EFFECTS OF DISSOLVED GAS SUPERSATURATION ON FISH RESIDING IN THE SNAKE AND COLUMBIA RIVERS, 1997

by

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EXECUTIVE SUMMARY

Large amounts of water spill at dams has commonly generated levels of dissolved gas that are higher than levels established by state and federal agencies setting criteria for acceptable water quality in the Columbia and Snake Rivers (maximum 110% of saturation). Large spill volumes are sometimes provided voluntarily to increase the proportion of migrating juvenile salmon (*Oncorhynchus* spp.) that pass dams through non-turbine routes. However, total dissolved gas saturation (TDGS) resulting from spill in past decades has led to gas bubble disease (GBD) in fish. Therefore, during the period of high spill in 1997, we monitored the prevalence and severity of GBD by sampling resident fish in Ice Harbor Reservoir and downstream from Ice Harbor and Bonneville Dams.

We made non-lethal visual examinations of all collected fish using 2.5- to 5-power magnification lenses to assess external signs of GBD (subcutaneous emphysema on fins, head, eyes, and body surface). All reference to GBD signs are made to external GBD signs unless otherwise noted. Subsamples of 10 resident fish per week from each reach were further examined with 20-power magnification for gas bubbles in the lateral line, branchial arteries, and gill lamellae.

Subsamples of resident nonsalmonid fish species were held in pens for 4 days and then examined for prevalence and severity of GBD. Three types of pens were used: surface cages held at a depth of 0 to 0.5 m; deep, submerged cages held at a depth of 2 to 3 m; and large net-pens with a sloping bottom that extended from the surface to a depth of 4 m.

Downstream from Ice Harbor Dam, weekly samples of up to 100 salmonids were taken with purse seines and examined for signs of GBD. Juvenile chinook salmon (*O. tshawytscha)* were more closely examined with a dissecting microscope for gas bubbles in the lateral line.

Gas Bubble Disease Signs in Resident Fish

Signs of GBD in fish were prevalent in Ice Harbor Reservoir, downstream from Ice Harbor Dam, and downstream from Bonneville Dam. Twenty of the 27 species captured displayed signs of GBD. During the period of highest TDGS, daily prevalence of GBD in sampled fish peaked at 22.4, 9.3, and 30.1% in the three respective reaches. From 11 May to 21 June; signs of GBD were observed in 9.8% of the 2,082 resident fish captured in Ice Harbor Reservoir; 23% of these fish displayed severe GBD signs (greater than 25% of a fin covered with emphysema or other body surfaces with emphysema). Levels of TDGS did not exceed 130% and were in the mid-120% range for approximately 45 days ending in mid-June, after which they dropped below 120%.

From 20 April to 23 June, signs of GBD were observed in 4.5% of the 3,788 resident fish captured downstream of Ice Harbor Dam; 29% of these fish displayed severe GBD signs. Levels of TDGS reached 133% and remained near 130% for about 2 months before dropping to approximately 120% and remaining there for the rest of the period. The incidence of GBD was lower this year than in past years despite high spill levels. Recently installed flow deflectors ("flip-lips") in Ice Harbor Dam spillway decreased TDGS levels downstream from the dam.

From 23 April to 25 June signs of GBD were observed in 18.0% of the 813 resident fish captured downstream from Bonneville Dam; 30% of these fish displayed severe GBD signs. TDGS reached 143.5% and remained near 130% for most of May and June, after which they dropped to 120%.

Gas Bubble Disease in Juvenile Salmonids

From 24 April to 10 June, signs of GBD were observed in 13.7% of the 738 juvenile salmonids examined for signs of GBD downstream 15 km from Ice Harbor Dam. These fish were captured mid-channel with a purse seine and examined according to Fish Passage Center (FPC) protocols. Prevalence of GBD in fish examined at Ice Harbor Dam (collected from the juvenile bypass system) was 5.2%, and was consistently less through the period of high dissolved gas than prevalence in cohorts traversing the 15-km reach downstream from the dam. Steelhead captured downstream from Ice Harbor Dam constituted 84% of the salmonid sample and displayed an average 49% higher prevalence of GBD signs than steelhead examined at Ice Harbor Dam ($P = 0.028$). Prevalence of GBD in seine samples suggests that results from GBD monitoring at Ice Harbor Dam do not represent fish egressing the Snake River.

From 14 March to 22 August, we examined 1,003 juvenile salmonids for signs of GBD downstream from Bonneville Dam; only 6 displayed signs of GBD. The majority of salmonids (98.5%) were captured from 14 to 23 March, when daily average TDGS did not exceed 117%.

Gas Bubble Disease in Captive Fish

The three species of resident nonsalmonid fish used for the net-pen studies were smallmouth bass, yellow perch, and peamouth. At introduction to the pens, individuals taken from the river often had GBD signs. After 4 days of holding, GBD signs among the captive fish usually persisted and generally showed an increase in prevalence. However, when TDGS in the river reach was less than 120% or decreasing substantially, GBD signs were static or decreased in these fish.

Upstream from Ice Harbor Dam, fish held in the 0- to 4-m pen showed increases of GBD signs in 5 of the 17 holding periods; prevalence of GBD signs ranged from 0.9 to 18.0%. When prevalence of GBD signs increased, mortality ranged from 4.0 to 19.4%.

Downstream from Ice Harbor Dam, fish held in the 0- to 4-m pen showed increases of GBD signs in 19 of the 24 holding periods; prevalence of GBD signs ranged from 0.2 to 59.1%. When prevalence of GBD signs increased, mortality ranged from 0.9 to 57.1%.

Model of Gas Bubble Disease Impacts

Our original research goal was to use data collected over multiple years for developing a model to estimate GBD-induced mortality based on measured dissolved gas levels from the Columbia River Operations Hydro-Met System. However, because dead fish can rarely be recovered from the river, it was necessary to use captive fish to assess mortality. Our first step in developing the model was to analyze the relationship between GBD signs and TDGS exposure of resident fish. The second step was to establish the relationship between GBD signs and mortality, based on data from net-pen holding experiments.

In an iterative process using 1994, 1995, and 1996 GBD-signs data and TDGS measurements, we developed a mathematical equivalence for TDGS exposure duration and level, termed the exposure index (EI), that correlated well with prevalence of GBD signs. The relationship was best described by the following second-order polynomial regression: %GBD signs = $[0.05(EI)^2 \times 0.21(EI) + 0.62]$, $R^2 = 0.79$. Based on the large amount of data from multiple locations utilized to formulate this regression, and the reasonably good coefficient of determination, we accept this model as a reasonably accurate predictor of GBD signs, given any specific 7-day dissolved gas exposure in the mainstem Snake and Columbia Rivers.

Unfortunately, our ability to predict mortality from 1994, 1995, and 1996 captive fish data was poor. There was no clear correlation between external GBD signs and mortality in captive fish when data from all species were combined. However, when the data were separated by species, a slightly stronger correlation was observed in smallmouth bass, yellow perch, and peamouth. In 1997, we focused our sampling and net-pen holding efforts on these three species to strengthen the data set. Our focused efforts did not yield an improved mortality model for any of the three species individually or combined, nor did it elucidate a promising direction in which to pursue a mortality model.

Recommendations

When TDGS levels are held below 120%, GBD signs are rare in resident fish. When TDGS levels exceed 120%, the equation relating GBD signs to TDGS exposure can accurately predict signs in resident fish where continuous TDGS readings are available. Therefore, we believe the extensive sampling of all species to monitor signs of GBD in the mainstem Columbia and Snake Rivers is no longer necessary.

Evaluating mortality due to TDGS has proved to be difficult, and after 4 years of data collection we believe that it is not feasible to develop a general model. Modeling mortality for individual species has proved to be just as problematic, and we believe additional data collection would not yield any significant results.

Juvenile salmonids examined in this study (resident and migrating), also displayed few GBD signs when TDGS remained below 120%. Based on GBD prevalence at the mouth of the Snake River, we believe that assessment of GBD at dams will not properly represent migrants passing through free-flowing, shallow, river reaches and areas downstream of dams where TDGS is high. When TDGS exceeds 120% we recommend monitoring of salmonids in river-run reaches and the tailraces of dams where spilled water stays separated from powerhouse flows.

CONTENTS

INTRODUCTION

In recent years, spill has been used to increase survival of juvenile salmonids (*Oncorhynchus* spp.) passing through Columbia and Snake River dams. Many studies have concluded that spill provides the safest route for juvenile salmonids passing dams on the Columbia and Snake Rivers. However, increased use of spill has raised concern that the resulting increase in dissolved gas levels in the water may be detrimental to aquatic biota. Supersaturation of dissolved atmospheric gases can lead to gas bubble disease (GBD), which is potentially lethal to fish and invertebrates.

During the spring freshet, dissolved gas levels in the Columbia and Snake Rivers often exceeded 110% of saturation, the maximum level permitted by the U.S. Environmental Protection Agency, Washington State Department of Ecology, Idaho Department of Environmental Quality, and Oregon State Department of Environmental Quality. The highest levels of supersaturation during this period resulted from conditions over which there was no control, such as high springtime river flows combined with turbine outages at some dams. However, some supersaturation occurred as a result of purposeful spill for enhanced fish passage.

The National Marine Fisheries Service (NMFS) obtained a temporary waiver for the 110% dissolved gas saturation standard from the Washington State Department of Ecology and Oregon State Department of Environmental Quality to accommodate spillway passage of juvenile salmon. Dissolved gas levels in tailraces at most dams on the lower Snake and Columbia Rivers were allowed to reach 120% of saturation. An intensified GBD monitoring program was instituted for juvenile salmonids at the dams to evaluate the consequences of this action.

Many studies on GBD and its effect on salmonids have been conducted. From 1968 to 1975, GBD in high-flow years contributed to high mortalities of juvenile salmonids migrating from the Snake River (Ebel et al. 1975). The severity of GBD was dependent upon species, life stage, body size, level of total dissolved gas, duration of exposure, water temperature, general physical condition of the fish, and swimming depth (Ebel et al. 1975). Thorough reviews of the literature on dissolved gas supersaturation and of recorded cases of GBD were compiled by Weitkamp and Katz (1980) and updated by Fidler and Miller (1993). Despite numerous studies, there are still questions regarding the total dissolved gas saturation (TDGS) that salmonids can safely tolerate under natural conditions.

When it first became apparent that dissolved gas supersaturation of river water was due to spill at dams and that it caused serious problems for juvenile and adult fish in the Columbia and Snake Rivers, the U.S. Army Corps of Engineers (COE) devised methods to reduce dissolved gas supersaturation (Ebel et al. 1975). The methods investigated and implemented were 1) to increase headwater storage to control flow during the spring freshet, 2) to install additional hydroelectric turbines at many dams, and 3) to install flow deflectors ("flip-lips") on spillway ogees at selected dams to reduce plunging and air entrainment of spilled water (Smith 1974). As a result of these remedial measures, there was little evidence of GBD in salmonids in the late 1970s and 1980s (Dawley 1986). However, as increased turbine capacity at dams helped reduce TDGS by allowing more river volume to pass through turbines, it also increased the proportion of juvenile salmonids passing dams via turbines. Thus, passage survival at dams was decreased because survival for turbine passage is less than for spillway passage (Schoeneman et al. 1961).

To improve survival of downstream migrating juvenile salmonids, the present program of increased spill was implemented in the 1980s. This spill program resulted in diurnal fluctuations of dissolved gas levels, and in 1985 and 1986 signs of GBD were observed in juvenile and adult salmonids in the Columbia River at McNary, John Day, The Dalles, and Bonneville Dams

(Dawley 1986). However, based on low prevalence of GBD signs, it appeared that impacts of dissolved gas supersaturation were minimal, probably because of the short duration of high supersaturation levels. In addition, these high levels of dissolved gas resulted from flows exceeding hydro-capacity, not from purposeful spill for enhanced fish survival.

The effects of dissolved gas supersaturation on aquatic biota other than salmonids are not fully understood. Most research has focused on trout and salmon (Weitkamp and Katz 1980), and studies that focused on the occurrence of GBD in resident fish in situ (Dell et al. 1974) were conducted before the implementation of the present spill regime, with its resulting diurnal fluctuations. These earlier studies were also conducted before the availability of meters that allow continuous recording of dissolved gas saturation levels.

The objectives of our study were to assess impacts of ambient levels of gas-supersaturated water on fish residing in the highest-risk reaches of the mainstem Columbia and Snake Rivers and to develop a model that can be used in "real time" by fisheries managers to predict GBD impacts on resident fish resulting from dissolved gas supersaturation.

METHODS

Sampling Locations and Dates

Sampling in 1997 to assess impacts of GBD on resident fish species was conducted in the lower Snake River in Ice Harbor Reservoir and downstream from Ice Harbor Dam, and in the lower Columbia River downstream from Bonneville Dam. Locations sampled in the previous 3 years included Priest Rapids Reservoir and Hanford Reach, but did not include Ice Harbor Reservoir. Resident fish species were collected weekly from each river reach during the spring freshet. Sampling in the lower 9 km of Ice Harbor Reservoir was conducted from 29 April to

16 July (Fig. 1), and from 1.6 to 13.7 km downstream from Ice Harbor Dam from 14 April to 29 July (Fig. 2). Sampling downstream from Bonneville Dam, from Columbia River Kilometer (RKm) 218.8 to RKm 229.1, was conducted from 22 April to 22 August (Fig. 3).

Sampling for yearling steelhead (*Oncorhynchus mykiss*) and chinook salmon (*Oncorhynchus tshawytscha*) was conducted 15 km downstream from Ice Harbor Dam from 24 April to 10 June (Fig. 2). Sampling for fall chinook salmon released from Spring Creek was conducted downstream from Bonneville Dam from 14 to 23 March (Fig. 3).

Sampling Methods

Electrofishing from a boat equipped with a pair of adjustable booms fitted with umbrella anode arrays was the primary means of fish collection. All electrofishing used pulsed direct current at 30 pulses/second, 400-500 volts, and 1-2 amperes. A 7.5-m 2-stick seine with 12.7-mm webbing was also used in some shallow areas (less than 1 m deep), with two people pulling the seine upstream along the beach.

Downstream from Bonneville Dam, along shorelines having steep gradients, a 3.4-m-deep, 50-m, variable-mesh beach seine was used to collect fish. The beach seine consisted of a 14.0-m panel of 19.0-mm mesh, a 17.1-m panel of 12.7-mm mesh, a 5.5-m panel of 9.5-mm mesh, and a 13.4-m panel of 19.0-mm mesh (all webbing sizes were stretch measure). For deployment, one end of the seine was anchored on shore and the other was swung upstream in a wide arc using a 5-m outboard-powered boat. The seine was pulled onto the beach by hand, crowding captured fish into the bunt.

Salmonids downstream from Bonneville Dam were primarily sampled by electrofishing, while those in the lower Snake River were collected using a purse seine 15 km downstream from Ice Harbor Dam. The seine, 100-m long by 7-m deep, was deployed with an 11-m barge and

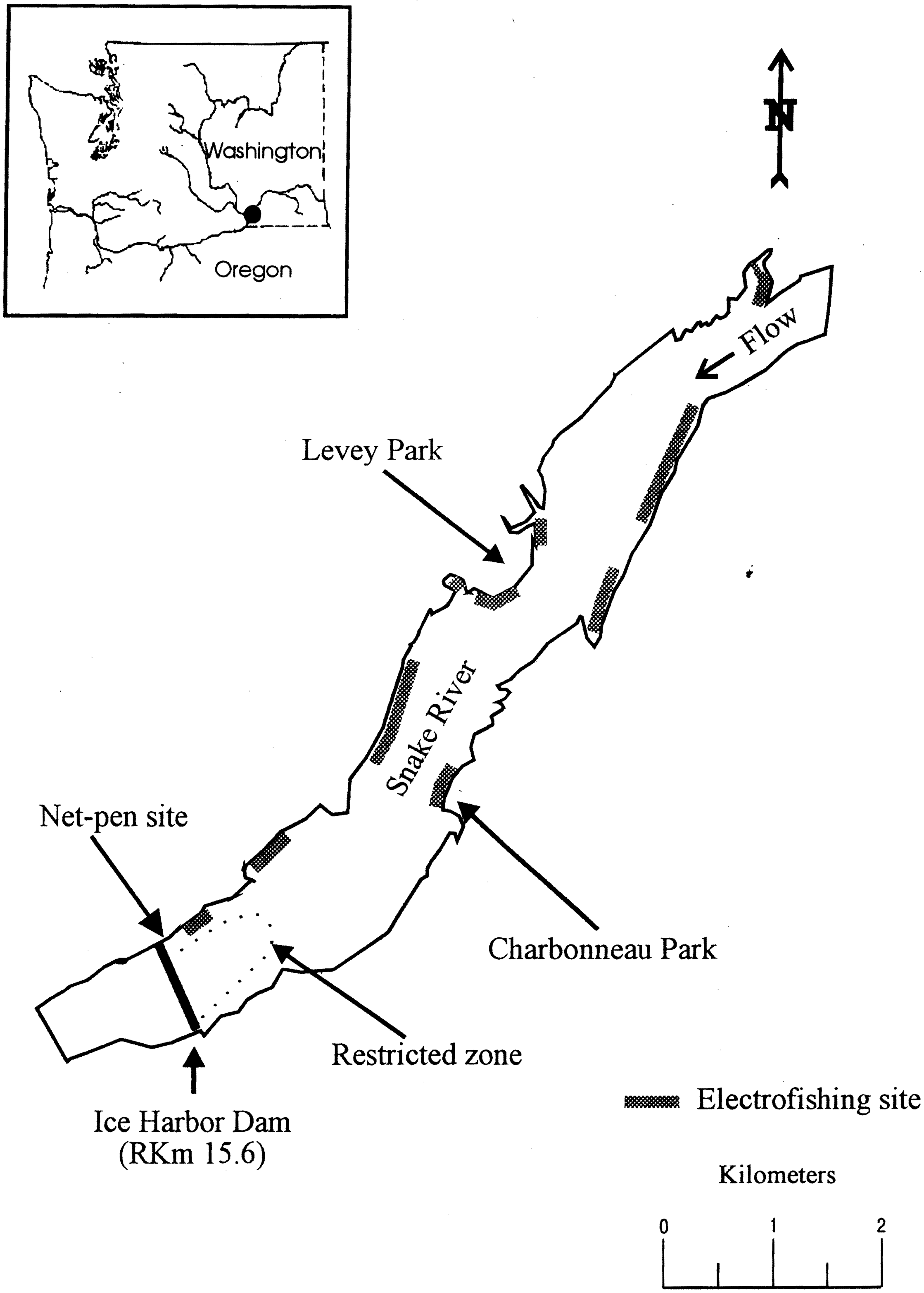

Figure 1. Sampling sites in Ice Harbor Reservoir, 1997.

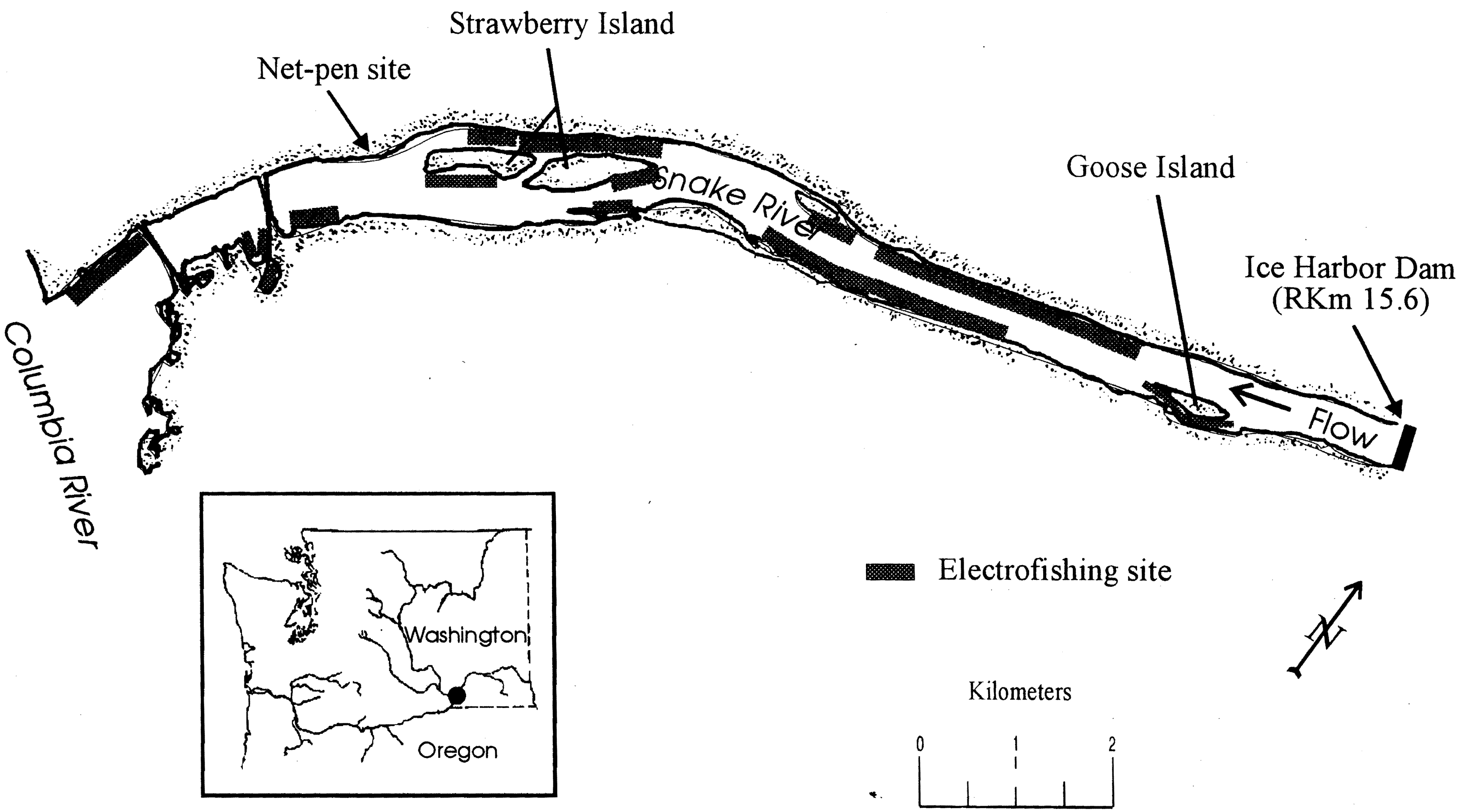

Figure 2. Sampling sites downstream from Ice Harbor Dam, 1997.

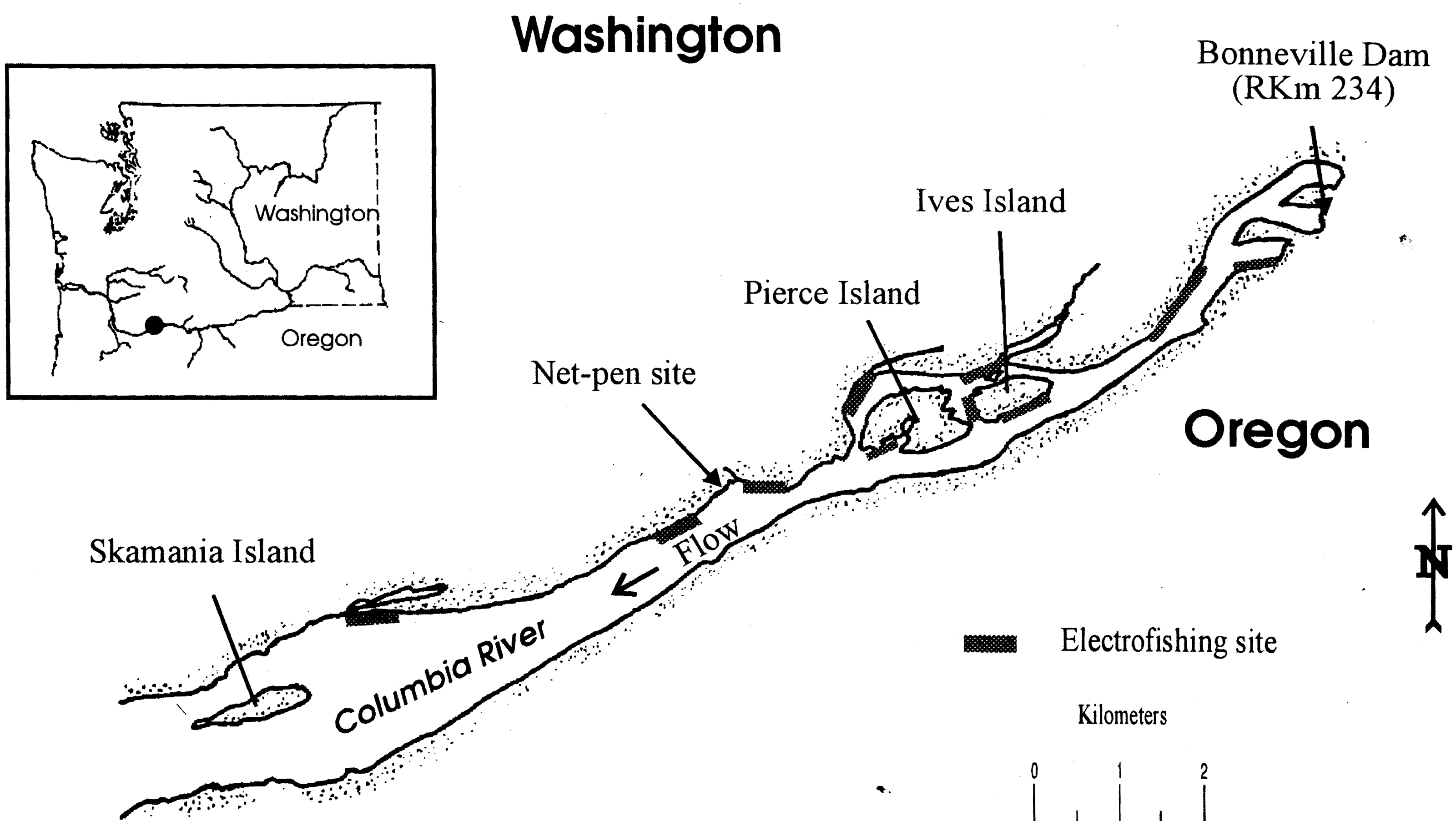

Figure 3. Sampling sites downstream from Bonneville Dam, 1997.

a 6-m skiff. It was towed against the current for 10 minutes, pursed, and pulled by hand until the fish could be dipped from the bunt end with a sanctuary dip-net. From the time the seine was pursed until the salmonids were examined, the fish were residing in 1 m or less of water (up to 30 minutes).

All fish were anesthetized using tricaine methane sulfonate (MS-222), identified, measured to the nearest millimeter, and examined for external injuries and external signs of GBD (subcutaneous emphysema on fins, head, eyes, and body surface). Individual fish were examined externally using a 2.5- to 5-power headband magnifying lens. We considered external signs of GBD severe when greater then 25% of a fin was occluded with bubbles or when bubbles were present on the head, eye, or body. Reference to GBD signs in this report are to external GBD signs unless otherwise noted. Internal examinations of fish were not conducted. Most examinations were made at sampling sites within 15 minutes of collection. During examinations, fish were held at ambient temperature and dissolved gas levels. All specimens were allowed to recover fully from the anesthetic prior to release or introduction into holding pens. Subsamples of 10 resident fish a week from each reach were examined for gas emboli in the lateral line and gill lamellae. Downstream from Bonneville Dam, subsamples of 10 fall chinook salmon were examined daily for gas emboli in the lateral line and gill lamellae from 14 to 23 March.

Net-Pen Studies

Weekly observations of survival rates and changes in prevalence of GBD were made for resident fish held captive in net-pens and cages. Up to 100 individuals of each species were collected from each river reach, examined for signs of GBD, held in enclosures for 4 days, and then reexamined for signs of GBD.

Three types of enclosures were used: 1) shallow cages held at the surface, which provided a maximum depth of 0.5 m (0.6 x 0.6 x 1.0 m made of perforated aluminum-plate); 2) deep submerged cages held from 2.0 to 3.0 m in depth (0.6 x 0.6 x 1.0 m made of perforated aluminum-plate), and 3) large net-pens (1.8 x 2.44 m) with an inclined bottom that extended from the surface to 4 m. Built into each net-pen was a webbing partition extending from the water surface to the bottom and running the entire length of the pen (Fig. 4). To help reduce intra-pen predation, fish over 140 mm were placed on one side of the partition and fish under 140 mm were placed on the other side. Fish held in net-pens had access from the water surface to a depth of 4 m. The large 0- to 4-m net-pen was intended as a surrogate for the river environment, while the two smaller cages were controls.

After 4 days of holding, all fish from each of the three enclosure types were reexamined for signs of GBD and injuries. Subsamples of up to 10 fish were examined more closely for gas bubbles in the lateral line, branchial arteries, and gill lamellae using a dissecting microscope with 20-power magnification. Mortalities were dissected and examined for external, lateral line, and gill lamellae signs of GBD except those in moderate to extreme states of decomposition.

Dissolved Gas Measurements

Tensionometers (D'Aoust et al. 1976) were used to measure TDGS at the time and place of sampling fish. Means and ranges of TDGS during 4-day holding periods were determined from dissolved gas data accessed from the Columbia River Operations Hydro-Met System (CROHMS) data network of the COE.

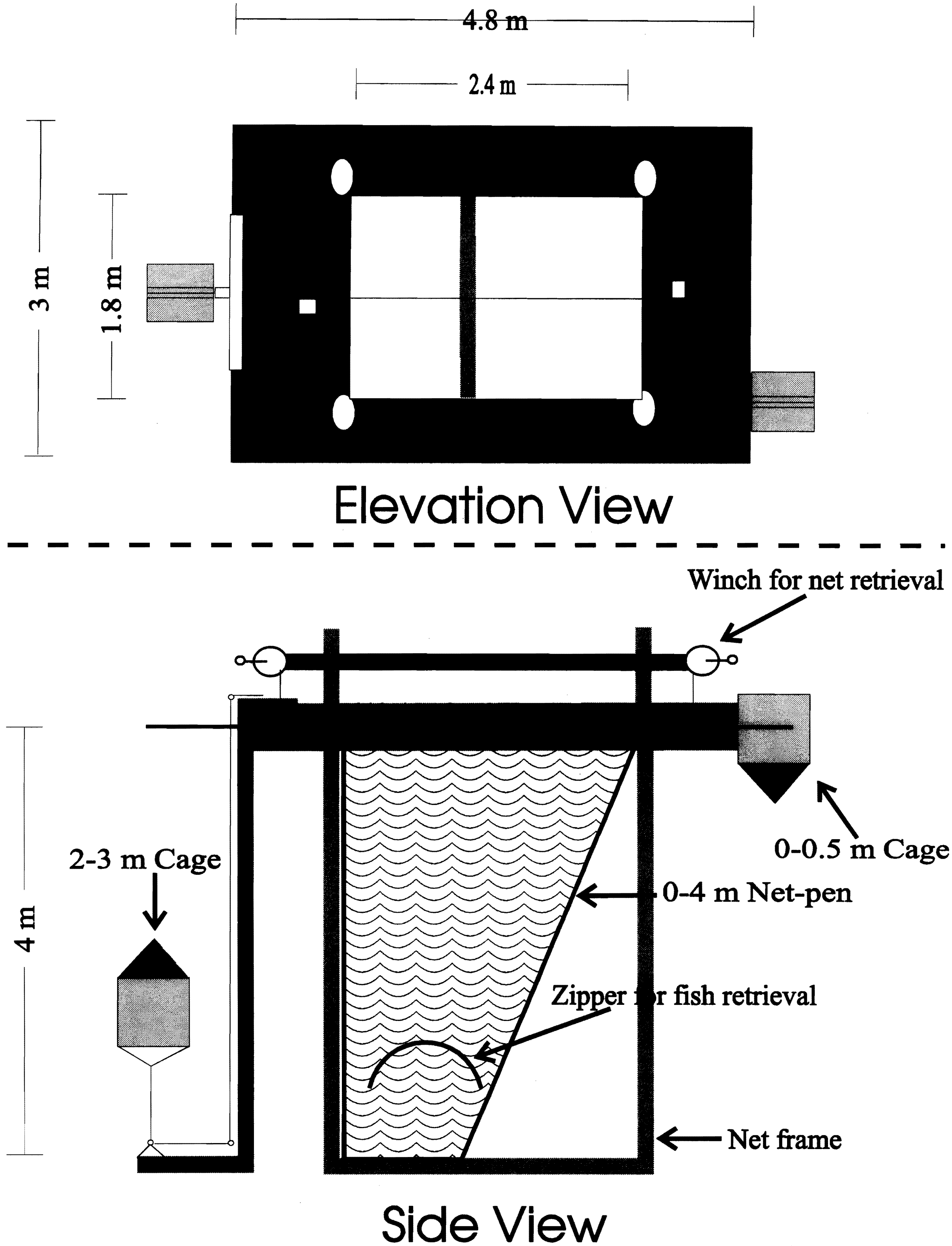

Figure 4. Net-pen, cages, and support barge used for resident fish holding experiments.

Gas Bubble Disease Effects Model

We used GBD prevalence and severity data only from resident fish sampled in areas where TDGS was within 7% of the CROHMS 24-hour mean mid-river saturation level.[1] This selection was intended to exclude GBD observations of fish inhabiting river locations where total dissolved gas saturations may have differed from those at monitoring stations; i.e., inhabitants of back-water ponds and sloughs. To eliminate anomalies due to small sample size, daily samples of less than 50 fish were not used for modeling.

We focused our sampling efforts in areas of known high concentrations of resident species and to depths between 0 and 3 m because the pressure compensation at the 3-m depth is approximately 30% of saturation: fish captured below 3-m would not experience effects from dissolved gas supersaturation until TDGS at the surface exceeded 130%.

Sampling and net-pen data were utilized for modeling only when there was continuity of dissolved gas measurements at that location. We required a dissolved gas reading at the time of observation and every 6 hours for the prior 7 consecutive days. This criterion eliminated use of data from observations downstream from Priest Rapids Dam and also eliminated most of our 1994 sampling data because of inconsistent and inaccurate TDGS measurements.

To ensure that mortality data from captive fish groups represented effects from GBD, only data from high saturation periods (>120%), when GBD signs were present on surviving fish, were utilized.

Correlations between GBD signs, mortality, and environmental factors were evaluated with regression analysis and bootstrapping statistics.

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[1] Mean of the 24 hourly readings taken from the CROHMS instrument located in the appropriate reach.

RESULTS

Sampling

Ice Harbor Reservoir

Individuals from 13 of the 19 taxa collected in 1997 from Ice Harbor Reservoir displayed GBD signs. Among the 3,313 resident fish examined, 7.9% displayed GBD signs (Table 1).

Daily mean mid-river TDGS was moderately high, remaining above 120% from 11 May to 21 June and exceeding 125% on 17 occasions. Signs of GBD during this period were observed on 9.8% of the 2,082 resident fish examined (Fig. 5); 23% of these fish displayed severe GBD signs (greater than 25% of a fin or other body surface affected by emphysema). This period corresponded with the greatest prevalence of GBD signs in sampled fish. High spill volumes[2] (up to 149,000 ft^3/second and 72% of the total river flow) at Lower Monumental Dam caused the increased TDGS levels. Daily prevalence of GBD signs ranged from 2.4 to 22.4% during the high TDGS period (samples greater than 25) (Table 2) (Fig. 5).

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[2] English units by COE convention; 1,000 ft^3/second = 28.3 m^3/second.

Table 1. Numbers sampled, size ranges, and prevalences of gas bubble disease (GBD) by taxon for fish collected from Ice Harbor Reservoir, 1997.

Common name	Scientific name	Sample size (n)	Length range[a] (mm)	Prevalence of GBD[b] (n)	Prevalence of GBD[b] (%)
Peamouth	*Mylocheilus caurinus*	730	60-335	27	3.7
Smallmouth bass	*Micropterus dolomieui*	690	47-437	85	12.3
Yellow perch	*Perca flavescens*	537	40-225	35	6.5
Sucker	*Catostomus* spp.	522	33-515	24	4.6
Bluegill	*Lepomis macrochirus*	194	34-183	30	15.5
Pumpkinseed	*Lepomis gibbosus*	157	39-180	22	14.0
Sculpin	*Cottus* spp.	102	50-149	12	11.8
Chiselmouth	*Acrocheilus alutaceus*	91	42-242	4	4.4
Largemouth bass	*Micropterus salmoides*	84	42-480	13	15.5
Northern squawfish	*Ptychocheilus oregonensis*	72	40-236	3	4.2
Crappie	*Pomoxis* spp.	39	37-297	3	7.7
Sand roller	*Percopsis transmontana*	38	53-97	0	0.0
Bullhead	*Ameiurus* spp.	28	31-484	3	10.7
Tench	*Tinca tinca*	23	68-243	2	8.7
Lamprey	*Lampetra* spp.	2	95-120	0	0.0
Whitefish	*Prosopium* spp.	2	76-78	0	0.0
Carp	*Cyprinus carpio*	1	232	0	0.0
Chinook salmon	*Oncorhynchus tshawytscha*	1	57	0	0.0
Redside shiner	*Richardsonius balteatus*	1	67	0	0.0
Total salmonids		1		0	0.0
Total nonsalmonids		3,313		263	7.9

[a] Total lengths measured for all nonsalmonids and fork lengths for salmonids.

[b] External examination for signs of GBD using a 2.5- to 5.0-power headband magnifying lens.

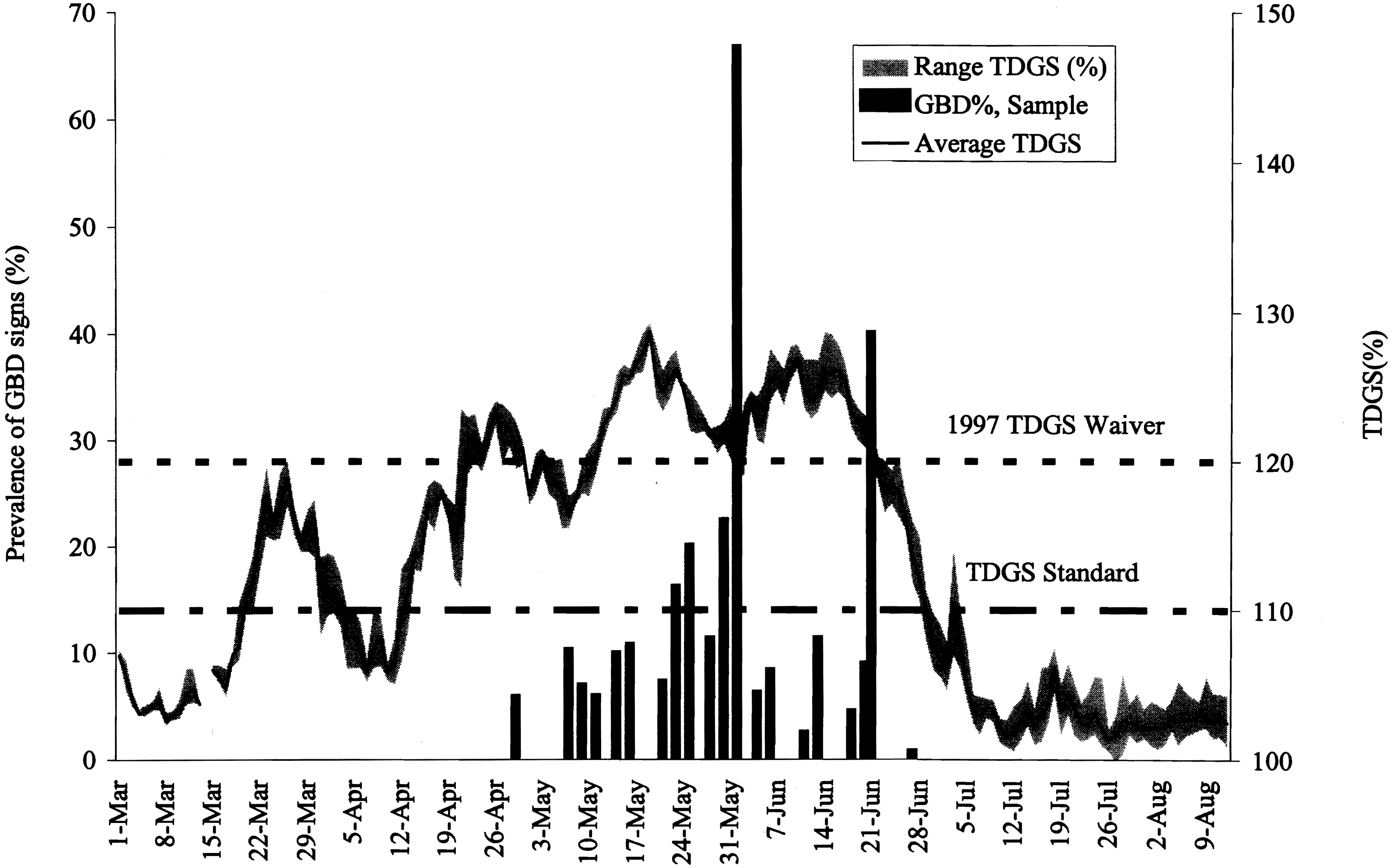

Figure 5. Prevalence of gas bubble disease (GBD) in resident fish collected in Ice Harbor Reservoir compared with daily average and range of total dissolved gas saturation (TDGS) (COE, Ice Harbor Dam forebay), 1997.

Table 2. Total dissolved gas saturation (TDGS) at sampling sites, prevalence of external signs of gas bubble disease (GBD) by severity, and total prevalence of GBD among resident fish sampled in Ice Harbor Reservoir, 1997.

		Prevalence of GBD by severity							
		Fins[a]							
		Rank	Rank	Rank	Rank	Body,	Total	% TDGS	
	Sample	1	2	3	4	eye, head	GBD[b]	at sampling site/s	
Date	(n)	(n)	(n)	(n)	(n)	(n)	(%)	Average	Range
29-Apr	138	2	3	2	0	1	5.8	123	120.9-123.8
7-May	313	14	3	0	1	14	10.2	117	116.4-117.6
9-May	247	10	4	0	0	3	6.9	120	119.1-121.0
11-May	17	1	0	0	0	0	5.9	121	One measurement
14-May	273	17	5	3	0	2	9.9	121	119.8-121.1
16-May	178	9	5	0	1	4	10.7	125	122.8-125.6
21-May	194	6	3	1	0	4	7.2	123	120.9-125.9
23-May	186	19	3	1	0	7	16.1	124	123.9-125.9
25-May	10	0	0	0	0	2	20.0	123	One measurement
28-May	231	18	6	0	0	2	11.3	120	118.4-122.9
30-May	67	11	3	1	0	0	22.4	121	120.9-121.8
1-Jun	9	6	0	0	0	0	66.7	121	One measurement
4-Jun	243	8	0	0	0	7	6.2	120	117.3-123.5
6-Jun	157	10	1	0	0	2	8.3	123	122.7-123.5
7-Jun	10	0	0	0	0	0	0.0	120	One measurement
11-Jun	82	1	0	1	0	0	2.4	124	120.4-128.2
13-Jun	124	9	1	0	0	4	11.3	123	120.0-125.3
14-Jun	10	0	0	0	0	0	0.0	124	One measurement
18-Jun	180	3	2	1	0	2	4.4	120	116.5-122.6
20-Jun	101	5	2	0	0	2	8.9	122	120.2-123.2
21-Jun	10	2	1	0	0	1	40.0	122	One measurement
27-Jun	139	1	0	0	0	0	0.7	114	111.4-115.3
28-Jun	10	0	0	0	0	0	0.0	113	One measurement
2-Jul	144	0	0	0	0	0	0.0	108	107.2-108.9
6-Jul	13	0	0	0	0	0	0.0	108	One measurement
9-Jul	118	0	0	0	0	0	0.0	104	101.3-106.3
13-Jul	10	0	0	0	0	0	0.0	106	One measurement
16-Jul	100	0	0	0	0	0	0.0	108	106.8-109.6

[a] Rank (determined from percent of total fin area with emphysema); 1 = 1-5%, 2 = 6-25%, 3 = 26-50%, 4 = >50%.

[b] Not including fish with GBD in lateral line and/or gills.

Downstream from Ice Harbor Dam

Individuals from 14 of the 22 taxa collected downstream from Ice Harbor Dam in 1997 displayed GBD signs. Among the 5,385 resident fish examined, 3.4% exhibited GBD signs (Table 3).

Daily mean mid-river TDGS was moderately high, remaining above 125% from 20 April to 23 June and exceeding 130% on six occasions. Signs of GBD during this period were observed on 4.5% of the 3,788 resident fish examined (Fig. 6); 29% of these displayed severe GBD signs. High spill volumes (up to 162,100 ft^3/second and 89% of total river flow) at Ice Harbor Dam caused the increased levels of TDGS. Daily prevalence of GBD signs never exceeded 10% in sampled fish (samples greater than 25) (Table 4) (Fig. 6)

Downstream from Bonneville Dam

Individuals from 10 of the 27 taxa collected downstream from Bonneville Dam in 1997 displayed GBD signs. Among the 2,046 resident fish examined, 7.0% exhibited GBD signs (Table 5).

Daily mean mid-river TDGS was high, remaining above 125% from 23 April to 25 June and exceeding 135% on 12 occasions. Signs of GBD during this period were observed on 18.0% of the 813 resident fish examined (Fig. 7); 30% of these displayed severe GBD signs. High spill volumes (up to 448,000 ft^3/second and 82% of total river flow) at Bonneville Dam caused the increased TDGS levels. Daily prevalence of GBD signs ranged from 4.1 to 30.1% and exceeded 20% on three separate days during the high TDGS period (Table 6) (Fig. 7).

Table 3. Numbers sampled, size ranges, and prevalences of gas bubble disease (GBD) by taxon for fish collected downstream from Ice Harbor Dam, 1997.

Common name	Scientific name	Sample (n)	Length range[a] (mm)	Prevalence of GBD[b] (n)	(%)
Peamouth	*Mylocheilus caurinus*	2,354	52-370	40	1.7
Sucker	*Catostomus* spp.	806	32-623	46	5.7
Smallmouth bass	*Micropterus dolomieui*	498	40-499	29	5.8
Yellow perch	*Perca flavescens*	434	74-235	17	3.9
Northern squawfish	*Ptychocheilus oregonensis*	376	41-454	15	4.0
Chiselmouth	*Acrocheilus alutaceus*	323	53-348	15	4.6
Largemouth bass	*Micropterus salmoides*	177	35-474	1	0.6
Redside shiner	*Richardsonius balteatus*	108	47-164	2	1.9
Sculpin	*Cottus* spp.	86	50-183	7	8.1
Bluegill	*Lepomis macrochirus*	45	37-188	5	11.1
Crappie	*Pomoxis* spp.	44	70-285	1	2.3
Whitefish	*Prosopium* spp.	34	59-320	1	2.9
Sand roller	*Percopsis transmontana*	29	64-115	0	0.0
Tench	*Tinca tinca*	24	62-240	1	4.2
Bullhead	*Ameiurus* spp.	14	75-274	0	0.0
Pumpkinseed	*Lepomis gibbosus*	13	58-122	1	7.7
Walleye	*Stizostedion vitreum*	7	170-320	0	0.0
Carp	*Cyprinus carpio*	6	110-153	0	0.0
Unidentified fish		4	149-307	0	0.0
Chinook salmon	*Oncorhynchus tshawytscha*	3	45-60	0	0.0
American shad	*Alosa sapidissima*	2	416-473	0	0.0
Lamprey	*Lampetra ayresi*	1		0	0.0
Total salmonids		3		0	0.0
Total nonsalmonids		5,385		181	3.4

[a] Total lengths measured for all nonsalmonids and fork lengths for salmonids.

[b] External examination for signs of GBD using a 2.5- to 5.0-power headband magnifying lens.

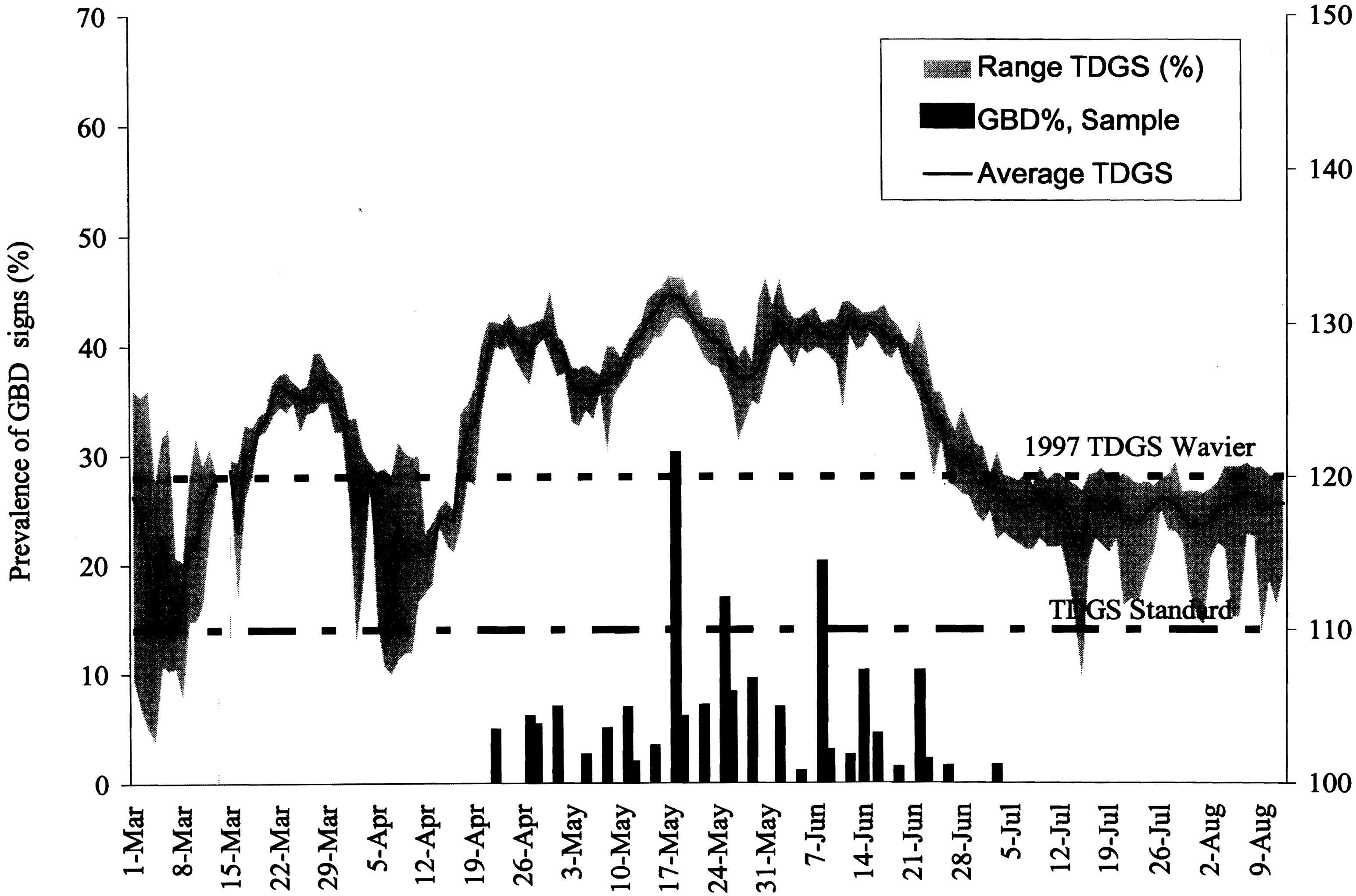

Figure 6. Prevalence of gas bubble disease (GBD) in resident fish collected downstream from Ice Harbor Dam compared with daily average and range of total dissolved gas saturation (TDGS) (COE, Ice Harbor Dam tailrace), 1997.

Table 4. Total dissolved gas saturation (TDGS) at sampling sites, prevalence of external signs of gas bubble disease (GBD) by severity, and total prevalence of GBD among resident fish sampled downstream from Ice Harbor Dam, 1997.

		Prevalence of GBD by severity							
		Fins[a]							
Date	Sample (n)	Rank 1 (n)	Rank 2 (n)	Rank 3 (n)	Rank 4 (n)	Body, eye, head (n)	Total GBD[b] (%)	% TDGS at sampling site/s Average	Range
14-Apr	29	0	0	0	0	0	0.0	117	116.1-117.5
18-Apr	180	0	0	0	0	0	0.0	118	114.8-120.9
22-Apr	43	1	0	0	0	1	4.7	126	126.1-126.2
27-Apr	17	0	1	0	0	0	5.9	122	120.9-122.8
28-Apr	196	6	2	1	0	1	5.1	122	119.6-124.9
1-May	207	11	1	0	0	2	6.8	119	116.0-123.8
5-May	250	2	1	1	0	2	2.4	116	115.0-118.4
8-May	190	3	3	1	1	1	4.7	117	115.3-118.6
11-May	45	1	1	0	0	1	6.7	126	One measurement
12-May	176	0	1	0	0	2	1.7	122	119.4-124.1
15-May	285	6	2	0	0	1	3.2	122	119.2-125.7
18-May	10	2	1	0	0	0	30.0	130	One measurement
19-May	205	3	2	0	0	7	5.9	123	120.9-126.7
22-May	219	8	3	2	0	2	6.8	120	117.8-123.0
25-May	12	1	1	0	0	0	16.7	125	One measurement
26-May	360	15	2	2	2	8	8.1	122	117.9-125.8
29-May	215	14	2	0	0	4	9.3	117	115.0-121.3
31-May	11	0	0	0	0	0	0.0	121	One measurement
2-Jun	120	7	1	0	0	0	6.7	120	One measurement
5-Jun	232	2	0	0	0	0	0.9	119	118.5-119.3
8-Jun	10	0	0	1	0	1	20.0	116	One measurement
9-Jun	181	2	0	0	0	3	2.8	119	116.1-121.3
12-Jun	130	3	0	0	0	0	2.3	124	121.3-125.8
14-Jun	10	1	0	0	0	0	10.0	124	One measurement
16-Jun	165	6	0	0	0	1	4.2	127	125.2-127.9
19-Jun	333	2	0	0	0	2	1.2	123	119.1-126.6
22-Jun	10	1	0	0	0	0	10.0	123	One measurement
23-Jun	156	3	0	0	0	0	1.9	121	120.6-121.7
26-Jun	308	3	1	0	0	0	1.3	114	111.4-115.5
28-Jun	10	0	0	0	0	0	0.0	118	One measurement
30-Jun	141	0	0	0	0	0	0.0	116	114.9-116.1
3-Jul	216	2	0	0	0	1	1.4	115	110.8-117.4
6-Jul	10	0	0	0	0	0	0.0	113	One measurement
7-Jul	217	0	0	0	0	0	0.0	112	107.5-117.5
10-Jul	160	0	0	0	0	0	0.0	122	120.9-123.6
12-Jul	12	0	0	0	0	0	0.0	118	One measurement
14-Jul	101	0	0	0	0	0	0.0	106	104.2-106.8
18-Jul	102	0	0	0	0	0	0.0	108	108.2-108.8
23-Jul	56	0	0	0	0	0	0.0	114	One measurement
29-Jul	58	0	0	0	0	0	0.0	113	One measurement

[a] Rank (determined from percent of total fin area with emphysema); 1 = 1-5%, 2 = 6-25%, 3 = 26-50%, 4 = >50%.

[b] Not including fish with GBD in lateral line and/or gills.

Table 5. Numbers sampled, size ranges, and prevalences of gas bubble disease (GBD) by taxon for fish collected downstream from Bonneville Dam 1997.

Common name	Scientific name	Sample (n)	Length range[a] (mm)	Prevalence of GBD[b] (n)	Prevalence of GBD[b] (%)
Chinook salmon	*Oncorhynchus tshawytscha*	999	38-223	5	0.5
Sucker	*Catostomus* spp.	819	27-600	84	10.3
Peamouth	*Mylocheilus caurinus*	555	32-418	42	7.6
Northern squawfish	*Ptychocheilus oregonensis*	193	38-550	10	5.2
Stickleback	*Gasterosteus aculeatus*	165	19-65	2	1.2
Largemouth bass	*Micropterus salmoides*	74	33-112	0	0.0
Sculpin	*Cottus* spp.	37	53-198	2	5.4
Redside shiner	*Richardsonius balteatus*	36	43-131	1	2.8
Whitefish	*Prosopium* spp.	28	117-360	1	3.6
Yellow perch	*Perca flavescens*	25	59-133	0	0.0
Carp	*Cyprinus carpio*	24	70-178	0	0.0
Smallmouth bass	*Micropterus dolomieui*	16	73-357	0	0.0
Crappie	*Pomoxis* spp.	13	53-103	0	0.0
Dace	*Rhinichthys* spp.	12	68-87	0	0.0
Chiselmouth	*Acrocheilus alutaceus*	9	137-272	0	0.0
Bluegill	*Lepomis macrochirus*	8	54-123	0	0.0
Bullhead	*Ameiurus* spp.	8	203-245	0	0.0
Killifish	*Fundulus diaphanus*	7	74-83	0	0.0
Pumpkinseed	*Lepomis gibbosus*	7	78-131	0	0.0
American shad	*Alosa sapidissima*	4	26-442	1	25.0
Coho salmon	*Oncorhynchus kisutch*	3	160-199	1	33.3
Sand roller	*Percopsis transmontana*	2	95-109	0	0.0
Goldfish	*Carassius auratus*	1	167	0	0.0
Lamprey	*Lampetra ayresi*	1	189	0	0.0
Steelhead	*Oncorhynchus mykiss*	1	181	0	0.0
Tench	*Tinca tinca*	1	169	0	0.0
Walleye	*Stizostedion vitreum*	1	442	0	0.0
Total salmonids		1,003		6	0.6
Total nonsalmonids		2,046		143	7.0

[a] Total lengths measured for all nonsalmonids and fork lengths for salmonids.

[b] External examination for signs of GBD using a 2.5- to 5.0-power headband magnifying lens.

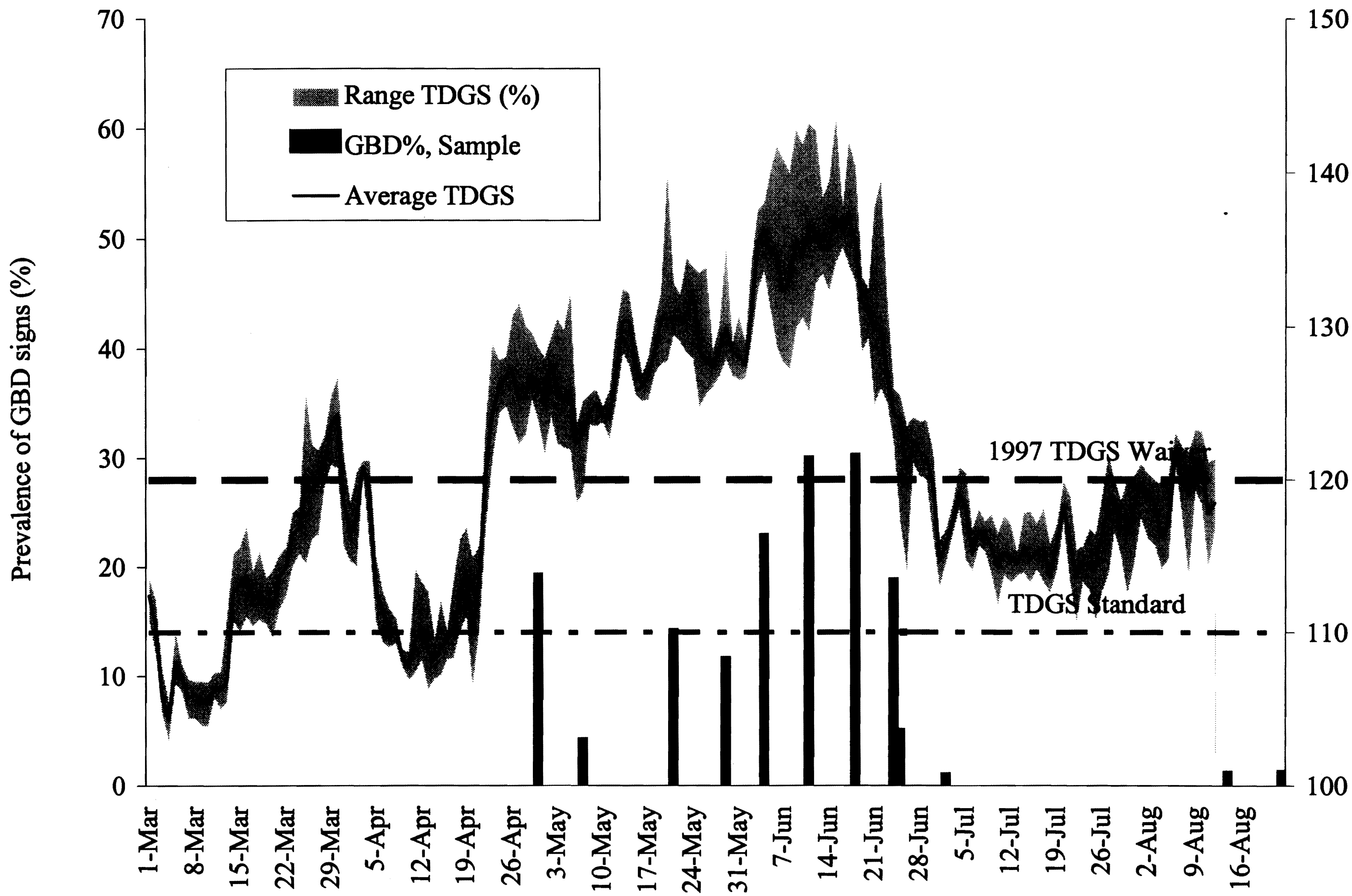

Figure 7. Prevalence of gas bubble disease (GBD) in resident fish collected downstream from Bonneville Dam compared with daily average and range of total dissolved gas saturation (TDGS) (COE, Skamania), 1997.

Table 6. Total dissolved gas saturation (TDGS) at sampling sites, prevalence of external signs of gas bubble disease (GBD) by severity, and total prevalence of GBD among resident fish sampled downstream from Bonneville Dam, 1997.

		Prevalence of GBD by severity							
		Fins[a]							
		Rank	Rank	Rank	Rank	Body,	Total	% TDGS	
	Sample	1	2	3	4	eye, head	GBD[b]	at sampling site/s	
Date	(n)	(n)	(n)	(n)	(n)	(n)	(%)	Average	Range
14-Mar	86	0	0	0	0	0	0.0	107	106.0-109.2
15-Mar	84	0	0	0	0	0	0.0	107	106.5-107.1
16-Mar	89	0	0	0	0	0	0.0	110	107.4-111.3
17-Mar	148	0	0	0	0	0	0.0	108	105.9-109.2
18-Mar	150	0	0	0	0	0	0.0	109	106.9-111.2
19-Mar	134	0	0	0	0	0	0.0	109	One measurement
20-Mar	147	0	0	0	0	0	0.0	110	107.8-113.8
21-Mar	150	0	0	0	0	0	0.0	113	112.5-114.3
22-Mar	134	0	0	0	0	0	0.0	112	110.8-114.0
23-Mar	82	0	0	0	0	0	0.0	116	114.3-117.3
22-Apr	101	0	0	0	0	0	0.0	117	117.2-117.8
30-Apr	94	14	4	0	0	0	19.1	126	123.9-127.2
7-May	49	1	1	0	0	0	4.1	122	120.1-123.6
21-May	57	7	1	0	0	0	14.0	126	117.7-130.9
29-May	113	7	4	1	0	1	11.5	127[c]	125.4-130.9[c]
4-Jun	101	11	7	0	1	4	22.8	134[c]	131.1-134.4[c]
11-Jun	107	11	8	4	7	2	29.9	134[c]	127.2-139.7[c]
18-Jun	83	15	3	1	2	4	30.1	130	129.5-130.3
24-Jun	107	5	2	1	0	12	18.7	122[c]	119.9-122.4[c]
25-Jun	102	1	0	0	0	4	4.9	121[c]	114.7-122.4[c]
2-Jul	113	0	0	0	0	1	0.9	116	114.6-116.6
8-Jul	129	0	0	0	0	0	0.0	110	One measurement
9-Jul	100	0	0	0	0	0	0.0	115	One measurement
17-Jul	122	0	0	0	0	0	0.0	113[c]	110.8-114.6[c]
18-Jul	94	0	0	0	0	0	0.0	111[c]	110.1-112.2[c]
25-Jul	57	0	0	0	0	0	0.0	113	One measurement
1-Aug	67	0	0	0	0	0	0.0	122	One measurement
7-Aug	70	0	0	0	0	0	0.0	120	One measurement
14-Aug	93	0	0	0	0	1	1.1	121	One measurement
22-Aug	86	0	0	0	0	1	1.2	122	120.1-122.9

[a] Rank (determined from percent of total fin area with emphysema); 1 = 1-5%, 2 = 6-25%, 3 = 26-50%, 4 = >50%.

[b] Not including fish with GBD in lateral line and/or gill.

[c] Estimated TDGS (adjusted from COE data, Skamania).

Juvenile Salmonids

While electrofishing for resident fish above and below Ice Harbor Dam, four salmonids were captured and one displayed GBD signs (Table 1 and 3).

Downstream 15 km from Ice Harbor Dam, juvenile salmonids were purse-seined in mid-channel from 24 April to 10 June. Signs of GBD were observed in 13.7% of the 738 juvenile salmonids (Table 7). Prevalence of GBD in salmonids collected from the smolt bypass system at Ice Harbor Dam was 5.2%. Prevalence at the dam was substantially less than in cohorts that traversed the 15-km reach downstream from the dam (Table 8). Steelhead captured downstream from Ice Harbor Dam constituted 84% of the salmonid sample and displayed an average 49% increase in prevalence of signs over steelhead examined at Ice Harbor Dam ($t = 2.77$, $P = 0.028$; Table 8) (Fig. 8). Regression analysis of GBD sign prevalence of seined steelhead in relation to TDGS levels upstream and downstream from Ice Harbor Dam revealed a strong correlation (R^2=0.761).

Downstream from Bonneville Dam from 14 March to 22 August 1997, we examined 1,003 juvenile salmonids for signs of GBD; only 6 displayed signs of GBD (Table 5). The majority of salmonids (98.5%) were captured from 14 to 23 March, when daily average TDGS did not exceed 117%.

Lateral Line and Gill Lamellae Signs

The was no consistency of lateral-line GBD signs at specific TDGS levels and no correlation between these signs and increasing TDGS levels. Signs of GBD in the gill lamellae were not observed among fish sampled in 1997 (Table 9).

Table 7. Numbers sampled, size ranges, and prevalences of gas bubble disease (GBD) by taxon for fish collected mid-river by purse seine downstream from Ice Harbor Dam, 1997.

Common name	Scientific name	Sample (n)	Length range[a] (mm)	Prevalence of GBD[b] (n)	Prevalence of GBD[b] (%)
Steelhead	*Oncorhynchus mykiss*	621	107-350	91	14.7
Chinook salmon	*Oncorhynchus tshawytscha*	117	71-260	10	8.5
Peamouth	*Mylocheilus caurinus*	8	78-331	0	0.0
Redside shiner	*Richardsonius balteatus*	3	146-162	0	0.0
Sucker	*Catostomus* spp.	3	118-400	0	0.0
Yellow perch	*Perca flavescens*	2	109-110	0	0.0
Bullhead	*Ameiurus* spp.	1	210	0	0.0
Northern squawfish	*Ptychocheilus oregonensis*	1	280	0	0.0
Total salmonids		738		101	13.7
Total nonsalmonids		18		0	0.0

[a] Total lengths measured for all nonsalmonids and fork lengths for salmonids.

[b] External examination for signs of GBD using a 2.5- to 5.0-power headband magnifying lens.

Table 8. Observations of gas bubble disease (GBD) signs in juvenile salmonids at and downstream from Ice Harbor Dam related to total dissolved gas supersaturation (TDGS) in the river reach, 1997.

Trap samples at Ice Harbor Dam

				Proportion of fish with emphysema			
				Fins[c]			
Date	24-h high TDGS%[a]	Spp[b]	(n)	Rank 1 (n)	Rank 2 (n)	Total external signs%	Lateral line emboli%
25-Apr	123	CH	74	1	0	1	1
		ST	100	1	0	1	1
29-Apr	123	CH	95	2	0	2	1
		ST	100	3	0	3	0
6-May	120	CH	15	0	0	0	0
		ST	100	2	0	2	1
13-May	124	CH	20	0	0	0	0
		ST	100	0	0	0	4
20-May	128	CH	17	1	2	18	12
		ST	100	9	2	11	2
27-May	123	CH	8	1	0	13	0
		ST	100	5	2	7	6
3-Jun	125	CH	24	1	0	4	0
		ST	100	3	1	4	6
10-Jun	128	CH	12	1	1	17	8
		ST	100	11	6	17	3

Purse seine samples 15 km downstream from Ice Harbor Dam

				Proportion of fish with emphysema						
				Fins[c]						
Date	24-h high TDGS%[a]	Spp[b]	Samp (n)	Rank 1 (n)	Rank 2 (n)	Rank 3 (n)	Rank 4 (n)	Body, eye or head (n)	Total external signs%	Lateral line emboli%
24-Apr	131	CH	29	0	0	0	0	0	0	--
		ST	80	1	0	0	0	0	1	--
30-Apr	130	CH	49	0	0	0	0	0	0	--
		ST	93	7	1	0	1	0	10	--
6-May	127	CH	10	0	0	0	0	0	0	--
		ST	141	0	0	0	0	0	0	--
16-May	130	CH	0	--	--	--	--	--	--	--
		ST	101	16	1	0	1	0	18	2
20-May	132	CH	17	3	2	0	0	0	29	6
		ST	67	16	6	1	0	1	36	--
27-May	128	CH	6	0	0	0	1	0	17	0
		ST	75	10	0	0	0	0	13	--
3-Jun	131	CH	3	0	0	0	0	0	0	0
		ST	55	9	0	0	0	0	16	--
10-Jun	130	CH	3	0	0	0	0	0	0	0
		ST	9	1	1	0	0	0	22	--

[a] Highest level of total dissolved gas saturation measured by the COE tailrace or forebay monitoring station.

[b] The two species of salmonids observed are abbreviated CH for chinook salmon and ST for steelhead.

[c] Rank (determined from percent of area of the unpaired fin affected most severely with emphysema); 1 = 1-5%, 2 = 6-25%, 3 = 26-50%, 4 = >50%.
Fish examined at Ice Harbor Dam displayed severity of GBD signs no greater than rank = 2 or signs on other body surfaces.

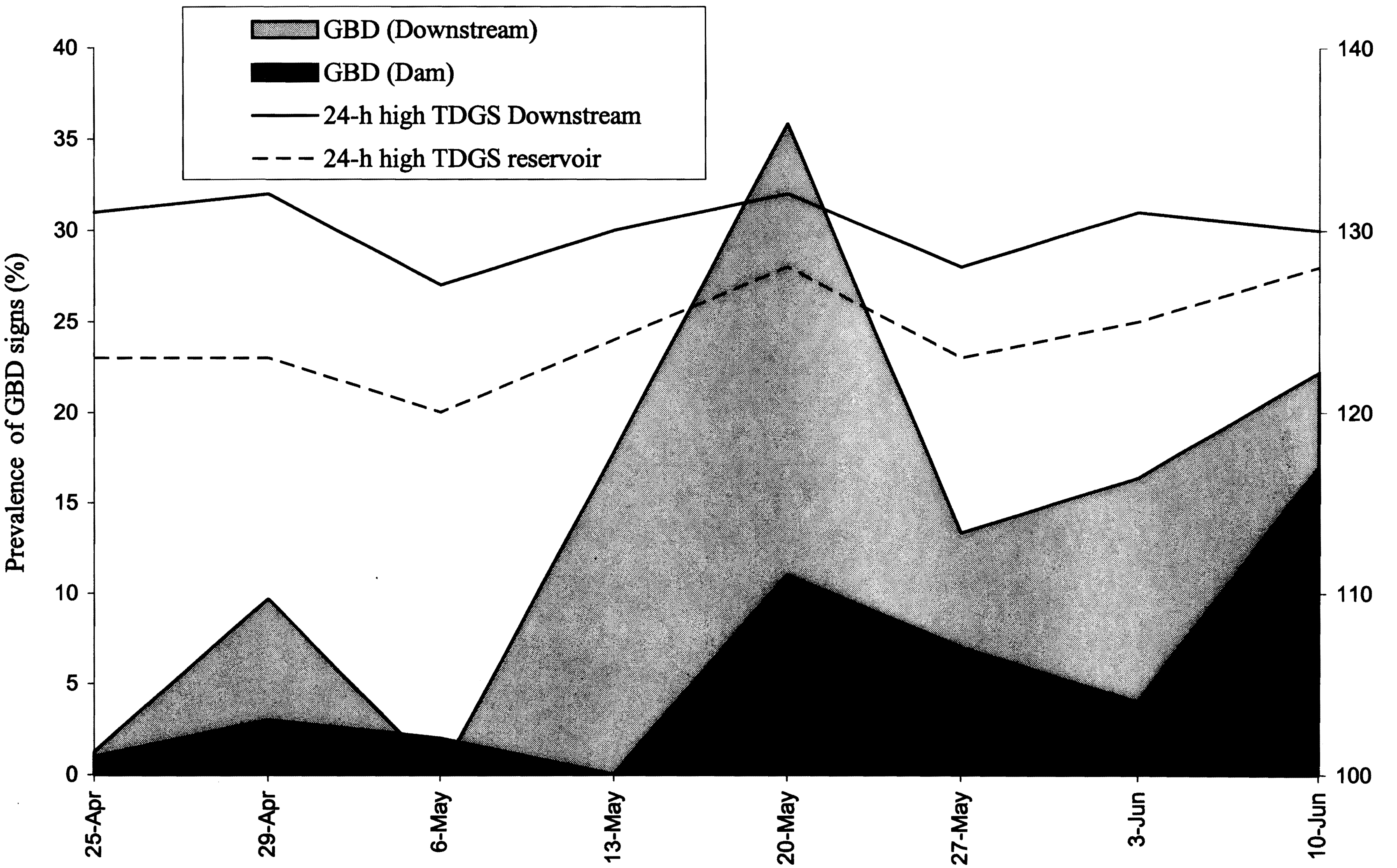

Figure 8. Prevalence of external signs of gas bubble disease (GBD) and total dissolved gas saturation (TDGS) observed on juvenile steelhead at Ice Harbor Dam and 15 km downstream from Ice Harbor Dam. Observation data at Ice Harbor Dam was provided by Mark Plumber, U.S. Army Corps of Engineers.

Table 9. Total dissolved gas saturation (TDGS) at sampling sites and prevalence of gas bubble disease (GBD) signs in the lateral line and gill lamellae among resident fish, 1997.

Downstream from Bonneville Dam[a]

Date	Lateral line[c]	Gill lamellae[d]	%TDGS at sampling site/s Average	Range Min.	Max.
14-Mar	0/10	0/10	107	106.0 - 109.2	
15-Mar	0/10	0/10	107	106.5 - 107.1	
16-Mar	0/10	0/10	110	107.4 - 111.3	
17-Mar	1/10	0/10	108	105.9 - 109.2	
18-Mar	0/10	0/10	109	106.9 - 111.2	
19-Mar	0/10	0/10	109	One measurement	
20-Mar	0/10	0/10	110	107.8 - 113.8	
21-Mar	0/10	0/10	113	112.5 - 114.3	
22-Mar	1/10	0/10	112	110.8 - 114.0	
23-Mar	0/10	0/10	116	114.3 - 117.3	
30-Apr	0/8	0/8	126	123.9 - 127.2	
21-May	0/10	0/10	126	117.7 - 130.9	
29-May	9/10	0/10	127[e]	125.4 - 130.9[e]	
4-Jun	2/10	0/10	134[e]	131.1 - 134.4[e]	
11-Jun	1/10	0/10	134[e]	127.2 - 139.7[e]	
18-Jun	0/10	0/10	130	129.5 - 130.3	
25-Jun	2/10	0/10	121[e]	114.7 - 122.4[e]	
2-Jul	1/10	0/10	116	114.6 - 116.6	
9-Jul	1/10	0/10	115	One measurement	
18-Jul	1/10	0/10	111[e]	110.1 - 112.2[e]	
25-Jul	0/10	0/10	113	One measurement	
1-Aug	1/10	0/10	122	One measurement	
7-Aug	0/10	0/10	120	One measurement	
14-Aug	0/10	0/10	121	One measurement	
22-Aug	0/8	0/8	122	120.1 - 122.9	

Downstream from Ice Harbor Dam[b]

Date	Lateral line[c]	Gill lamellae[d]	%TDGS at sampling site/s Average	Range Min.	Max.
27-Apr	0/13	0/13	122	120.9 - 122.8	
11-May	3/12	0/12	126	One measurement	
18-May	1/10	0/10	130	One measurement	
25-May	2/10	0/10	125	One measurement	
31-May	1/10	0/10	121	One measurement	
8-Jun	5/10	0/10	116	One measurement	
14-Jun	3/10	0/10	124	One measurement	
22-Jun	1/10	0/10	123	One measurement	
28-Jun	1/10	0/10	118	One measurement	
6-Jul	0/10	0/10	113	One measurement	
12-Jul	3/11	0/12	118	One measurement	
14-Jul	1/10	0/10	106	104.2 - 106.8	
18-Jul	0/6	0/6	108	108.2 - 108.8	
23-Jul	0/10	0/10	114	One measurement	
29-Jul	0/10	0/10	113	One measurement	

Ice Harbor Reservoir

Date	Lateral line[c]	Gill lamellae[d]	%TDGS at sampling site/s Average	Range Min	Max
11-May	1/10	0/10	121	One measurement	
25-May	0/10	0/10	123	One measurement	
1-Jun	1/9	0/9	121	One measurement	
7-Jun	2/10	0/10	120	One measurement	
14-Jun	3/10	0/10	124	One measurement	
21-Jun	0/10	0/10	122	One measurement	
28-Jun	1/10	0/10	113	One measurement	
6-Jul	1/10	0/10	108	One measurement	
9-Jul	0/10	0/10	104	101.3 - 106.3	
13-Jul	0/10	0/10	106	One measurement	

[a] Includes subyearling chinook salmon targeted in March.

[b] Does not include juvenile salmonids or resident fish sampled by purse seine.

[c] Number of fish with GBD signs in the lateral line / number examined.

[d] Number of fish with GBD signs in gill lamellae / number examined.

[e] Estimated TDGS (adjusted from COE data, Skamania).

Gas Bubble Disease Observations 1994-97

Over the 4-year study we took 202 weekly samples of resident fish, signs of GBD were present in 115 of the weekly samples. The 202 weekly samples contained 27 taxa and 39,924 individual fish with 3.9% displaying GBD signs. In 1994 and 1995, we also took samples of invertebrates downstream from Ice Harbor and Bonneville Dams. We sampled 5,434 individual invertebrates and found only 7 displaying signs of GBD.

Ice Harbor Reservoir

Resident fish in Ice Harbor Reservoir were not sampled for GBD impacts until 1997. In 1997, daily average TDGS was moderately high, remaining above 120% from 11 May to 21 June and exceeding 125% on 17 occasions; GBD signs during this period were observed on 9.8% of the 2,082 resident fish examined.

Downstream from Ice Harbor Dam

Downstream from Ice Harbor Dam in 1994, the daily average TDGS remained above 120% from 4 May to 15 June and exceeded 125% on three occasions; GBD signs during this period were observed on 2.9% of the 3,367 fish examined. In 1995 downstream from Ice Harbor Dam, the CROHMS data were erroneous. However, our intermittent measurements suggest that TDGS levels were high and generally near or above 130% from 8 May to 23 June; GBD signs during this period were observed on 18.1% of the 1,126 fish examined. Daily prevalence of GBD exceeded 20% on two occasions during the high TDGS period and reached 40.8% on 9 May. In 1996, daily average TDGS was high, exceeding 135% from 15 May to 20 June; GBD signs during this period were observed on 18.6% of the 826 fish examined. Daily prevalence of GBD exceeded 30% on three occasions during the high TDGS period, reaching a maximum of 35.5%.

Despite extremely high flow and spill in 1997, daily average TDGS was only moderately high, remaining above 125% from 20 April to 23 June and exceeding 130% on six occasions; GBD signs during this period were observed on 4.5% of the 3,788 fish examined. The relatively low TDGS levels in 1997 were most likely due to the installation of flow deflectors ("flip lips") at Ice Harbor Dam, which decreased plunging and air entrapment from spill. Daily prevalence of GBD never exceeded 10% (maximum 9.3%) (samples greater than 25 fish).

Priest Rapids Reservoir

In Priest Rapids Reservoir during 1994, our sampling was limited to the month of June, when TDGS did not exceed 120%. No signs of GBD were observed on the 750 resident fish examined. In 1995, average daily TDGS exceeded 120% on only 17 occasions from 13 April to 20 June, reaching a maximum of 123.3% on 27 April; GBD signs were observed on 0.9% of the 2,511 fish examined. Daily prevalence of GBD never exceeded 10% and reached a maximum of 5.4% on 1 June. In 1996, daily average TDGS was moderately high, exceeding 120% from 15 April to 8 May and exceeding 125% from 21 May to 26 June. From 12 to 15 July, TDGS exceeded 130% only twice. GBD signs during these periods were observed on 9.2% of the 1,507 resident fish examined. Daily prevalence of GBD exceeded 10% on three occasions during the high TDGS period, reaching a maximum of 23.1%.

Downstream from Priest Rapids Dam

Downstream from Priest Rapids Dam in 1994, the daily average TDGS did not exceed 120% from 4 May to 15 June. Only 5 of the 1,239 (0.4%) resident fish examined during this period displayed GBD signs. In 1996, average daily TDGS was moderately high, remaining above 125% from 23 May to 21 June, but never exceeding 130%. GBD signs during this period were observed on 7.1% of the 451 resident fish examined. Daily prevalence of GBD exceeded 10% on two occasions during the high TDGS period, reaching a maximum of 13.7%. The CROHMS TDGS meter was not operational in April and early May 1996.

Downstream from Bonneville Dam

Downstream from Bonneville Dam in 1994, the daily average TDGS never exceeded 120% and only 3 of 4,955 resident fish examined displayed GBD signs. In 1995, the daily average TDGS in mid-river exceeded 120% only four times and never exceeded 123%. GBD signs were observed on only 2 of 1,963 (0.1%) resident fish. In 1996 at these same locations, daily average TDGS in mid-river exceeded 120% from 11 April to 1 May and from 15 May to 21 June exceeding 130% on 1 June; GBD signs during these periods were observed on 5.1% of the 1,116 resident fish examined. Daily prevalence of GBD exceeded 10% on two occasions during the high TDGS periods, reaching a maximum of 15.8%. In addition to our regular sampling in 1996, from 6 June to 8 August 1,227 Catostomidae larvae were sampled, with 14.3% displaying signs of GBD. Daily average TDGS was the highest of all 4 years in 1997, remaining above 125% from 23 April to 25 June and exceeding 135% on 12 days. GBD signs during this period were observed on 18.0% of the 813 fish examined. Daily prevalence of GBD exceeded 10% on seven occasions during the high TDGS period, reaching a maximum of 19.1%.

Gas Bubble Disease in Captive Fish Groups

Ice Harbor Reservoir

Results of net-pen holding experiments with resident fish conducted in Ice Harbor Reservoir are summarized in Table 10. In 5 of the 17 holding periods, surviving resident fish from the 0- to 4-m pen showed increases (0.9-18.0%) of GBD signs (Fig. 9). When GBD prevalence increased during holding periods, mortality ranged from 4.0 to 19.4% (Table 10). Prevalence of gas emboli in the lateral line and gills of surviving fish ranged from 0 to 75% and 0 to 25%, respectively.

Table 10. Gas bubble disease (GBD), mortality, and total dissolved gas saturation (TDGS) during net-pen experiments holding resident fish in Ice Harbor Reservoir, 1997.

Date/ Conditions[g]	Introduction[a] external[c] GBD (n)	(%)	Survivors Examined[b] external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)	Mortality (n)	(%)	Decom.[f] (n)	Mortalities Examined external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)
April 29-May 3									**TDGS 120 (117.1 - 122.7)[h]**								
deep (2-3 m)[i]	10	0.0	6	0.0	3	0.0	3	0.0	4	40.0	0	4	0.0	3	0.0	1	0.0
0-4 m	38	0.0	29	13.8	4	0.0	4	0.0	7	19.4	2	5	60.0	2	0.0	2	0.0
surface (0-0.5 m)	10	10.0	4	25.0	3	0	3	0	6	60.0	6	0	--	0	--	0	--
May 7-11									**TDGS 118 (115.5 - 121.5)**								
deep (2-3 m)[i]	10	0.0	8	0.0	3	0.0	3	0.0	2	20.0	0	2	0.0	2	0.0	2	0.0
0-4 m	107	15.0	68	7.4	4	0.0	4	0.0	3	4.2	0	3	0.0	1	0.0	1	0.0
surface (0-0.5 m)	10	10.0	10	10.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
May 9-13									**TDGS 121 (117.6 - 123.6)**								
deep (2-3 m)[i]	9	11.1	6	0.0	3	0.0	3	0.0	3	33.3	0	3	0.0	3	33.3	3	0.0
0-4 m	79	13.9	79	2.5	4	0.0	4	0.0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	3	0.0	3	0.0	3	66.7	3	0.0	0	0.0	0	0	--	0	--	0	--
May 14-18									**TDGS 126 (123.2 - 128.6)**								
deep (2-3 m)[i]	6	0.0	0	--	0	--	0	--	6	100.0	0	6	16.7	5	40.0	3	0.0
0-4 m	172	7.6	106	25.5	7	42.9	7	0.0	11	9.4	0	11	9.1	10	20.0	7	0.0
surface (0-0.5 m)	12	0.0	5	40.0	3	0.0	3	0.0	7	58.3	0	7	42.9	7	42.9	6	0.0
May 16-20									**TDGS 127 (124.3 - 129.2)**								
deep (2-3 m)[i]	7	0.0	2	0.0	2	0.0	2	0.0	3	60.0	0	3	0.0	3	0.0	2	0.0
0-4 m	99	8.1	93	0.0	8	0.0	8	25.0	4	4.1	0	4	75.0	4	50.0	3	33.3
surface (0-0.5 m)	5	20.0	0	--	0	--	0	--	5	100.0	0	5	80.0	5	40.0	4	0.0
May 21-25									**TDGS 125 (122.0 - 127.4)**								
deep (2-3 m)	No fish held in deep-pen																
0-4 m	100	8.0	38	13.2	10	20.0	10	0.0	4	9.5	0	4	25.0	4	0.0	3	0.0
surface (0-0.5 m)	1	0.0	1	0.0	0	--	0	--	0	0.0	0	0	--	0	--	0	--
May 23-27									**TDGS 124 (121.9 - 127.4)**								
deep (2-3 m)	10	0.0	9	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	91	14.3	87	8.0	3	0.0	3	0.0	2	2.2	0	2	0.0	2	0.0	2	0.0
surface (0-0.5 m)	11	9.1	9	0.0	3	33.3	3	0.0	2	18.2	0	2	0.0	2	50.0	2	100.0
May 28-June 1									**TDGS 121 (118.7 - 123.8)**								
deep (2-3 m)	12	8.3	13	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	124	12.9	107	8.4	4	0.0	4	0.0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	10	0.0	8	12.5	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
May 30-June 3									**TDGS 122 (118.7 - 124.7)**								
deep (2-3 m)	No fish held in deep-pen																
0-4 m	44	22.7	42	0.0	7	14.3	7	0.0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	3	0.0	3	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--

Table 10. cont.

Date/ Conditions[g]	Introduction[a] external[c] GBD (n)	(%)	Survivors Examined[b] external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)	Mortality (n)	(%)	Decom.[f] (n)	Mortalities Examined external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)
June 4-8									**TDGS 124 (121.1 - 127.6)**								
deep (2-3 m)	7	0.0	7	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	126	4.8	75	1.3	4	75.0	4	0.0	4	5.1	0	4	0.0	2	0.0	2	0.0
surface (0-0.5 m)	11	9.1	8	12.5	2	50.0	2	0.0	2	20.0	0	2	0.0	2	100.0	2	100.0
June 6-10									**TDGS 126 (123.8 - 127.9)**								
deep (2-3 m)	No fish held in deep-pen																
0-4 m	102	6.9	100	1.0	7	14.3	7	0.0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	7	0.0	3	33.3	3	66.7	3	0.0	4	57.1	0	4	25.0	3	33.3	4	50.0
June 11-15									**TDGS 125 (122.9 - 128.7)**								
deep (2-3 m)	2	0.0	2	0.0	2	0.0	2	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	36	2.8	24	20.8	6	0.0	6	16.7	1	4.0	0	1	0.0	0	--	0	--
surface (0-0.5 m)	2	0.0	2	0.0	2	0.0	2	0.0	0	0.0	0	0	--	0	--	0	--
June 13-17									**TDGS 126 (123.3 - 128.7)**								
deep (2-3 m)	2	0.0	2	50.0	2	0.0	2	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	79	7.6	74	1.4	5	0.0	5	0.0	1	1.3	0	1	0.0	0	--	0	--
surface (0-0.5 m)	5	0.0	3	33.3	3	0.0	3	0.0	2	40.0	0.0	2	5.0	1	100.0	1	0.0
June 18-22									**TDGS 122 (118.5 - 124.4)**								
deep (2-3 m)	6	0.0	5	0.0	3	0.0	3	0.0	1	16.7	0	1	0.0	1	0.0	0	--
0-4 m	111	7.2	90	2.2	4	0.0	4	0.0	5	5.3	0	5	0.0	5	20.0	4	0.0
surface (0-0.5 m)	10	0.0	10	10.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
June 20-24									**TDGS 120 (116.5 - 123.1)**								
deep (2-3 m)	2	0.0	2	0.0	2	0.0	2	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	64	6.3	54	7.4	6	0.0	6	0.0	4	6.9	4	4	0.0	4	0.0	4	50.0
surface (0-0.5 m)	2	50.0	2	0.0	2	0.0	2	0.0	0	0.0	0.0	0	--	0	--	0	--
June 27-July 1									**TDGS 110 (105.6 - 116.0)**								
deep (2-3 m)	12	0.0	9	0.0	3	0.0	3	0.0	2	18.2	0	2	0.0	2	0.0	0	--
0-4 m	79	1.3	79	0.6	4	0.0	4	0.0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	7	0.0	7	28.6	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
July 2-6									**TDGS 106 (102.4 - 114.1)**								
deep (2-3 m)	2	0.0	2	0.0	2	0.0	2	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	71	0.0	66	0.0	8	0.0	8	0.0	2	2.9	0	2	0.0	2	0.0	2	0.0
surface (0-0.5 m)	No fish held in surface-pen																

[a] Fish placed in holding pen at beginning of experiment.
[b] Live fish removed from pen at end of experiment.
[c] External signs of GBD.
[d] Signs of GBD in the lateral line.
[e] Signs of GBD in branchial arteries and gill filaments.
[f] Number of dead fish that were too decomposed to examine for GBD signs.
[g] Pen depth.
[h] Average and range of TDGS during holding period (COE, Ice Harbor Dam forebay).
[i] Mortalities due to adverse conditions inherent from sampling and holding.

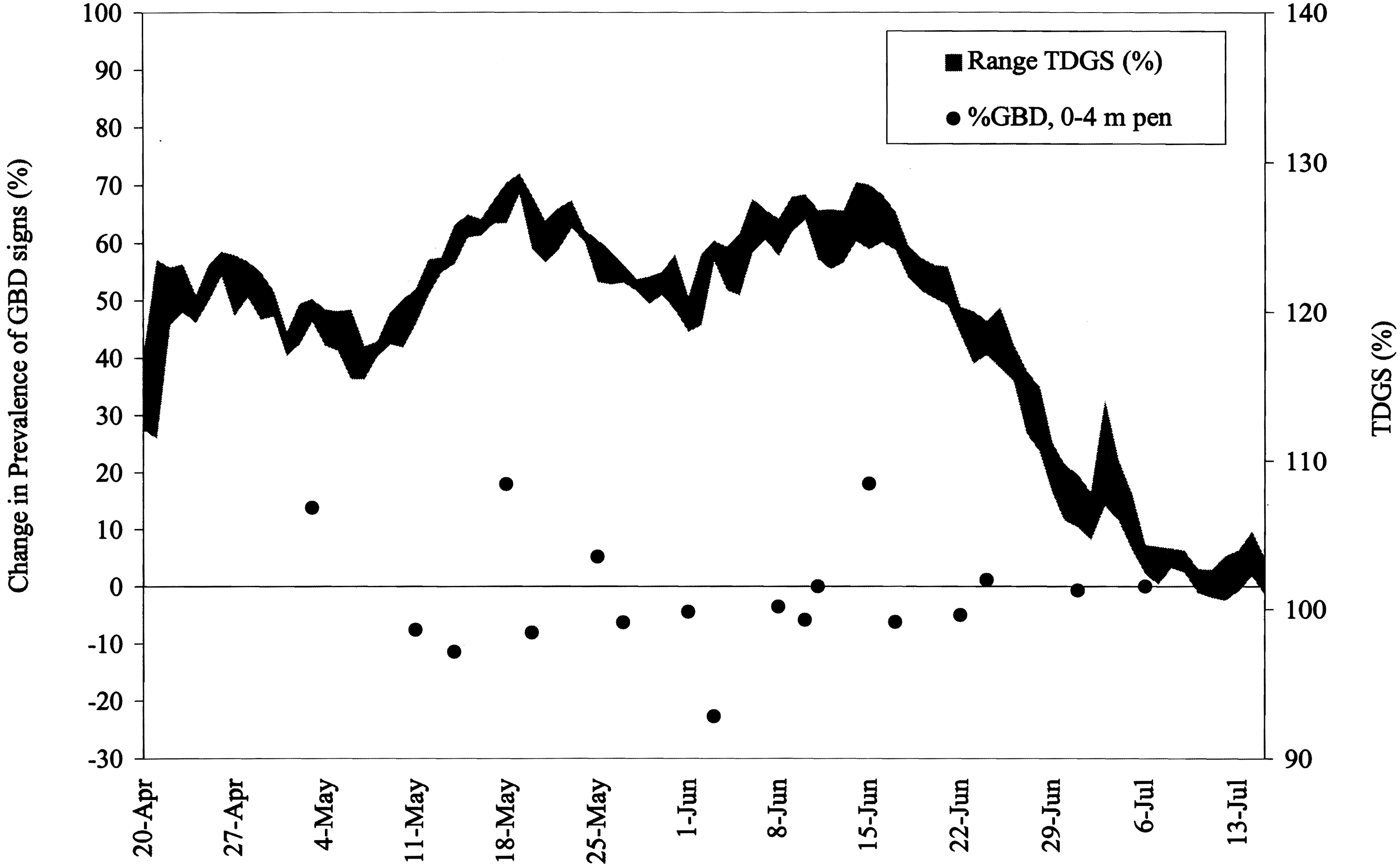

Figure 9. Change in gas bubble disease (GBD) prevalence in resident fish held 4 days in river water in Ice Harbor Reservoir compared with range of total dissolved gas saturation (TDGS) (COE, Ice Harbor Dam forebay), 1997.

Downstream from Ice Harbor Dam

Results of net-pen holding experiments conducted downstream from Ice Harbor Dam with resident fish are summarized in Table 11. In 19 of the 24 holding periods, surviving resident fish from the 0- to 4-m pen showed increases (0.2-59.1%) of GBD signs (Fig. 10). When GBD prevalence increased during holding periods, mortality ranged from 1 to 57.1% (Table 11). Prevalence of gas emboli in the lateral line and gills of surviving fish ranged from 0 to 100% and 0 to 50%, respectively.

Modeling

Gas Bubble Disease Effects Model

We found that mortality in resident fish populations cannot be properly evaluated through sampling because dead fish were rarely observed in the lower Snake and Columbia Rivers. Similar conclusions were made by Merrell et al. (1971), wherein less than 5% of dead salmon released downstream from Bonneville Dam were recovered or observed. The 4-day holding tests in net-pens were intended as a surrogate for evaluating GBD-induced mortality among resident fish, but test results suggested that impacts from GBD were greater for captive fish than for free-swimming fish. Prevalence of GBD signs for captive fish was 13% greater than for in-river fish sampled during the previous week (downstream from Ice Harbor Dam, 1995 and 1996). Because fish held in pens were not a good surrogate for in-river fish, we developed a model to predict prevalence and severity of GBD signs in feral resident fish in relation to dissolved gas exposure. We then estimated mortality based on a relationship between percent GBD signs and percent mortality derived from our net-pen experiments.

Table 11. Gas bubble disease (GBD), mortality, and total dissolved gas saturation (TDGS) during net-pen experiments holding resident fish downstream from Ice Harbor Dam, 1997.

Date/ Conditions[g]	Introduction[a] external[c] (n)	Introduction[a] external[c] GBD (%)	Survivors Examined[b] external[c] (n)	Survivors Examined[b] external[c] GBD (%)	Survivors Examined[b] LL[d] (n)	Survivors Examined[b] LL[d] GBD (%)	Survivors Examined[b] gill[e] (n)	Survivors Examined[b] gill[e] GBD (%)	Mortality (n)	Mortality (%)	Decom.[f] (n)	Mortalities Examined external[c] (n)	Mortalities Examined external[c] GBD (%)	Mortalities Examined LL[d] (n)	Mortalities Examined LL[d] GBD (%)	Mortalities Examined gill[e] (n)	Mortalities Examined gill[e] GBD (%)
April 18-22									**TDGS 126 (119.4 - 130.1)[h]**								
deep (2-3 m)[i]	12	0.0	1	0.0	0	--	0	--	2	66.7	0	2	0.0	0	--	0	--
0-4 m	38	0.0	17	23.5	3	0.0	3	0.0	11	39.3	0	11	9.1	0	--	0	--
surface (0-0.5 m)	10	0.0	10	0.0	0	--	0	--	0	0.0	0	0	--	0	--	0	--
April 22-26									**TDGS 129% (127-131%)**								
deep (2-3 m)[i]	10	0.0	4	0.0	4	25.0	4	0.0	4	50.0	0	4	0.0	4	25.0	4	0.0
0-4 m	17	5.9	6	16.7	1	0.0	1	0.0	8	57.1	0	8	0.0	8	37.5	8	12.5
surface (0-0.5 m)	10	0.0	2	0.0	2	100.0	2	50.0	8	80.0	0	8	62.5	7	85.7	7	42.9
April 28-May 2									**TDGS 129% (127-132%)**								
deep (2-3 m)[i]	10	10.0	0	--	0	--	0	--	9	100.0	0	9	33.3	3	33.3	2	50.0
0-4 m	82	4.9	46	50.0	10	20.0	10	0.0	21	31.3	0	21	19.0	6	33.3	3	0.0
surface (0-0.5 m)	10	0.0	0	--	0	--	0	--	10	100.0	0	10	40.0	7	100.0	7	14.3
May 1-5									**TDGS 126% (123-129%)**								
deep (2-3 m)	12	0.0	9	33.3	3	33.3	3	0.0	1	10.0	0	1	0.0	1	0.0	1	0.0
0-4 m	70	1.4	54	35.2	2	100.0	2	0.0	11	16.9	0	11	18.2	9	0.0	8	0.0
surface (0-0.5 m)	14	0.0	11	54.5	4	25.0	4	0.0	3	21.4	0	3	66.7	3	33.3	3	0.0
May 5-9									**TDGS 126% (122-129%)**								
deep (2-3 m)	18	0.0	5	0.0	5	80.0	5	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	80	2.5	45	37.8	0	--	0	--	8	15.1	0	8	75.0	7	71.4	7	14.3
surface (0-0.5 m)	12	8.3	11	18.2	6	33.3	6	0.0	1	8.3	0	1	100.0	1	100.0	1	100.0
May 8-12									**TDGS 127% (122-129%)**								
deep (2-3 m)	13	0.0	13	0.0	5	0.0	5	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	74	4.1	84	10.7	3	0.0	3	0.0	5	5.6	0	5	60.0	5	20.0	5	20.0
surface (0-0.5 m)	5	20.0	4	75.0	2	50.0	2	0.0	5	55.6	0	5	20.0	5	80.0	5	60.0
May 12-16									**TDGS 130% (128-132%)**								
deep (2-3 m)	10	0.0	10	0.0	3	33.3	3	33.3	0	0.0	0	0	--	0	--	0	--
0-4 m	93	0.0	113	15.0	5	20.0	4	0.0	1	0.9	0	1	0.0	1	0.0	1	0.0
surface (0-0.5 m)	12	0.0	3	33.3	3	33.3	3	100.0	9	75.0	0	9	66.7	9	55.6	7	14.3
May 15-19									**TDGS 131% (129-133%)**								
deep (2-3 m)[i]	21	0.0	6	0.0	3	66.7	3	0.0	1	14.3	0	1	100.0	1	0.0	0	--
0-4 m	108	1.9	60	33.3	4	100.0	4	0.0	9	13.0	0	9	44.4	7	57.1	5	60.0
surface (0-0.5 m)	12	8.3	9	33.3	2	50.0	2	0.0	3	25.0	0	3	66.7	3	33.3		
May 19-23									**TDGS 130 (127.3 - 133.0)**								
deep (2-3 m)[i]	14	7.1	5	0.0	3	66.7	3	0.0	5	50.0	0	5	0.0	3	100.0	2	0.0
0-4 m	63	1.6	22	59.1	4	25.0	4	0.0	11	33.3	0	11	54.5	10	60.0	6	0.0
surface (0-0.5 m)	12	0.0	10	50.0	3	33.3	3	0.0	2	16.7	0	2	100.0	2	100.0	1	100.0

Table 11. cont.

Date/ Conditions[g]	Introduction[a]		Survivors Examined[b]									Mortalities Examined					
	external[c]		external[c]		LL[d]		gill[e]		Mortality		Decom.[f]	external[c]		LL[d]		gill[e]	
	(n)	GBD (%)	(n)	GBD (%)	(n)	GBD (%)	(n)	GBD (%)	(n)	(%)	(n)	(n)	GBD (%)	(n)	GBD (%)	(n)	GBD (%)
May 22-26									**TDGS 128% (125-130%)**								
deep (2-3 m)	3	33.3	3	33.3	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	128	5.5	116	56.9	3	66.7	3	0.0	4	3.3	0	4	75.0	4	100.0	4	50.0
surface (0-0.5 m)	8	0.0	6	33.3	4	0.0	4	0.0	2	25.0	0	4	25.0	4	0.0	4	0.0
May 26-30									**TDGS 126% (122-131%)**								
deep (2-3 m)[i]	14	0.0	8	0.0	4	0.0	4	0.0	1	11.1	0	1	0.0	1	0.0	1	0.0
0-4 m	142	9.9	79	17.7	3	66.7	3	0.0	8	9.2	0	8	50.0	8	12.5	7	42.9
surface (0-0.5 m)	13	7.7	11	9.1	3	0.0	3	0.0	1	8.3	0	1	100.0	1	100.0	0	--
May 29 - Jun 2									**TDGS 129% (125-133%)**								
deep (2-3 m)[i]	20	5.0	11	0.0	3	0.0	3	0.0	8	42.1	0	8	0.0	8	25.0	1	0.0
0-4 m	93	8.6	63	9.5	3	0.0	3	0.0	6	8.7	1	5	40.0	5	20.0	3	33.3
surface (0-0.5 m)	13	7.7	10	20.0	3	0.0	3	33.3	1	9.1	1	0	--	0	--	0	--
June 2-6									**TDGS 130 (127.1 - 132.8)**								
deep (2-3 m)[i]	9	0.0	6	0.0	3	100.0	3	0.0	3	33.3	0	3	66.7	3	33.3	2	0.0
0-4 m	84	8.3	80	47.5	4	25.0	4	0.0	2	2.4	0	2	100.0	2	100.0	1	100.0
surface (0-0.5 m)	7	0.0	4	50.0	4	0.0	4	0.0	3	42.9	0	3	100.0	3	66.7	3	0.0
Jun 5-9									**TDGS 129% (128-131%)**								
deep (2-3 m)[i]	12	0.0	12	0.0	3	0.0	3	0.0	2	14.3	0	2	0.0	2	50.0	2	0.0
0-4 m	150	0.7	145	11.7	3	66.7	3	0.0	3	2.0	0	3	33.3	3	100.0	3	33.3
surface (0-0.5 m)	10	0.0	8	37.5	3	0.0	3	0.0	2	20.0	0	2	100.0	2	100.0	2	0.0
June 9-13									**TDGS 129% (124-131%)**								
deep (2-3 m)	10	0.0	6	33.3	2	50.0	2	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	101	5.0	69	21.7	4	50.0	4	50.0	11	13.8	0	11	72.7	9	66.7	5	40.0
surface (0-0.5 m)	10	0.0	7	42.9	3	33.3	3	0.0	1	12.5	0	1	100.0	1	100.0	1	100.0
Jun 12-16									**TDGS 130% (128-131%)**								
deep (2-3 m)[i]	7	0.0	6	16.7	6	66.7	6	0.0	1	14.3	0	1	0.0	0	--	0	--
0-4 m	95	0.0	86	9.6	4	25.0	4	0.0	2	2.3	0	2	50.0	1	100.0	1	100.0
surface (0-0.5 m)	4	0.0	4	50.0	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
Jun 16-20									**TDGS 129% (127-131%)**								
deep (2-3 m)[i]	10	0.0	8	12.5	3	0.0	3	0.0	1	11.1	0	1	0.0	1	0.0	1	0.0
0-4 m	95	5.3	86	11.6	4	0	4	25	2	2.3	0	2	100.0	2	50.0	2	100.0
surface (0-0.5 m)	10	0.0	10	70.0	4	75.0	4	0.0	0	0.0	0	0	--	0	--	0	--
June 19-23									**TDGS 127% (123-130%)**								
deep (2-3 m)	11	0.0	5	0.0	1	0.0	1	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	177	0.6	105	21.9	6	33.3	6	0.0	3	2.8	0	3	33.3	3	66.7	3	0.0
surface (0-0.5 m)	11	0.0	8	87.5	3	33.3	3	0.0	3	27.3	0	3	33.3	3	0.0	3	66.7
June 23-27									**TDGS 123 (119.3 - 128.1)**								
deep (2-3 m)[i]	10	0.0	2	0.0	2	0.0	2	0.0	2	50.0	0	2	0.0	2	0.0	1	0.0
0-4 m	66	4.5	58	3.4	5	0.0	5	0.0	2	3.3	0	2	0.0	2	0.0	0	--
surface (0-0.5 m)	10	0.0	10	10.0	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--

Table 11. cont.

Date/ Conditions[g]	Introduction[a] external[c] GBD (n)	(%)	Survivors Examined[b] external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)	Mortality (n)	(%)	Decom.[f] (n)	Mortalities Examined external[c] GBD (n)	(%)	LL[d] GBD (n)	(%)	gill[e] GBD (n)	(%)
Jun 26-30									**TDGS 121% (118-124%)**								
deep (2-3 m)	12	0.0	12	0.0	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	165	1.2	142	1.4	4	25.0	4	0.0	2	1.4	0	2	50.0	1	0.0	0	--
surface (0-0.5 m)	11	0.0	11	0.0	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
Jun 30 - Jul 4									**TDGS 119% (116-122%)**								
deep (2-3 m)	12	0.0	13	0.0	3	0	3	0	0	0.0	0	0	--	0	--	0	--
0-4 m	74	0.0	75	0.0	4	0	4	0	0	0.0	0	0	--	0	--	0	--
surface (0-0.5 m)	14	0.0	9	11.1	3	33.3	3	0.0	1	10.0	0	0	--	0	--	0	--
July 3-7									**TDGS 118% (115-122%)**								
deep (2-3 m)	10	0.0	8	33.3	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m	101	0.0	39	0.0	4	25.0	4	0.0	1	2.5	0	1	0.0	1	0.0	1	0.0
surface (0-0.5 m)	10	0.0	6	0.0	3	66.7	3	0.0	1	14.3	0	1	0.0	1	0.0	1	0.0
Jul 7-11									**TDGS 118% (115-121%)**								
deep (2-3 m)[i]	10	0.0	9	11.1	3	0.0	3	0.0	1	10.0	0	1	0.0	1	0.0	1	0.0
0-4 m[i]	119	0.0	67	0.0	4	25.0	4	0.0	8	10.7	4	4	0.0	4	0.0	4	0.0
surface (0-0.5 m)	12	0.0	11	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--
July 10-14									**TDGS 117% (111-120%)**								
deep (2-3 m)	10	0.0	7	0.0	3	33.3	3	0.0	0	0.0	0	0	--	0	--	0	--
0-4 m[i]	64	0.0	44	0.0	4	0.0	4	0.0	5	10.2	0	5	0.0	5	20.0	5	0.0
surface (0-0.5 m)	10	0.0	10	0.0	3	0.0	3	0.0	0	0.0	0	0	--	0	--	0	--

[a] Fish placed in holding pen at beginning of experiment.
[b] Live fish removed from pen at end of experiment.
[c] External signs of GBD.
[d] Signs of GBD in the lateral line.
[e] Signs of GBD in branchial arteries and gill filaments.
[f] Number of dead fish that were too decomposed to examine for GBD signs.
[g] Pen depth.
[h] Average and range of TDGS during holding period (COE, Ice Harbor Dam tailrace).
[i] Mortalities due to adverse conditions inherent from sampling and holding.

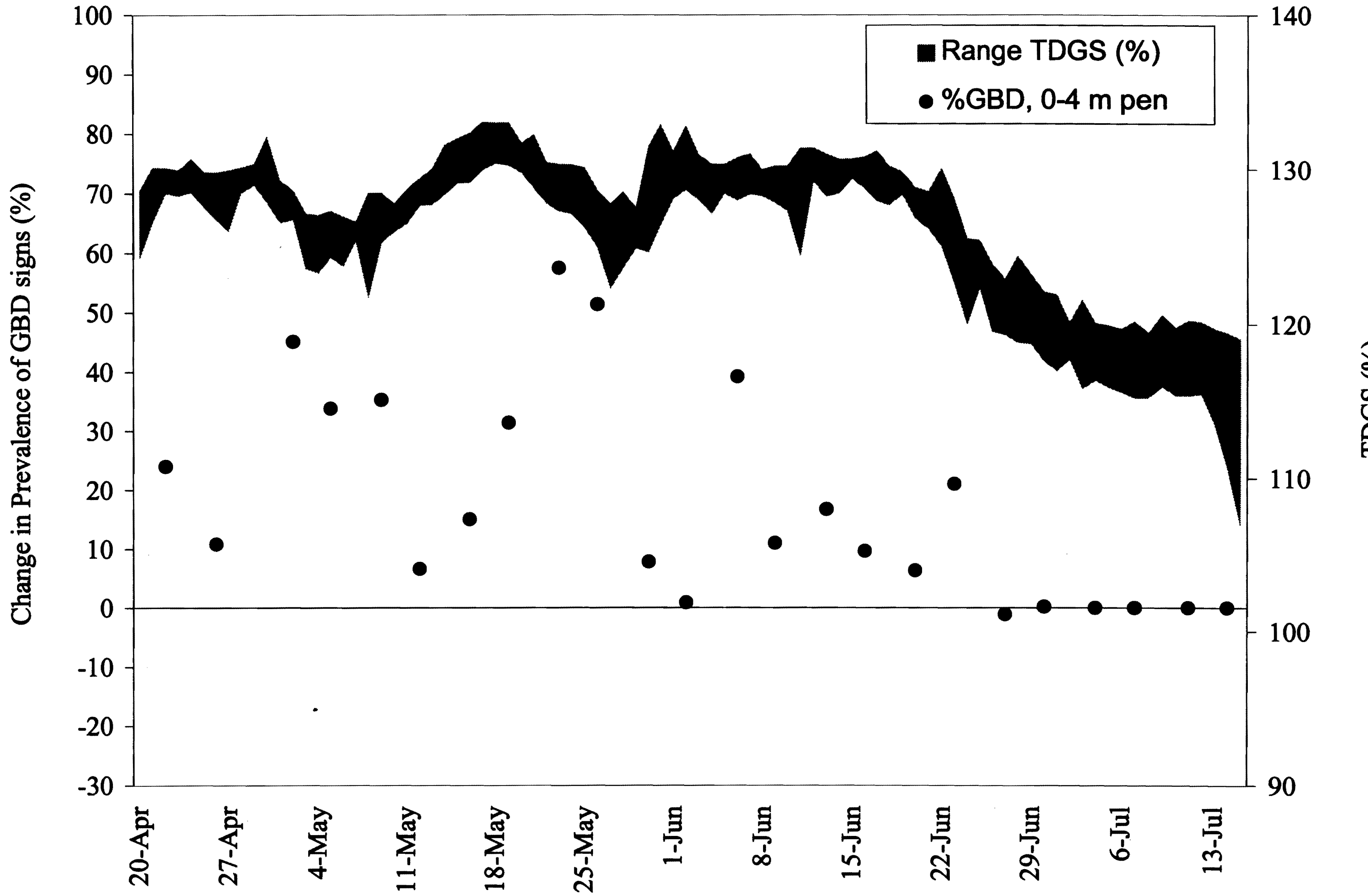

Figure 10. Change in gas bubble disease (GBD) prevalence in resident fish held 4 days in river water downstream from Ice Harbor Dam compared with range of total dissolved gas saturation (TDGS) (COE, Ice Harbor Dam tailrace), 1997.

Exposure vs. Gas Bubble Disease Signs

An exposure index describing effects of increasing, static, and decreasing TDGS exposures on resident fish was developed by comparing percent prevalence and severity of GBD signs to TDGS in mid-river (CROHMS). Few signs of GBD were observed when TDGS was less than 120%. We speculate that depth distribution of resident fish generally provided sufficient compensation to prevent formation of GBD signs.

Many model trials were conducted to determine the best increments of exposure level and exposure duration for indexing TDGS to prevalence and severity of GBD signs. Based on the 120% threshold and on statistical trials, the narrowest confidence intervals were obtained using daily ranks for mean 24-hour TDGS levels in mid-river (CROHMS), which were then divided into 5% increments. Each increment was assigned a rank, and the best model was achieved by summation of daily ranks through a 7-day exposure duration. The scale for daily exposure was ranked as follows: <120%TDGS = rank 0; 120-124.9% = 1; 125-129.9% = 2; 130-134.9% = 3; 135-139.9% = 4; 140-144.9% = 5; and 145% or greater = 6. Daily exposure ranks were summed to represent a 7-day cumulative exposure index (EI) (Table 12).

In 1996, we used second-order polynomial regression to compare 7-day exposure index vs. percent GBD signs (Fig. 11). This produced a strong relationship ($R^2 = 0.79$), leaving us confident that by using the EI we could reliably predict GBD signs from the equation, $\%GBD = 0.05(EI)^2 \times 0.21(EI) + 0.62$. A bootstrapping technique was used to confirm the statistical analysis, and it produced a nearly identical correlation. This regression is based on a random sample of 13,642 fish of all species sampled in the top 3 m of the water column. The same exposure index and second-order polynomial regression were used to predict GBD signs of

Table 12. Ranking scale and example of the exposure index used to establish impacts of total dissolved gas saturation (TDGS) on resident fish.

Scale

%TDGS	Daily exposure rank[a]
100 - 119%	0
120 - 124%	1
125 - 129%	2
130 - 134%	3
135 - 139%	4
140 - 144%	5

Example

Date	%TDGS[b]	Daily exposure rank[a]	Exposure index[c]
Day -6	135	4	--
Day -5	131	3	--
Day -4	124	1	--
Day -3	128	2	--
Day -2	120	1	--
Day -1	118	0	--
Day -0[d]	122	1	12

Sample Data Downstream From Ice Harbor Dam, 1996

Date	%TDGS	Daily exposure rank[a]	Exposure index[c]	Daily sample (%GBD) rank[d]
23-Apr	122.0	1		
24-Apr	138.9	4		
25-Apr	137.0	4		
26-Apr	136.2	4		
27-Apr	135.8	4		
28-Apr	129.7	2		
29-Apr	125.4	2	21	37.8%
30-Apr	126.5	2		
1-May	123.2	1		
2-May	121.3	1		
3-May	121.5	1		
4-May	118.6	0		
5-May	120.6	1		
6-May	118.7	0	6	5.5%
7-May	120.9	1		
8-May	118.9	0		
9-May	119.7	0	3	7.8%

[a] Daily exposure base on 24-hour mean mid-river TDGS measurments from Columbia River Operations Hydro-Met System (CROHMS).

[b] Average daily TDGS near the fish sampling site (CROHMS data).

[c] Index based on sum of daily ranks for the sampling day and 6 days prior.

[d] Percent of sampled fish displaying external signs of gas bubble disease.

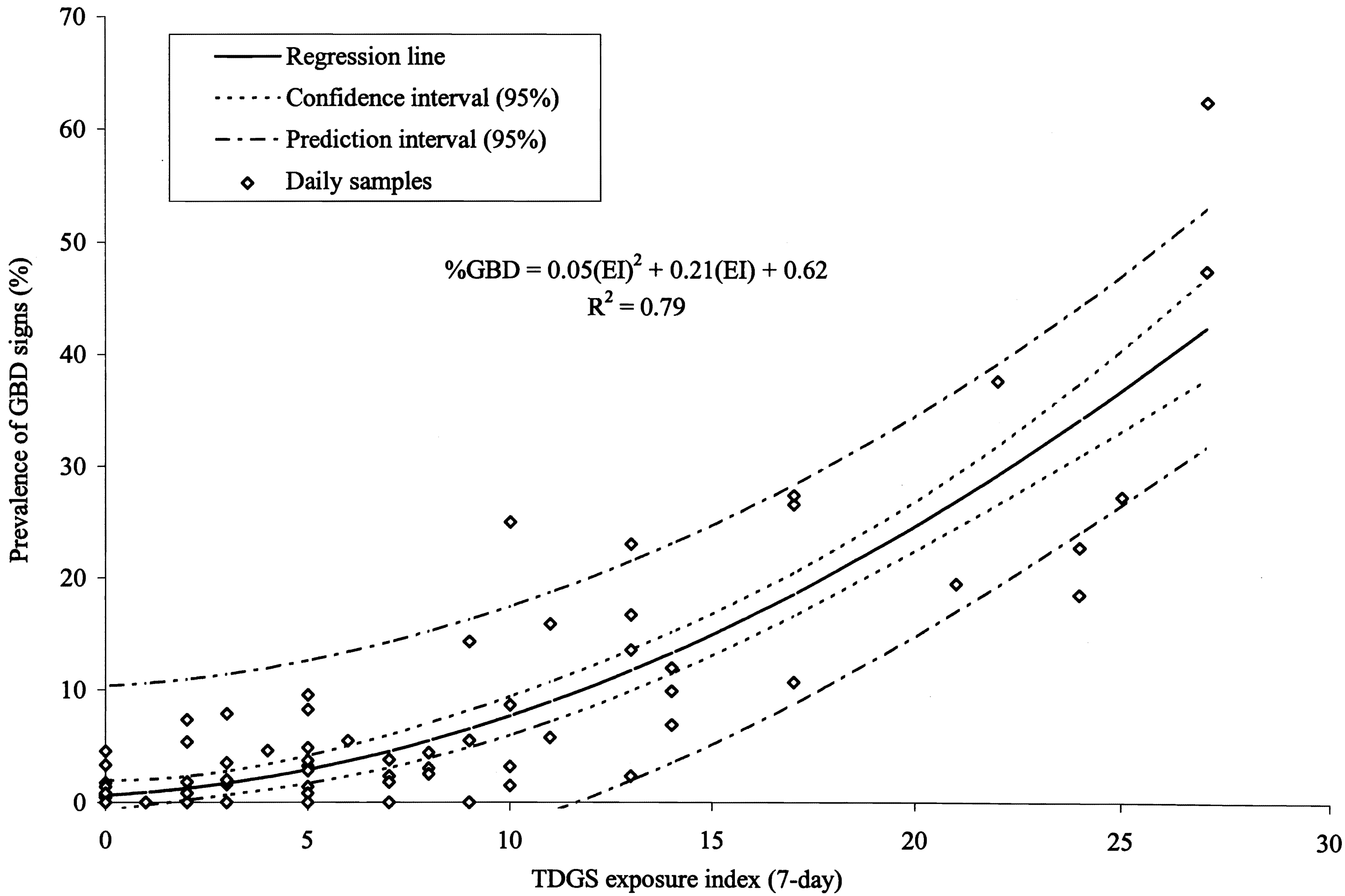

Figure 11. Prevalence of gas bubble disease (GBD) in resident fish collected from the Snake and Columbia Rivers compared with 7-day total dissolved gas saturation (TDGS) exposure index (EI).

nonsalmonid fry in relation to TDGS exposure. These data also produced a strong regression relationship: $\%GBD = 0.05(EI)^2 + 2.8(EI) - 0.64$ ($R^2 = 0.82$). However, we caution that the fry model is only preliminary. There were only 10 samples containing fry (925 total); all were collected downstream from Bonneville Dam in 1996.

Our 1997 sampling effort targeted smallmouth bass, peamouth, and yellow perch, which made up 54% of the catch. In previous years these three species only made up 30% of the catch. Therefore, the 1997 data were not utilized for the combined species model; instead, these data were exclusively used for individual species models. Combining data from all years relating TDGS to percent GBD signs for individual species did not produce strong regression relationships: $R^2 = 0.39$ for smallmouth bass, $R^2 = 0.48$ for yellow perch, and $R^2 = 0.29$ for peamouth. The individual species models require considerably more data for development.

Gas Bubble Disease Signs vs. Mortality

In 1995, using data from combined fish species held in net-pens, regression analysis explained 54% of the observed variability between prevalence of GBD signs and percent mortality. Although the resulting R^2 value (0.54) reflected a relatively good correlation, we assumed that it was anomalous because the data were distributed at two extremes. When we utilized data from 1994, 1995, and 1996 for combined fish species, the regression resulted in a poor correlation ($R^2 = 0.049$) (Fig. 12). Additional data analysis using severity of GBD signs and EI in lieu of prevalence yielded no significant improvements.

While data from most individual fish species showed no clear relationship between prevalence of GBD signs and percent mortality in captivity, a few species showed promising results. The strongest relationships between prevalence of GBD signs and percent mortality from data collected from 1994 to 1996 were for smallmouth bass, peamouth, and yellow perch.

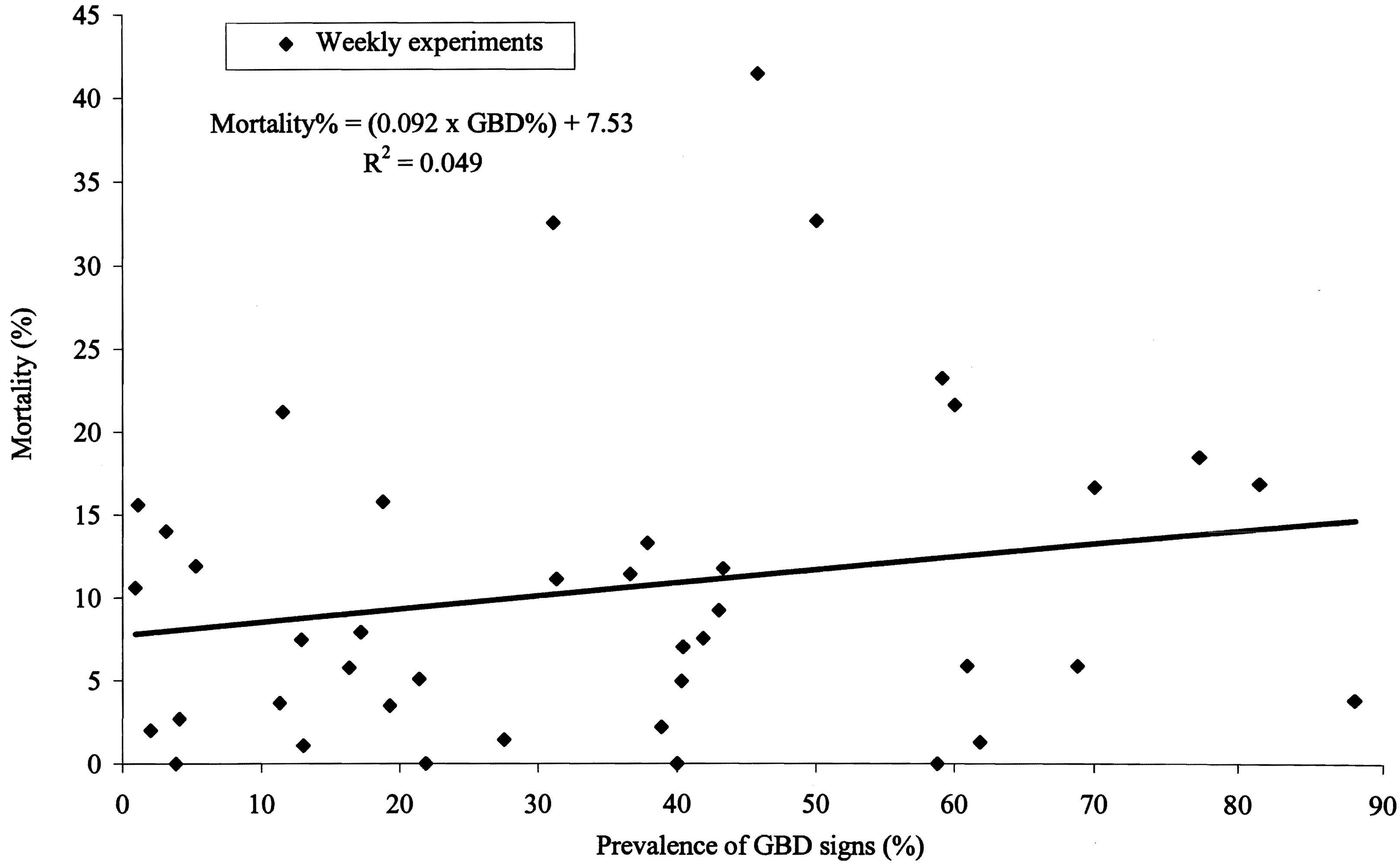

Figure 12. Percent gas bubble disease (GBD) signs for surviving fish in the 0-4 m pen vs. percent mortality for 4-day experiments, 1994-1996. Total dissolved gas saturation had to average above 120% and GBD signs had to be present in the group of fish surviving the experiment.

By combining data for the three species, data distributions were improved (R^2=0.41); however, because of the small sample size and a protracted distribution of data, we did not believe the relationship was well defined. With the addition of 2,339 observations of these three species in 1997, the variability became more apparent and the relationships of signs to mortality became less well defined. The best correlation was observed for the three species combined, wherein %mortality = 0.18 + log (%GBD) x 0.06; R^2 = 0.28. Utilizing severity of GBD signs and EI as the predictors of mortality elicited no improvements.

DISCUSSION

Prevalence of Gas Bubble Disease

Based upon sampling results from 1994 to 1997, GBD signs in resident fish (nonsalmonids) captured in the mainstem Snake and Columbia Rivers were rare when TDGS levels were less than 120%. We speculate that depth distribution of resident fish generally provided sufficient compensation to prevent formation of GBD signs. At constant TDGS levels of 120-125%, 125-130%, 130-135%, and greater than 135%, prevalence of GBD signs among resident fish averaged approximately 5%, 10%, 25%, and 45%, respectively. Dell et al. (1974) found similar results in the mid-Columbia River with GBD signs being rare when TDGS levels were less than 120%. Unfortunately, monitors to continually record TDGS levels were not available in that era; but the correlation between TDGS levels and GBD prevalence above 120% was similar to the correlation we found between TDGS and GBD prevalence.

Previous laboratory studies with largemouth bass (*Micropterus salmoides*) and northern squawfish (*Ptychocheilus oregonensis*) suggest that mortality due to GBD would occur at the TDGS levels encountered during our holding experiments (Bentley and Dawley 1981) and

(Bouck et al. 1976). Unfortunately, our data for prevalence and severity of GBD signs in resident fish populations were poorly correlated with mortality, and no information is available for sublethal or synergistic effects. This does not mean that mortality did not occur due to GBD, but that there are other factors that influenced the vitality and tolerance to dissolved gas of resident fish being held.

As observed in resident fish species, prevalence of GBD signs in salmonids was rare when TDGS remained below 120%. Significant findings came from comparing prevalence of signs observed on migrating juvenile salmonids collected 15 km downstream from Ice Harbor Dam to prevalence at Ice Harbor Dam. Steelhead displayed a 49% ($P = 0.028$) increase in GBD-sign prevalence downstream from Ice Harbor Dam. There was too much variability due to small sample size, both at Ice Harbor Dam and 15 km downstream, to compare prevalences of GBD signs on chinook salmon. While these findings are based on one location and have not been repeated, they do carry some serious implications. We presume that exposures to high TDGS in the shallow water environs downstream of the dam, coupled with the dissolved gas body-burden contracted during migration through the reservoirs from Little Goose Dam to Ice Harbor Dam, was sufficient to substantially increase prevalence of GBD signs. It should be cautioned that prior to examination, juvenile salmonids captured downstream from Ice Harbor Dam were held up to 30 minutes in shallow (<1 m) water, which may have increased external GBD signs. However, this seems unlikely because the shallow-water holding period was generally less than 30 minutes and with such a short period it is unlikely that GBD signs would increase.

Gas Bubble Disease Effects Model

The regression equation relating GBD signs to TDGS exposure seems complete and accurate for fish residing in shallow waters of the Columbia River Basin. However, computed GBD impacts (prevalence of GBD signs) only pertain to those river reaches where dissolved gas levels are represented by TDGS monitoring data. Areas of lower dissolved gas (by model definition 7% less) at shoreline peripheries are not properly represented by the TDGS monitoring data (CROHMS). In general, slack-water areas have lower TDGS and present less risk of GBD to resident fish than areas of the main river.

The equation relating GBD signs to mortality was not precise because there appeared to be species-specific behavior that caused high variability for net-pen mortality in multi-species tests. Species such as suckers, sculpins, and bullheads commonly reside on the bottom, and the environment they came from may have been shallow enough for TDGS to have an impact. However, the bottom of our net-pen was 4 m deep, and therefore provided compensation for TDGS up to 138% at the surface. Other species of fish such as smallmouth bass, yellow perch, and peamouth are not bottom dwellers and were more likely to establish a depth similar to that occupied before they were captured.

To evaluate this problem, we split the resident fish into groups: first by species and then by behaviors. While we found no clear relationship for all residents, a small sample of smallmouth bass, yellow perch, and peamouth showed less variability. However, when we focused our effort on these three species we found even more unexplainable variability, causing us to abandon efforts to develop a GBD-related mortality model. Additional observations utilizing present methods likely would not improve the model. A similar lack of correlation between GBD signs and mortality of juvenile salmonids was observed in studies by Biological Resources Division researchers (Matthew Mesa, USGS, BRD, Columbia River Research Laboratory, Cook WA 98605, Pers. commun., November 1997).

Use of the Model

It is important to emphasize that our model relating TDGS exposure to GBD signs is based on average 24-hour mid-river TDGS levels. Once TDGS averages for the river reach of interest have been obtained, GBD signs can be calculated from the combined species exposure model. To make these calculations, we summed the daily exposure rankings starting with the day of interest and including the 6 days prior (<120%TDGS = rank 0; 120-124.9% = 1; 125-129.9% = 2; 130-134.9% = 3; 135-139.9% = 4; 140-144.9% = 5; and 145% or greater = 6), then solved the equation $\%GBD = 0.05(EI)^2 \times 0.21(EI) + 0.62$. The result is the predicted percentage of shoreline inhabitant resident fish displaying GBD signs on that day in that river reach.

CONCLUSIONS AND RECOMMENDATIONS

1) When TDGS levels are held below 120%, GBD signs are rare in resident fish. When TDGS levels exceed 120%, the equation relating GBD signs to TDGS exposure can accurately predict signs in resident fish where continuous TDGS readings are available. Therefore, we believe the extensive sampling of all species to monitor signs of GBD in the mainstem Columbia and Snake Rivers is no longer necessary. Sampling should be continued if an individual species warrants extensive research.

2) Evaluating mortality due to TDGS has proved to be difficult, and after 4 years of data collection we believe that it is not feasible to develop a general model. Modeling mortality for individual species has proved to be just as problematic, and we believe additional data collection would not yield any significant results. We speculate that the variables compromising model development include changes in tolerance related to species, individual variability, water temperature, depth, and lateral distribution in the river reaches.

3) Juvenile salmonids examined in this study (resident and migrating), also displayed few GBD signs when TDGS remained below 120%. Based on GBD prevalence at the mouth of the Snake River, we believe that assessment of GBD at dams will not properly represent migrants passing through free-flowing, shallow, river reaches and areas downstream of dams where TDGS is high. When TDGS exceeds 120% we recommend monitoring of salmonids in river-run reaches and the tailraces of dams where spilled water stays separated from powerhouse flows.

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