Verbal communication, Einer Wold, former fish pathologist at Dworshak Hatchery, Ahsahka, Idaho.

chinook was nearly as high as that measured for steelhead. Several factors contributed to the higher survival of steelhead and native chinook in 1975.

These included: 1) the installation of traveling screens which diverted about 1.5 million fingerlings from turbine intakes of Lower Granite and Little Goose Dams and; 2) installation of spillway deflectors at Lower Granite and Lower Monumental Dams which reduced dissolved gas levels. Losses attributable to exposure to supersaturation were not estimated in 1975.

Experiments to measure the effects of supersaturation of atmospheric gas on juvenile fall chinook migrants in the lower Columbia River have also been conducted and these show that losses as high as 40 percent[18] have been attributed to exposure of these stocks to high levels of supersaturation. For example in 1970, fall chinook (Sims, 1975) released from Spring Creek Hatchery in April before supersaturation was high survived at a rate of about 90 percent. Releases in late May and June after gas saturation levels increased suffered a 50 percent loss.

The Fish Commission of Oregon conducted similar experiments in 1969 and concluded that losses exceeding 50 percent [18] occurred during periods of supersaturation.

In summation, losses of juvenile chinook and steelhead migrating from the Salmon River to The Dalles Dam have ranged from about 40 to 95 percent since 1968. The proportion of this loss that can be attributed to exposure of fish to supersaturation of nitrogen varies from zero in low-flow years as in 1973 to 80 percent in high-flow years as in 1971.

Effect of Supersaturation on Adult Fish

Spawning migrations of steelhead trout and chinook and sockeye salmon take place in the Columbia River Basin when levels of dissolved gases are at critically high levels. Evidence of detrimental consequences are found in both laboratory experiments and field observations.

Laboratory Studies

The most comprehensive laboratory study conducted to date was by Nebeker (footnote 5). In this study, groups of adult salmon and steelhead trout were held at various levels of supersaturation while the water temperature was maintained at 10°C. The fish were observed and the resistance times until 50 percent mortality were determined.

Table 6.—Hours to median mortality (50 percent dead) of various adult salmonids at various levels of supersaturation (From Nebeker, 1973, footnote 5).

Species	Sex	Level of supersaturation			
		115% hr	120% hr	125% hr	130% hr
Spring chinook	Female	526	46;80	17.5	7.8
Spring chinook	Male	526	40;68.5	16.3	8.8
Sockeye	Not spec.	30% in 192	82	18	—
Coho	Female	166	45;51	21	—
Coho	Male	264	74;86	20	—
Winter steelhead	Female	10% in 350	92	—	—
Winter steelhead	Male	30% in 350	76	—	—
Summer steelhead	Not spec.	—	118	31	—

Coho salmon were the most susceptible of the adults tested (Table 6), with 50 percent mortality occurring after slightly less than 7 days exposure at 115 percent saturation. Spring chinook were the most tolerant, requiring about 22 days exposure at 115 percent to reach the 50 percent level of mortality.

Coutant and Genoway[19] held groups of fish at one of two levels of nitrogen supersaturation (low 110 percent, high 118 percent) for 5 days and then transferred them into either high or low level nitrogen conditions with the water elevated 5°C (from approximately 17° to 22°C). The objective was to determine if a 5°C raise in temperature (that was not in itself lethal) would result in mortality when combined with effects of supersaturated gases.

In this study, they found that fish held for the 5-day period in the high nitrogen level water at control temperatures showed visible symptoms of gas bubble disease (bubbles in the dorsal fin) within 24 hours. Coloration and alertness were affected after 4 days. Fish held at the low nitrogen level water at control temperatures showed no gas bubble disease symptoms and retained good coloration, skin texture, and alertness throughout the 27-day test period. All fish, regardless of nitrogen acclimation level, died within 24 hours when placed into high nitrogen water with the water temperature elevated 5°C. Those fish stressed at the high nitrogen level died sooner. External symptons of gas bubble disease that were evident on fish disappeared rapidly after death; nearly all symptoms were lost within 24 hours.

Bouck, Chapman, Schneider, and Stevens[20] confirmed gas bubble disease among wild adult sockeye salmon migrating upstream through the Columbia River in 1968 and 1969. Adult sockeye salmon were taken from the river and examined in July 1968 and July 1969 when dissolved nitrogen levels were in excess of 120 percent throughout the lower 600 km of the Columbia River.

In July 1968, seven live sockeye salmon were collected near the south entrance to the Oregon shore fishway at John Day Dam (river km 345). These fish were examined for external symptoms of gas bubble disease and then immediately killed so histological and other internal examinations could be carried out. Three of the seven fish had external symptoms of gas bubble disease (gas bubbles in skin and on fins and eye damage). Histological studies revealed microscopic sized vesicles in the extravascular spaces of the spleen and other tissues, but it was not possible to state whether the vesicles existed during life or evolved during fixation. Aneurysms filled with blood

[18]Verbal communication, Kirk Beiningen, Oregon Dept. of Fish and Wildlife, 17330 S.E. Evelyn St., Clackamas, Oreg. 97015.

[19]Coutant, Charles C. and Robert G. Genoway. 1968. Final report on an exploratory study of interaction of increased temperature and nitrogen supersaturation on mortality of adult salmonids to U.S. Bureau of Commercial Fisheries, Seattle, Wash. Battelle Mem. Inst., Pac. Northwest Lab., Richland, Wash., November 28, 1968, 28 p.

[20]Bouck, G. R., G. A. Chapman, P. W. Schneider Jr., and D. G. Stevens. 1970. Observations on gas bubble disease in adult Columbia River sockeye salmon (*Oncorhynchus nerka*). Environ. Prot. Agency, Western Fish Toxicol. Sta., Corvallis, Oreg., June 30, 1970. Unpubl. manuscr., 19 p.

were found in the gill lamellae of all fish that had macroscopic gas bubbles in the skin or fins.

In July 1969, 123 adult sockeye salmon collected from the Washington shore fishway at Bonneville Dam (river km 235) were held at the Oregon Fish Commission's hatchery at Bonneville Dam. A cursory external examination of these fish revealed gas bubble disease symptoms in 13 fish. The 123 fish were divided into four groups, and each group was held in water of a different temperature but with the nitrogen level maintained at approximately 100 percent. Visible symptoms of eye damage developed that were compatible with the eye damage observed in the sockeye salmon at John Day Dam in 1968. The results of the study are summarized in Table 7 taken directly from Bouck et al. (Footnote 22). As a result of their work in 1968 and 1969, the authors concluded that dissolved nitrogen gas causes significant damage to salmon in the Columbia River.

Field Studies

In 1962, during an investigation of a high rate of prespawning mortality among chinook salmon at the McNary spawning channel, it was noted that a high percentage of the dead fish were blind. Subsequent investigation (Westgard, 1964) revealed that the problem was a result of gas bubble disease caused by high levels (up to 130 percent) of dissolved gases in the water. In addition, test lots of chinook salmon were placed in live boxes located in water having one of two levels of nitrogen supersaturation: 1) low, 104-107 percent; and 2) high, 116-130 percent. Thirty-four percent of the fish held in the high nitrogen level water were blind within 10 days. Eighty-eight percent of the blinded fish died before spawning (only 6 percent of the non-blind died before spawning). In addition, blinded females did not dig redds and blinded males were unable to successfully cover eggs with milt.

Surveys were conducted during 1967 to determine the levels of supersaturation of dissolved nitrogen in the Columbia River and its effect on salmon and steelhead (Ebel, 1969). During periods of high nitrogen, adult salmon and steelhead were examined for symptoms of gas bubble disease. Saturation levels of dissolved nitrogen gas were found to be high enough and persisted for a long enough period in a large enough area to be potentially dangerous to adult salmon and steelhead trout. In July, symptoms of gas bubble disease were observed in 10 out of 1,000 sockeye salmon examined at McNary Dam. No symptoms were noted in 1,762 chinook salmon and 1,461 steelhead trout. Field evidence

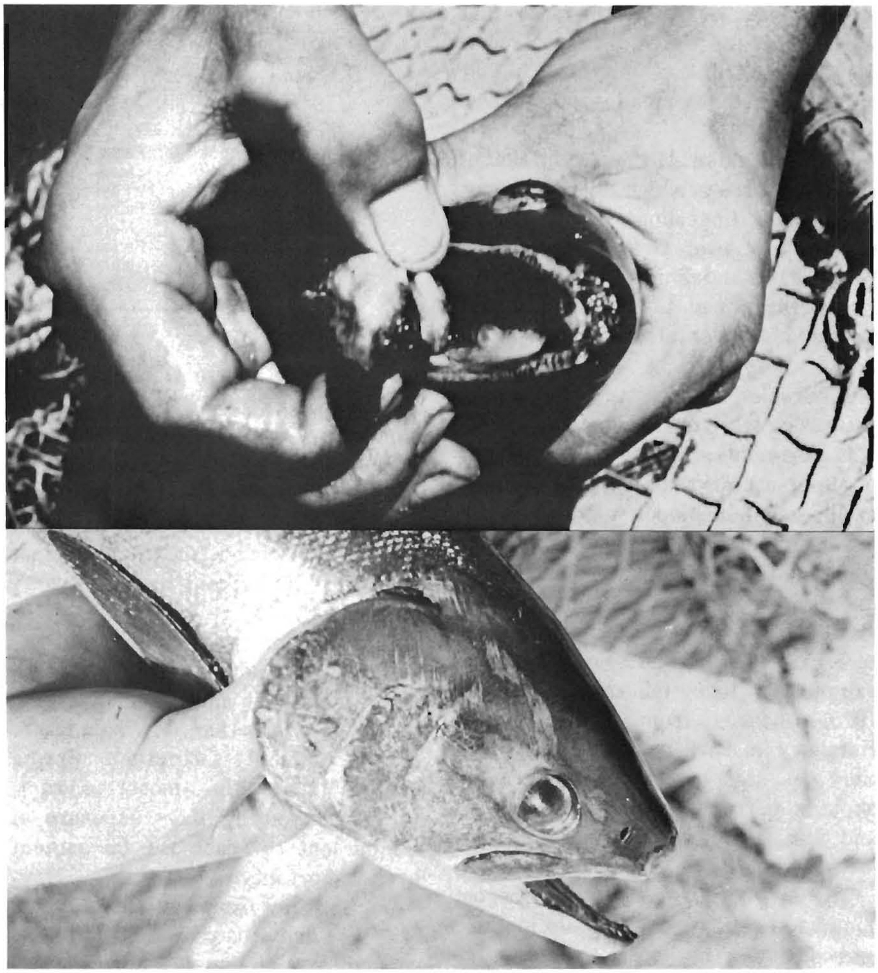


Figure 13.—Above, vesicles in roof of mouth and distended eyes of adult sockeye salmon captured at entrance to south ladder at John Day Dam, 20 July 1968. Below, large gas bubble in eye tissue and numerous gas bubbles on operculum of adult sockeye salmon captured at entrance to south ladder at John Day Dam, 20 July 1968. (Photo source: Beiningen and Ebel, 1970.)

Table 7.—Incidence of eye damage and mortality among adult Columbia River sockeye salmon, *Oncorhynchus nerka*, during a post-capture holding period at various temperatures (from Bouck et al., 1970, footnote 22).

	Tank #1	Tank #2	Tank #3	Tank #4
Test temperature (C°)	10	16 (ambient)	20	22.5
Number of specimens	31	31	30	31
Incidence of eye damage				
Left eye only	19%	10%	33%	35%
Right eye only	3%	0%	7%	10%
Both eyes	13%	19%	13%	19%
Blindness in at least one eye	35%	29%	53%	65%
Total mortality	19% in 44 days[1]	32% in 44 days[1]	100% in 31 days	100% in 12 days

[1]Experiment terminated on the 44th day.

did not positively indicate that high nitrogen in the Columbia River in 1967 caused substantial mortality of adult salmon but the possibility cannot be discounted.

The first substantial loss of adult salmon and steelhead was documented in 1968 by Beiningen and Ebel (1970). Concentrations of dissolved nitrogen gas were measured in the Columbia River from April to September 1968 to determine the effect of newly constructed John Day Dam on nitrogen saturation. Adult salmon were also observed for symptoms of gas bubble disease and mortality. Nitrogen levels of 123-143 percent saturation were measured below the dam. These concentrations were considerably higher than measured previously, and they persisted throughout the salmon migration. During the period of high nitrogen levels, a high incidence of injury and death to adult fish from gas bubble disease was observed near John Day Dam. As many as 13 sockeye and 365 chinook salmon were recovered in one day below John Day Dam. Fish captured at the entrance to the ladder at John Day Dam exhibited obvious symptoms of gas bubble disease: eyes distended and hemorrhaged; bubbles in the subcutaneous layers surrounding the eyeball (Fig. 13); and large vesicles in the roof of the mouth and on the outside of the opercula. Reports from fish counters observing fish at the underwater viewing chamber in the south fishway at John Day Dam are replete with the observations of typical gas bubble disease symptoms. Tissue specimens of salmon and steelhead trout collected by Gerald R. Bouck, EPA, indicated definite tissue damage from gas bubble disease in spleen and gill lamellae of sockeye salmon as well as tentative indications of gas emboli in gill filaments of chinook salmon.

Based on the recovery of dead salmon, the Fish Commission of Oregon estimated that over 20,000 summer chinook were missing in the area of concern.

Investigations were carried out in the upper Columbia River from 1965 to 1969 by Meekin and Allen (1974) to determine the effect of Grand Coulee and Chief Joseph dams on dissolved nitrogen gas levels and their effect on spawning salmon. They found that nitrogen levels of from 125 to 135 percent occurred each year as a result of spilling at Grand Coulee Dam. The supersaturated water did not equilibrate while passing through Chief Joseph Reservoir and subsequent spilling at the dam maintained or increased the high levels. Boat searches and aerial surveys from 1967 between Chief Joseph and Wells dams revealed that mortalities of unspawned summer chinook and sockeye salmon occurred during the spill season and terminated after spilling stopped.

In 1970, spilling was greatly reduced and nitrogen levels were considerably lower than 1967 to 1969 (generally less than 118 percent). Field surveys during this time showed that both adult chinook and sockeye salmon mortalities were substantially reduced from previous years.

Estimated losses of adult sockeye and summer chinook below Chief Joseph Dam, 1967-70.

Year	Percent loss		Nitrogen level
	Chinook	Sockeye	
1967	68	46	High
1968	44	—	High
1969	56	—	High
1970	5	30	Low

We have examined the relationship between dissolved gas supersaturation in the Snake River and the number of spring and summer chinook redds on the spawning grounds in the Salmon River system. Redd count index number was calculated by dividing the number of redds counted during spawning ground surveys (Idaho Fish and Game Department) by the number of spring and summer chinook salmon counted over Ice Harbor Dam minus the subsequent sports catch and hatchery returns. In general, we found a sharp reduction in the redd count index number after 1968 when nitrogen levels sharply increased. However, in 1972 when the nitrogen levels were reduced through the use of slotted bulkheads and in 1973 when very low flows eliminated spilling, there was a return to the higher redd count index numbers.

Relation of nitrogen supersaturation in the Snake River to spring and summer chinook redd counts in the Salmon River system.

Period	N_2 Level (Mid-April through May)	Redd Count Index No.[1] (Range)
1963-1968	Low (100-110%)	11-19
1969-1971	High (125-135%)	6- 8
1972-1973	Low (100-110%)	10-13

[1]Index no. = Redd counts (spring, summer chinook) in Salmon River system. / Number of spring and summer chinook over Ice Harbor Dam minus sport catch and hatchery return.

SUMMARY AND CONCLUSIONS

In summation, there is ample evidence, both in laboratory and field studies, that adult and juvenile salmon and steelhead are jeopardized by gas bubble disease in the Columbia River Basin. The severity of the disease and its consequences depend on the level of supersaturation, the duration of exposure, water temperature, general physical condition of the fish, and the swimming depth maintained by the fish.

During spill, levels of dissolved gases measured at and between major dams are well above critical levels. Unfortunately, even with maximum utilization of turbine capacities, the dissolved gas levels during average and high flow years will continue to be high enough to cause problems for upstream and downstream migrants. Because all reaches of the Columbia and Snake Rivers through which adult and juvenile salmon and steelhead must migrate are significantly supersaturated, the total time of exposure is serious, and any undue delays that fish may encounter could prove disastrous.

Information currently available on depth distribution of juvenile salmonids (Mains and Smith, 1964; Smith, Pugh, and Monan, 1968; Monan, McConnell, Pugh, and Smith, 1969; and Smith, 1974) all indicate that the largest percentage of downstream migrants are found in the top 5 feet of water. This means that the average hydrostatic compensation achieved is about 7.5 percent of saturation—insufficient to compensate for levels as high as 135-140 percent which occur over wide areas during high flow years.

Even if migrants are able to gain relief by traveling deep in the river, adults are forced to utilize restricted depths when entering and negotiating fishways at dams. Radio tracking studies (Monan and Liscom[21]) have shown that the amount of time adult salmon spend negotiating fishways can be a substantial period that varies from dam to dam. For example, a group of spring chinook salmon tracked through the fishways at Bonneville Dam took from 4 to 57 hours each (average 22 hours), while the same fish tracked through the fishways at The Dalles Dam took 3 to 23 hours (average 7 hours). During the time the fish are in the fishways, they are restricted to a maximum depth of about 7 feet. Observations at various dams indicate the fish are frequently near the surface in the fishways. Even though there is some reduction in the dissolved gas levels in the ladder, the restricted depth places an additional stress on fish previously equilibrated to high levels of gas supersaturation.

Several conclusions regarding the effect of supersaturation of atmospheric gas on fish in the Columbia River can be made from the laboratory and field data presented. The main conclusions we reached are:

1) Supersaturation of atmospheric gas has exceeded 130 percent over long stretches of the Columbia and Snake Rivers during several years since 1968.

2) Juvenile and adult salmonids confined to shallow water (one meter) suffer substantial mortality at 115 percent (TDG) saturation after 25 days of exposure.

3) Juvenile or adult salmonids allowed the option to sound and obtain hydrostatic compensation either in the laboratory or in the field, still suffer substantial mortality when saturation levels (TDG) exceed 120 percent saturation after more than 20 days exposure.

4) On the basis of survival estimates made in the Snake and Columbia Rivers from 1966 to the present, we conclude that juvenile fish losses ranging from 40 to 95 percent do occur and a major portion of this mortality can be attributed to fish exposure to supersaturation of atmospheric gases during years of high flow.

5) Juvenile salmonids subjected to sublethal periods of exposure to supersaturation can recover when returned to normally saturated water, but adults do not recover and generally die from direct and indirect effects of the exposure to supersaturation.

[21]Monan, Gerald E., and Kenneth L. Liscom. 1973. Radio tracking of adult spring chinook salmon below Bonneville and The Dalles Dams, 1972. Northwest Fish. Cent. Natl. Mar. Fish. Serv., NOAA, Seattle, Wash., Rep. to U.S. Army Corps of Engineers, delivery order DACW57-72-0398, 37 p. Processed.

LITERATURE CITED

Beiningen, K. T., and W. J. Ebel. 1970. Effect of John Day Dam on dissolved nitrogen concentrations and salmon in the Columbia River, 1968. Trans. Am. Fish. Soc. 99:664-671.

Dawley, E.M., and W.J. Ebel. 1975. Effects of various concentrations of dissolved atmospheric gas on juvenile chinook salmon and steelhead trout. Fish. Bull., U.S. 73: 787-796.

Dawley, E. M., M. Schiewe, and B. Monk. 1976. Effects of long-term exposure to supersaturation of dissolved atmospheric gases on juvenile chinook salmon and steelhead trout in deep and shallow test tanks. *In* D. H. Fickeisen and M. J. Schneider (eds.), Gas bubble disease: Proceedings of a workshop held at Richland, Wash., October 8-9, 1974, p. 1-10. Energy Res. Dev. Admin., Oak Ridge, Tenn.

Ebel, W. J. 1969. Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout. U. S. Fish Wildl. Serv., Fish. Bull. 68:1-11.

________. 1971. Dissolved nitrogen concentrations in the Columbia and Snake Rivers in 1970 and their effect on chinook salmon and steelhead trout. U. S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-646, 7p.

Mains, E. M., and J. M. Smith. 1964. The distribution, size, time and current preferences of seaward migrant chinook salmon in the Columbia and Snake Rivers. Wash. Dep. Fish., Fish. Res. Pap. 2(3):5-43.

Meekin, T. K., and R. L. Allen. 1974. Summer chinook and sockeye salmon mortality in the upper Columbia River and its relationship to nitrogen supersaturation. Wash. Dep. Fish., Tech. Rep. 12:127-153.

Monan, G. E., R. J. McConnell, J. R. Pugh, and J. R. Smith. 1969. Distribution of debris and downstream-migrating salmon in the Snake River above Brownlee Reservoir. Trans. Am. Fish. Soc. 98:239-244.

Newcomb, T. W. 1974. Changes in blood chemistry of juvenile steelhead trout, *Salmo gairdneri*, following sublethal exposure to nitrogen supersaturation. J. Fish. Res. Board Can. 31:1953-1957.

Raymond, H. L. 1968. Migration rates of yearling chinook salmon in relation to flows and impoundments in the Columbia and Snake Rivers. Trans. Am. Fish. Soc. 97: 356-359.

________. 1969. Effect of John Day Reservoir on the migration rate of juvenile chinook salmon in the Columbia River. Trans. Am. Fish. Soc. 98:513-514.

Rucker, R. R. 1975. Gas bubble disease: Mortalities of coho salmon, *Oncorhynchus kisutch*, in water with constant total gas pressure and different oxygen-nitrogen ratios. Fish. Bull., U.S. 73:915-918.

Rucker, R. R., and E. M. Tuttle. 1948. Removal of excess nitrogen in a hatchery water supply. Prog. Fish-Cult. 10:88-90.

Schiewe, M. H. 1974. Influence of dissolved atmospheric gas on swimming performance of juvenile chinook salmon. Trans. Am. Fish. Soc. 103:717-721.

Shirhata, S. 1966. Experiments on nitrogen gas disease with rainbow trout fry. [In Jap., Engl. abstr.] Bull. Freshwater Fish. Res. Lab. 15(2):197-211.

Smith, H. A., Jr. 1973. A detrimental effect of dams on environment - nitrogen supersaturation? Int. Comm. on Large Dams, 11th Congr. on Large Dams, Madrid, p. 237-253.

Smith, J. R. 1974. Distribution of seaward-migrating chinook salmon and steelhead trout in the Snake River above Lower Monumental Dam. Mar. Fish. Rev. 36(8):42-45.

Smith, J. R., J. R. Pugh, and G. E. Monan. 1968. Horizontal and vertical distribution of juvenile salmonids in upper Mayfield Reservoir, Washington. U. S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 556, 11 p.

Weber, D. D. and M. H. Schiewe. 1976. Morphology and function of the lateral line of juvenile steelhead trout in relation to gas bubble disease. Journal of Fish Biology, Academic Press, London.

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

MFR Paper 1191. From Marine Fisheries Review, *Vol. 38, No. 7, July 1976. Copies of this paper, in limited numbers, are available from D825, Technical Information Division, Environmental Science Information Center, NOAA, Washington, DC 20235. Copies of* Marine Fisheries Review *are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 for $1.10 each.*