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Modeling the Effects of Dissolved Gas Supersaturation on Resident Aquatic Biota in the Mainstem Snake and Columbia Rivers

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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 outmigrating juvenile salmonids passing hydroelectric dams. However, increased use of spill has raised concern that the resulting increase in dissolved gas levels of the water may detrimentally affect 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 spill at dams over which there was no control, such as high springtime river flows combined with turbine outages. However, some supersaturation occurred as a result of purposeful spill for enhanced fish passage.

Fishery agencies 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). Methods investigated and implemented were these: increase headwater storage to control flow during the spring freshet, install additional hydroelectric turbines at many dams, and 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 lower than for spillway passage (Schoeneman et al. 1961).

To improve survival of downstream migrating juvenile salmonids, the present program of increased spill to pass fish during evening and night hours 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 again observed in juvenile and adult salmonids in the Columbia River (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.

The effects of dissolved gas supersaturation on aquatic biota other than salmonids are not well documented. 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 current spill regime, with its resulting diurnal fluctuations. These earlier studies were also conducted before the availability of instruments 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 for "real time" use by fisheries managers to predict GBD impacts on resident fish (nonsalmonids) resulting from dissolved gas supersaturation.

Study Site

During the spring freshets (April-July) of 1994-1997, resident fish were collected and examined for signs of GBD. Weekly sampling in two, three, or four river reaches of the mainstem Snake and Columbia Rivers was conducted to evaluate effects of spill at several upstream dams (Figure 1).

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Methods

Sampling

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 two-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.

Along shorelines having steep gradient, 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.

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). Reference to GBD signs in this report are to external GBD signs unless otherwise noted. Individual fish were examined externally using a 2.5- to 5-power headband magnifying lens. Internal examinations of fish were not conducted, and most examinations were made at sampling sites within 15 min 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 at 20-

power magnification for gas emboli in the lateral line, branchial arteries, and gill lamellae.

For clarity, reference to GBD prevalence denotes external GBD signs, regardless of severity. Reference to severe GBD signs denotes external GBD signs wherein greater than 25% of a fin is enveloped with emphysema or when subcutaneous emphysema or petechial hemorrhaging is present on the body, head, or eye.

Developmental stage may affect the susceptibility of fish to GBD (Harvey and Cooper 1962), and for this reason larval fish were not included in our resident fish data. Larval fish were instead considered independently of other fish samples. Signs of GBD in larval fish included gas bubbles within the body observed through the body wall at 20-power magnification. We considered larval fish at the "stage following hatching that is unlike the juvenile or adult in form and pigmentation and must transform or metamorphose before assuming juvenile/adult characteristics" (Moser 1996).

Benthic and epibenthic macroinvertebrates were collected from depths of up to 0.6-m using a hydraulic epibenthic pump and Ponar bottom sampler. These samples were washed with water through a 0.5-mm screen, and all macroinvertebrates were retained. A 0.6-m-diameter plankton net with 0.5-mm mesh was used to collected zooplankton samples at the water surface. We examined organisms immediately after collection with a dissecting microscope using 10- to 40-power magnification. Invertebrates were examined for gas-bubble emboli in the body fluids, gut, and under the carapace by viewing through the body wall, as described by Nebeker et al. (1976).

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 d, and then reexamined for signs of GBD.

Three types of enclosures were used: shallow cages held at the surface, which provided a maximum depth of 0.5 m (0.6 × 0.6 × 1.0 m, made of perforated aluminum plate); deep, submerged cages held from 2.0 to 3.0 m in depth (0.6 × 0.6 × 1.0 m, made of perforated aluminum plate), and large net-pens (1.8 × 2.44 m) with an inclined bottom that extended from the surface to a depth of 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 (Figure 2). To help reduce intrapen predation, fish over 140 mm were placed on one side of the partition, while resident 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 emboli in the lateral line, branchial arteries, and gill lamellae with 20-power magnification. Except those in moderate to extreme states of decomposition, mortalities were dissected and examined for external, lateral line, branchial arteries, and gill lamellae signs of GBD .

Dissolved Gas Measurements

Tensionometers (D'Aoust et al. 1976) were used to measure TDGS at the time and place of fish sampling. Means and ranges of TDGS during 4-d holding periods were determined from dissolved gas data accessed from the Columbia River Operations Hydro-met System (CROHMS) data network of the COE (Mary Todd Uhler, COE, North Pacific Division, Portland, OR 97208, Pers. commun., June 1997).

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-h 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., fish inhabiting 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 at depths between 0 and 3 m because the pressure compensation at the 3-m depth is approximately 30% of saturation. Thus 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 h for the prior 7 consecutive days. This criterion eliminated use of some data due to inconsistent and inaccurate TDGS measurements.

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

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

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

Results

During the 4-year study, a wide range of river flows were encountered. For example, at the Dalles Dam, annual flows of 71, 114, 118, and 129% of normal were measured from 1994 through 1997, consecutively (Mary Todd Uhler, COE, North Pacific Division, Portland, OR 97208, Pers. commun., March 1998). Over the entire study, we took 202 weekly samples of resident fish, and in 115 of these, signs of GBD were present. The 202 weekly samples contained 27 taxa and 39,924 individual fish, with 3.9% displaying GBD signs (Table 1). In 1994 and 1995 we also took samples of invertebrates, but of 5,434 individual invertebrates examined, we found only 7 with signs of GBD.

Ice Harbor Dam

Below Ice Harbor Dam in 1994, daily average TDGS remained above 120% for over 6 weeks and exceeded 125% on three occasions. Signs of GBD during this period were observed on 2.9% of 3,367 fish examined. In 1995 the CROHMS data for this site were erroneous; however, our intermittent measurements suggested that TDGS levels were high and generally near or above 130% during most of May and June. Signs of GBD were observed on 18.1% of 1,126 fish examined, with daily prevalence of GBD exceeding 20% on two occasions and reaching a maximum of 40.8%. Daily average TDGS was again high in 1996, exceeding 135% for 5 consecutive weeks. Signs of GBD were observed on 18.6% of 826 fish examined, and daily prevalence of GBD exceeded 30% on three occasions, reaching a maximum of 35.5% (Figure 3).

Despite extremely high flow and spill in 1997, the daily average TDGS was only moderately higher than in previous years, remaining above 125% for 9 weeks and exceeding 130% on six occasions. Signs of GBD during this period were observed on 4.5% of 3,788 fish examined. These relatively low TDGS levels were most likely due to the installation of flow deflectors ("flip lips") at Ice Harbor Dam prior to the 1997 spring runoff, which decreased plunging and air entrainment from spill. Daily prevalence of GBD reached a maximum of 9.3% (in samples greater than 25 fish).

Resident fish in Ice Harbor Reservoir were sampled for GBD impacts in 1997, when daily average TDGS was moderately high. Levels of TDGS in the reservoir remained above 120% for about 5 weeks and exceeded 125% on 17 occasions. Signs of GBD were observed on 9.8% of the 2,082 resident fish examined.

Priest Rapids Dam

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 17 occasions over a 10-week period, reaching a maximum of 123.3%. Signs of GBD were observed on 0.9% of 2,511 fish examined, and daily prevalence of GBD reached a maximum of 5.4%.

In 1996, daily average TDGS was moderately high: levels exceeded 120% for 3 weeks and then exceeded 125% for 5 weeks. In addition, TDGS levels exceeded 130% twice between 12 and 15 July. Signs of GBD during these periods were observed on 9.2% of the 1,507 resident fish examined, and daily prevalence of GBD exceeded 10% on three occasions during the high-TDGS period, reaching a maximum of 23.1% (Figure 4).

Downstream from Priest Rapids Dam in 1994, daily average TDGS did not exceed 120% during the sampling period. Only 0.4% (5) of the 1,239 resident fish examined displayed GBD signs. In 1996, average daily TDGS was moderately high, remaining above 125% from 23 May to 21 June, but never exceeding 130%. Signs of GBD 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% (Figure 5). The CROHMS TDGS meter was not operational in April and early May of 1996.

Bonneville Dam

Downstream from Bonneville Dam in 1994, daily average TDGS never exceeded 120%, and only 3 of 4,955 resident fish examined displayed GBD signs. The following year, 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 resident fish. In 1996 at these same locations, daily average TDGS in mid-river exceeded 120% from mid-April to early May and again from mid-May through much of June, with levels exceeding 130% on 1 June. Signs of GBD 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 these periods, reaching a maximum of 15.8%. We collected 1,227 Catostomidae larva in addition to our regular sampling below Bonneville Dam in 1996; 14.3% displayed signs of GBD.

Daily average TDGS was the highest of all 4 years in 1997, remaining above 125% for nearly 10 weeks and exceeding 135% on 12 d. Signs of GBD during this period were observed on 18.0% of the 813 fish examined, and daily prevalence of GBD exceeded 10% on seven occasions, reaching a maximum of 19.1% (Figure 6).

Gas Bubble Disease in Captive Fish Groups

In 1994, we conducted 28 net-pen holding experiments downstream from Ice Harbor, Priest Rapids, and Bonneville Dams. Average TDGS during the 4-d holding experiments ranged from 108 to 125%, and signs of GBD were present on surviving fish in 5 of these experiments, while mortalities occurred in 21. In 1995, we conducted 39 of the same holding experiments downstream from Ice Harbor and Bonneville Dams and in Priest Rapids Reservoir. Average TDGS ranged from 106 to 130%, with signs of GBD observed in 15 experiments and mortalities occurring in 35. We conducted 43 holding experiments at these same locations in 1996, when average TDGS ranged from 114 to 137%. Signs of GBD were present on surviving fish in 31 of the 43 experiments, while mortalities occurred in 41 experiments.

Finally, in 1997 we conducted 41 4-d holding experiments in Ice Harbor Reservoir and downstream from Ice Harbor Dam, where average TDGS ranged from 106 to 131%, and signs of GBD were present on surviving fish in 34 experiments, while mortalities were present in 36.

Modeling

Gas Bubble Disease Effects Model

We found that riverine sampling of resident fish to characterize GBD impacts produced a data set in which fluctuations of GBD signs consistently correlated well with fluctuations of ambient dissolved-gas concentrations. We developed an exposure model which reliably predicted prevalence of GBD signs in free-swimming fish based on dissolved gas exposure. However, we concluded that mortality could not be properly evaluated through sampling, because dead fish are rarely recovered from these rivers. Similar conclusions were made by Merrell et al. (1971), who found that less than 5% of dead adult salmon released downstream from Bonneville Dam were later recovered or observed.

To properly evaluate mortality, we intended to utilize data from the 4-d holding tests. However, results of these tests indicated that impacts from GBD were greater for captive fish than for free-swimming fish: prevalence of GBD signs among captive fish was 13% greater than for free-swimming fish from the same river reach. Because captive fish were not appropriately representative of GBD impacts to free-swimming fish, we utilized the relationship between GBD signs and mortality in captive fish to index the mortality of free-swimming fish.

Exposure vs. Gas Bubble Disease Signs

We developed an exposure index describing the effects of increasing, static, and decreasing TDGS exposures on resident fish by comparing percent prevalence and severity of GBD signs to TDGS in mid-river using CROHMS data. Few signs of GBD were observed when TDGS was less than 120%. Based on the 120% threshold and on statistical trials, we observed the narrowest confidence intervals by dividing mean 24-h mid-river TDGS levels into 5% increments and assigning daily ranks based on these increments. We then summed these daily ranks through a 7-d exposure. The incremental scale for daily exposure rank is shown in Table 2A. Daily exposure ranks were then summed to represent a 7-d cumulative exposure index (EI) (Table 2B).

We used second-order polynomial regression to compare 7-d exposure index vs. percent prevalence of GBD signs, using data from the first 3 years of the study (Figure 9). This produced a strong relationship ($R^2 = 0.79$) based on data from 13,642 individual fish, leaving us confident that by using the EI we could reliably predict GBD signs from the following equation:

$$\%GBD = 0.05(EI)^2 \times 0.21(EI) + 0.62 \qquad (1)$$

A bootstrapping technique was used to confirm the statistical analysis, and it produced a nearly identical correlation. This regression is based on a random subsample 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 Catostomidae larva in relation to TDGS exposure. These data also produced a strong regression relationship ($R^2 = 0.82$):

$$\%GBD = 0.05(EI)^2 + 2.8(EI) - 0.64 \qquad (2)$$

However, we caution that the larva model is only preliminary. There were only 10 samples containing 925 total larva, and all were collected from the same site during the same year.

Gas Bubble Disease Signs vs Mortality

In 1995, using data from combined fish species held in net-pens, our regression analysis explained 54% of the observed variability between prevalence of GBD signs and percent mortality. Although the results reflected a relatively strong correlation ($R^2 = 0.54$), 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 much weaker correlation ($R^2 = 0.049$) (Figure 10). Additional data analysis using severity of GBD signs and EI in lieu of prevalence yielded no significant improvements.

While 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 *Micropterus dolomieu*, peamouth *Mylocheilus caurinus*, and yellow perch *Perca flavescens*. 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 consider the relationship well defined. With the addition of 2,339 observations of these three species in 1997, the variability became more pronounced, and the relationships between signs and mortality appeared less definite. The highest correlation ($R^2 = 0.28$) was observed for the three species combined using the following equation:

$$\%mort = 0.18 + \log(\%GBD) \times 0.06 \qquad (3)$$

Utilizing severity of GBD signs and EI as predictors of mortality elicited no further clarity.

Discussion

Based upon sampling results from 1994 to 1997, GBD signs in resident fish (non-salmonids) were rare when TDGS levels were less than 120%. We speculated that depth distribution generally provided sufficient compensation to prevent formation of GBD signs in resident fish at these levels. 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, with GBD signs being rare when TDGS levels were less than 120%. Unfortunately, monitors to continually record TDGS levels were not available at the time of their study, but the correlation between GBD prevalence and TDGS levels above 120% was similar to our findings.

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, 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 of the resident fish held and of tolerance to dissolved gas.

We took a large sample of invertebrates over a range of TDGS levels documented to have produced GBD signs (Nebeker et al. 1976), but we rarely observed these signs in invertebrates. The lack of invertebrates with GBD signs was perplexing and may relate to our sampling methods or some other environmental factors. Brammer (1991) found a similar lack of GBD signs for invertebrates downstream of Yellowtail Dam on the Bighorn River when TDGS levels exceeded levels he had shown to induce GBD signs in bioassays.

The current waiver for the dissolved gas standard (TDGS levels of 115% in reservoirs and 120% in tailraces of dams on the Snake and Columbia Rivers) allows increased spill to facilitate dam passage of juvenile salmonids. The results of our survey and holding experiments suggest little or no detriment to resident fish populations at those levels of dissolved gas. However, our data suggested that an increase in this waiver would result in increased prevalence of GBD signs for resident nonsalmonids. Even though we found no relationship between GBD signs and mortality, we believe that presence of GBD signs indicates a negative condition to be avoided in maintaining the health of aquatic biota.

The regression equation relating GBD signs in resident nonsalmonids to TDGS exposure seems complete and reasonably precise for fish residing in the shallow waters of the mainstem Snake and Columbia Rivers. 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 were not properly represented by the CROHMS monitoring data. In general, slack-water areas have lower TDGS and present less risk of GBD to resident fish than mainstem areas.

The equation relating GBD signs to mortality in all resident nonsalmonids was not precise because in multispecies tests, species-specific behavior appeared to cause high variability in net-pen mortality. Species such as suckers, sculpin, and bullheads are normally bottom dwellers; however, although the bottom of our net-pen was 4 m deep and provided compensation for TDGS up to 138% at the surface, it may not have represented the depth at which these species reside in the natural environment. 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. Although we found no clear relationship for all residents, a small sample of smallmouth bass, yellow perch, and peamouth showed less variability. When we focused our effort on these three species we found even more unexplained variability, and this convinced us to abandon efforts to develop a GBD-related mortality model.

We believe that additional observations utilizing the methods presently available would not likely improve the model: Dawley and Ebel (1975) observed a similar lack of correlation between GBD signs and mortality of juvenile salmonids, as did researchers from the Biological Resources Division of the U.S. Geological Survey (Matthew Mesa, USGS, BRD, Columbia River Research Lab., Cook WA 98605, Pers. commun., November 1997). 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.

It is important to emphasize that our model relating TDGS exposure to GBD signs is based on average 24-h mid-river TDGS levels. Once we obtain TDGS averages for the river reach of interest, we can calculate GBD signs from the combined species exposure model in Equation 1. To develop the value of the exposure index (EI), the daily exposure rankings (Table 2A) are summed, starting with the day of interest and including the 6 d prior (Table 2B). The result is the predicted percentage of shoreline-inhabitant resident fish displaying GBD signs on that day in that river reach.

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Table 1. Number sampled and prevalence of GBD signs by species for juvenile and adult fishes collected from the Snake and Columbia Rivers during the spring freshets of 1994-97.

Species	Scientific name	Individuals examined (n)	Length range[a] (mm)	Prevalence of GBD[b] (n)	(%)
Peamouth	*Mylocheilus caurinus*	8804	15-480	149	1.7
Sucker	*Catostomus spp.*	7695	19-760	474	6.2
Northern squawfish	*Ptychochelilus oregonensis*	5304	9-744	101	1.9
Smallmouth bass	*Micropterus dolomieui*	3748	16-670	348	9.3
Stickleback	*Gasterosteus aculeatus*	2559	18-119	7	0.3
Sculpin	*Cottus* spp.	2464	18-420	145	5.9
Yellow perch	*Perca flavescens*	1915	43-430	98	5.1
Redside shiner	*Richardsonius balteatus*	1839	22-219	13	0.7
Chiselmouth	*Acrocheilus alutaceus*	1259	41-352	62	4.9
Pumpkinseed	*Lepomis gibbosus*	889	39-187	41	4.6
Bluegill	*Lepomis macrochirus*	840	34-202	49	5.8
Largemouth bass	*Micropterus salmoides*	774	35-526	28	3.6
Carp	*Cyprinus carpio*	459	60-730	6	1.3
Crappie	*Pomoxis* spp.	455	34-297	13	2.9
Bullhead	*Ictalurus* spp.	189	35-484	8	4.2
Whitefish	*Prosopium* spp.	184	45-444	3	1.6

Sandroller	*Percopsis transmontana*	181	50-150	6	3.3
Unidentified fish		156	12-307	0	0
American shad	*Alosa sapidissima*	57	35-473	1	1.8
Tench	*Tinca tinca*	48	68-243	3	6.3
Walleye	*Stizostedion vitreum*	26	58-710	0	0
Killifish	*Fundulus diaphanus*	26	52-100	0	0
Dace	*Rhinichthys* spp.	24	32-90	0	0
Goldfish	*Carassius auratus*	20	76-300	0	0
Lamprey	*Lampertra* spp.	5	95-210	0	0
Channel catfish	*Ictalurus punctatus*	2	195-510	0	0
White Sturgeon	*Acipenser transmontanus*	1	550	0	0
Starry flounder	*Platichthys stellatus*	1	115	0	0
Total fishes		39924		1555	3.9

[a] Total lengths measured for all fishes.

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

Table 2A. Ranking scale of the exposure index (EI) used to establish impacts of total dissolved gas saturation (TDGS) on resident fish. Daily exposure is based on 24-h mean mid-river TDGS measurements from Columbia River Operations Hydro-Met System (CROHMS).

TDGS (%)	Daily exposure index (EI) rank
100-119.0	0
120-124.9	1
125-129.9	2
130-134.9	3
135-139.9	4
140-144.0	5

Table 2B. Example of the use of daily ranking exposure index. Percent TDGS is based on average daily TDGS near the fish sampling site. The exposure index is based on the sum of daily ranks for the sampling day and 6 d prior.

Date	TDGS (%)	Daily exposure rank	Exposure index
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	122	1	12

Table 2C. Sample data collected downstream from Ice Harbor Dam in 1996. The daily sample rank is based on the percent of sampled fish displaying external signs of gas bubble disease.

Date	TDGS (%)	Daily exposure rank	Exposure index	Daily sample (% GBD) rank
23 Apr	122	1		
24 Apr	138.9	4		
25 Apr	137	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%

Figure Captions

Figure 1. Sampling locations on the Snake and Columbia Rivers, 1994-97.

Figure 2. Net-pen, cages, and support barge used for resident fish holding experiments.

Figure 3. Prevalence of GBD signs in resident fish collected from the Snake River in Ice Harbor Dam tailrace compared with daily average and range of total dissolved gas saturation (TDGS), 1996.

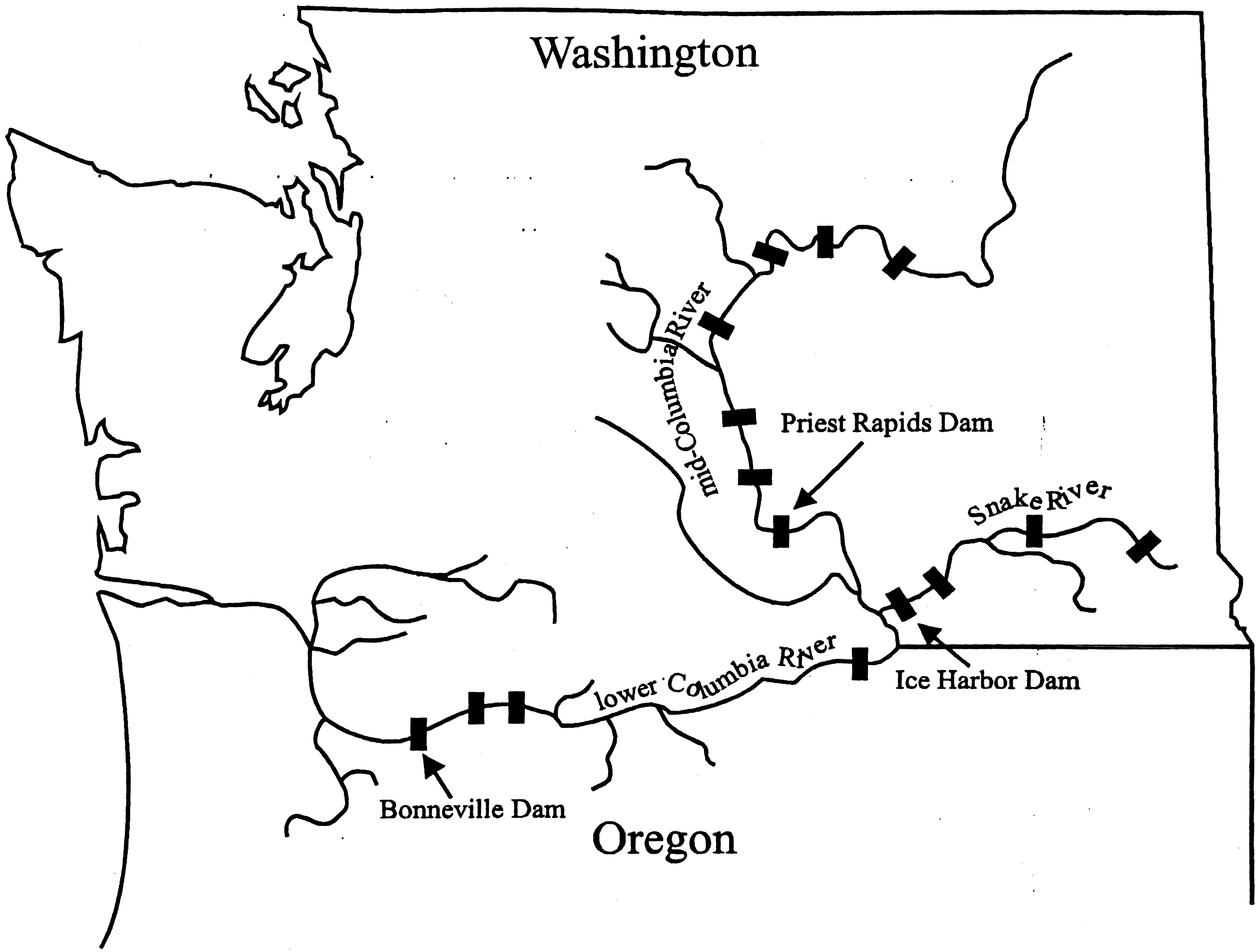
Figure 4. Prevalence of GBD signs in resident fish collected from the Columbia River in Priest Rapids Reservoir compared with daily average and range of total dissolved gas saturation (TDGS), 1996.

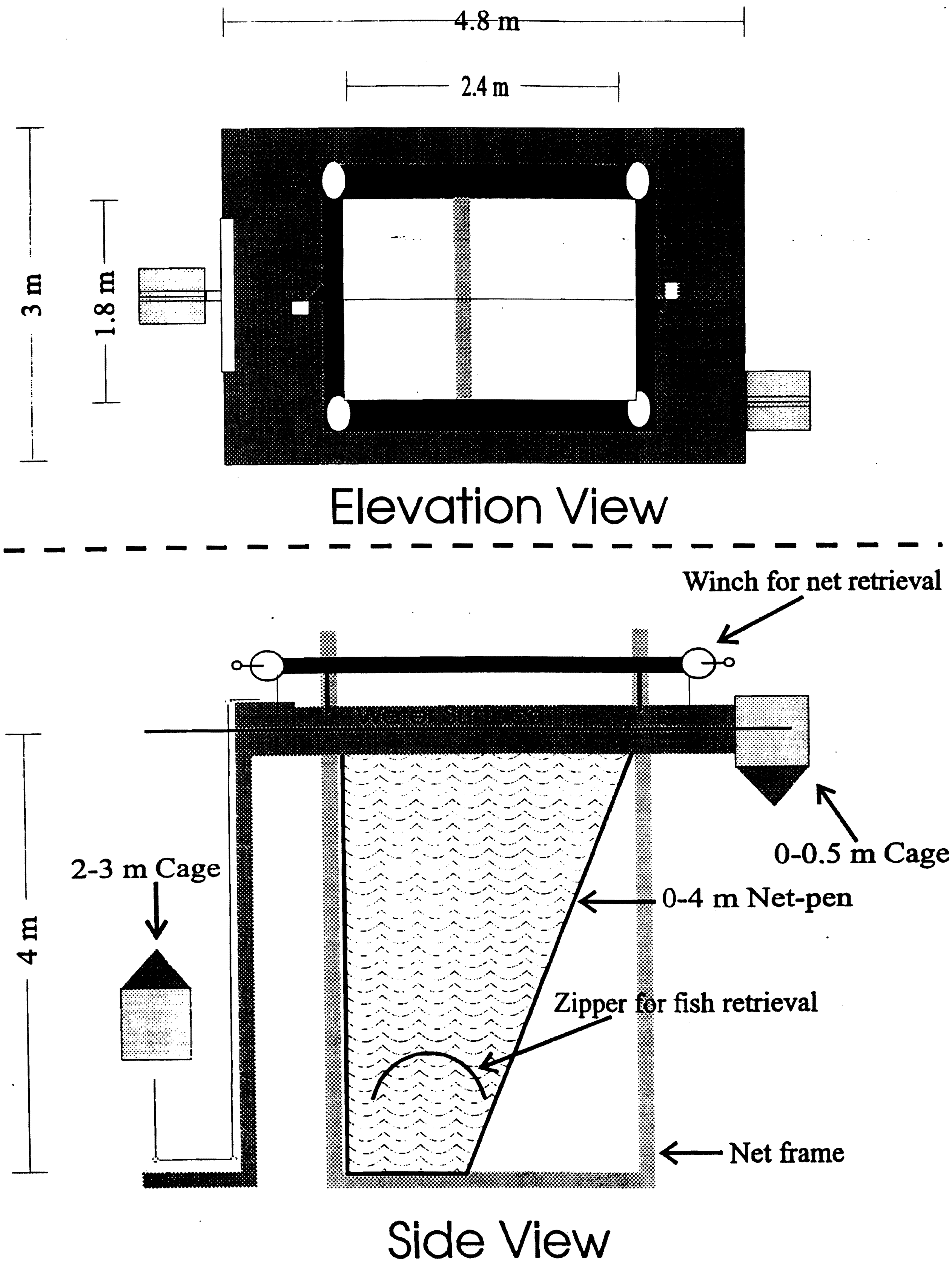
Figure 5. Prevalence of GBD signs in resident fish collected from the Columbia River in Priest Rapids Reservoir compared with daily average and range of total dissolved gas saturation (TDGS), 1996.

Figure 6. Prevalence of GBD signs in resident fish collected downstream from Bonneville Dam compared with daily average and range of total dissolved gas saturation (TDGS), 1997.

Figure 7. Prevalence of GBD signs in resident fish collected from the Snake and Columbia rivers compared with 7-d total dissolved gas saturation (TDGS) exposure index (EI), 1995-96.

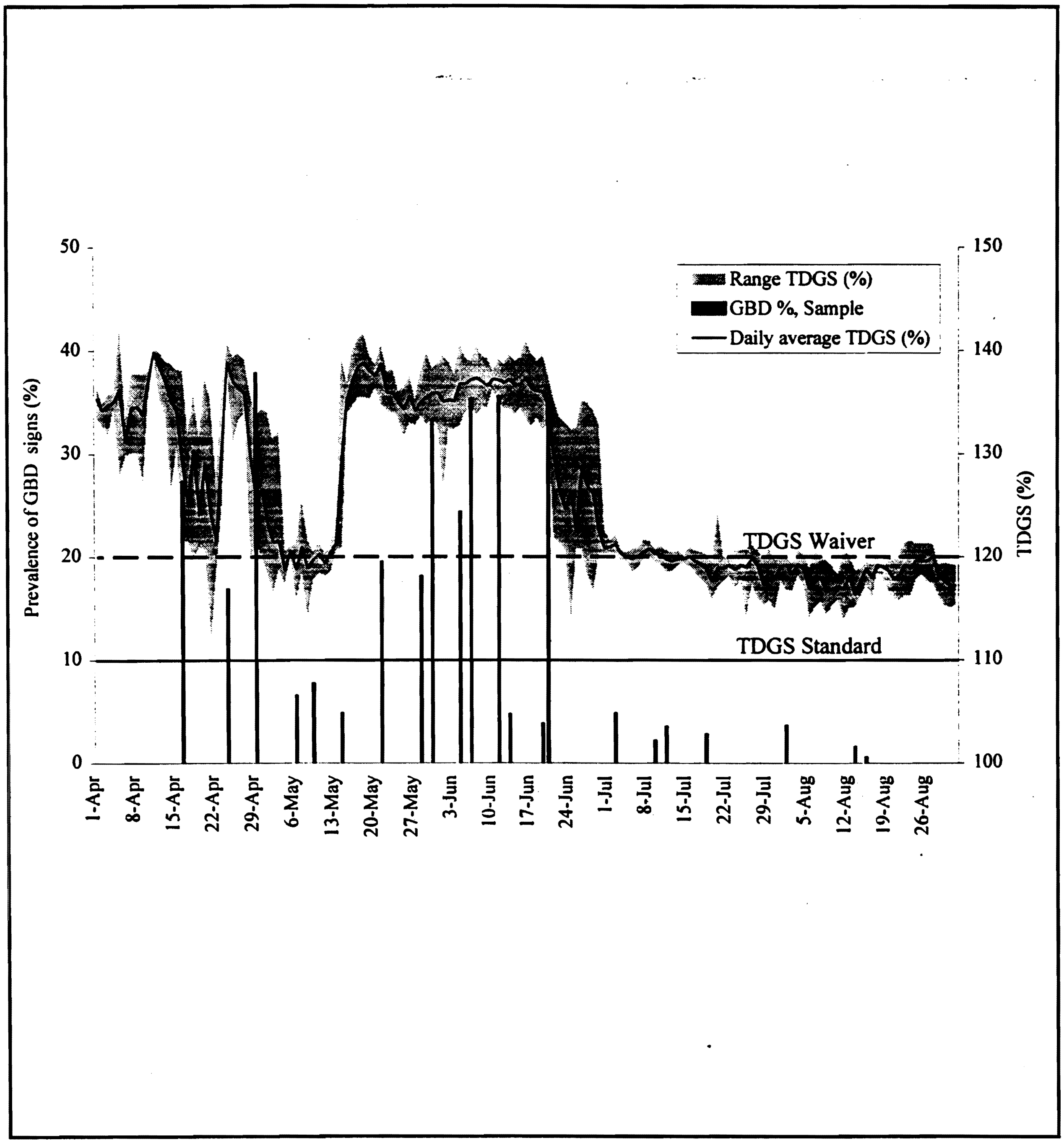
Figure 8. Percent gas bubble disease (GBD) signs for surviving fish in the 0- 4 m pen vs percent mortality for 4-d experiments, 1994-1996. Total dissolved gas saturation had to average >120% and GBD signs had to be present in the group of fish surviving the experiment.


Washington
mid-Columbia River
Priest Rapids Dam
Snake River
Ice Harbor Dam
lower Columbia River
Bonneville Dam
Oregon



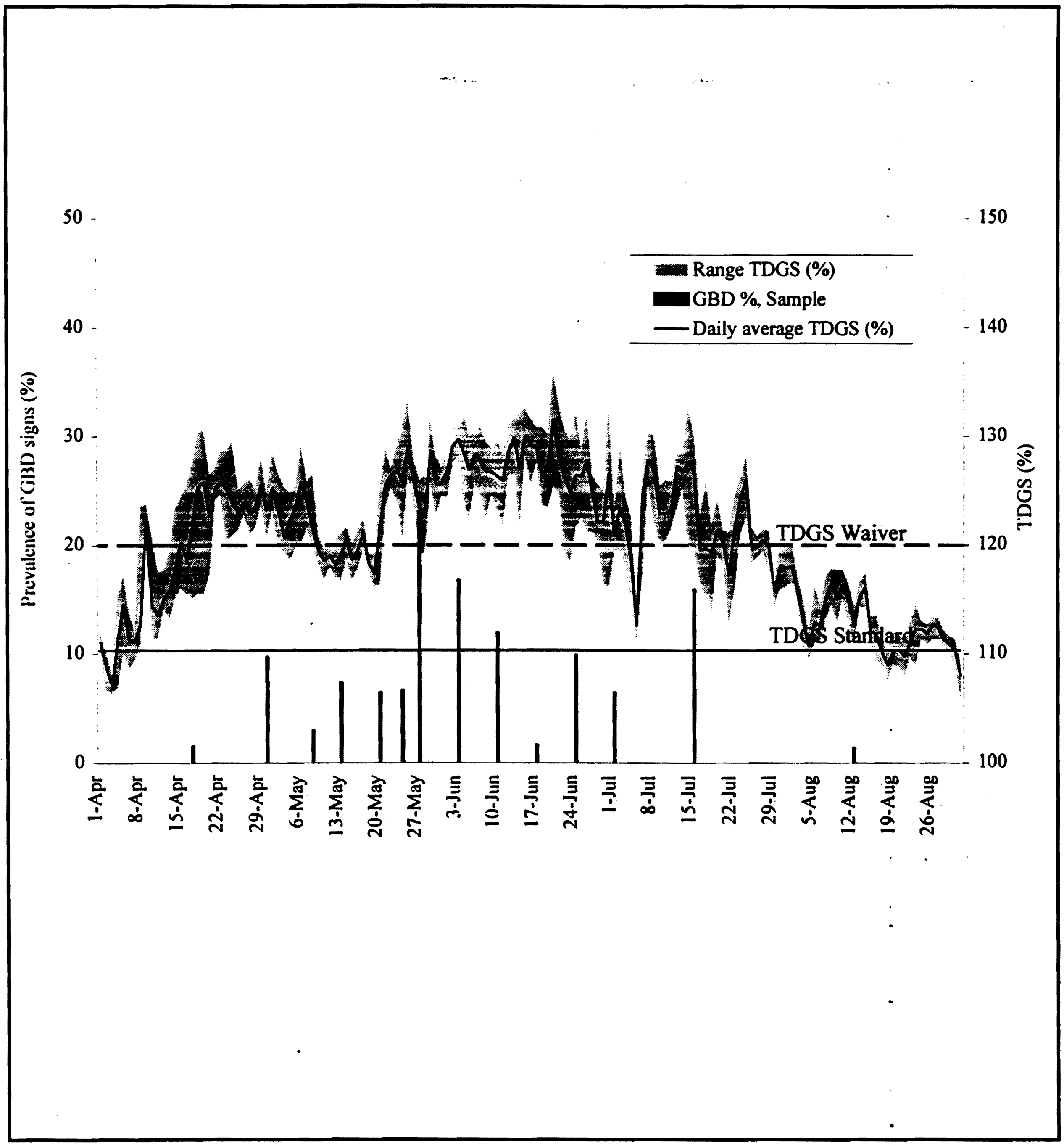
4.8 m
2.4 m
3 m
1.8 m
Elevation View
Winch for net retrieval
0-0.5 m Cage
2-3 m Cage
0-4 m Net-pen
4 m
Zipper for fish retrieval
Net frame
Side View

Figure 3



Range TDGS (%)
GBD %, Sample
Daily average TDGS (%)
Prevalence of GBD signs (%)
TDGS (%)
TDGS Waiver
TDGS Standard
50
40
30
20
10
0
150
140
130
120
110
100
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug

Figure 4



Range TDGS (%)
GBD %, Sample
Daily average TDGS (%)
TDGS Waiver
Prevalence of GBD signs (%)
TDGS (%)
50
40
30
20
10
0
150
140
130
120
110
100
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug

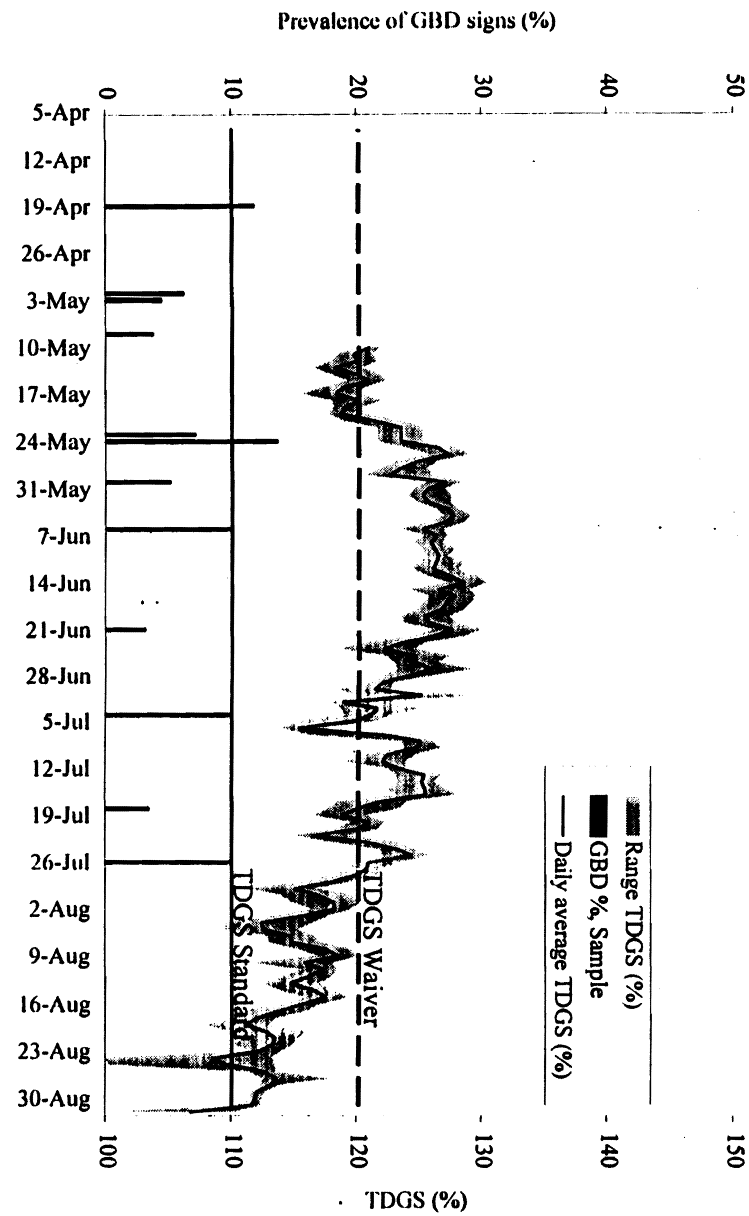

Prevalence of GBD signs (%)
0
10
20
30
40
50
5-Apr
12-Apr
19-Apr
26-Apr
3-May
10-May
17-May
24-May
31-May
7-Jun
14-Jun
21-Jun
28-Jun
5-Jul
12-Jul
19-Jul
26-Jul
2-Aug
9-Aug
16-Aug
23-Aug
30-Aug
TDGS Standard
TDGS Waiver
Range TDGS (%)
GBD %, Sample
Daily average TDGS (%)
100
110
120
130
140
150
TDGS (%)

Figure 5

Figure 6

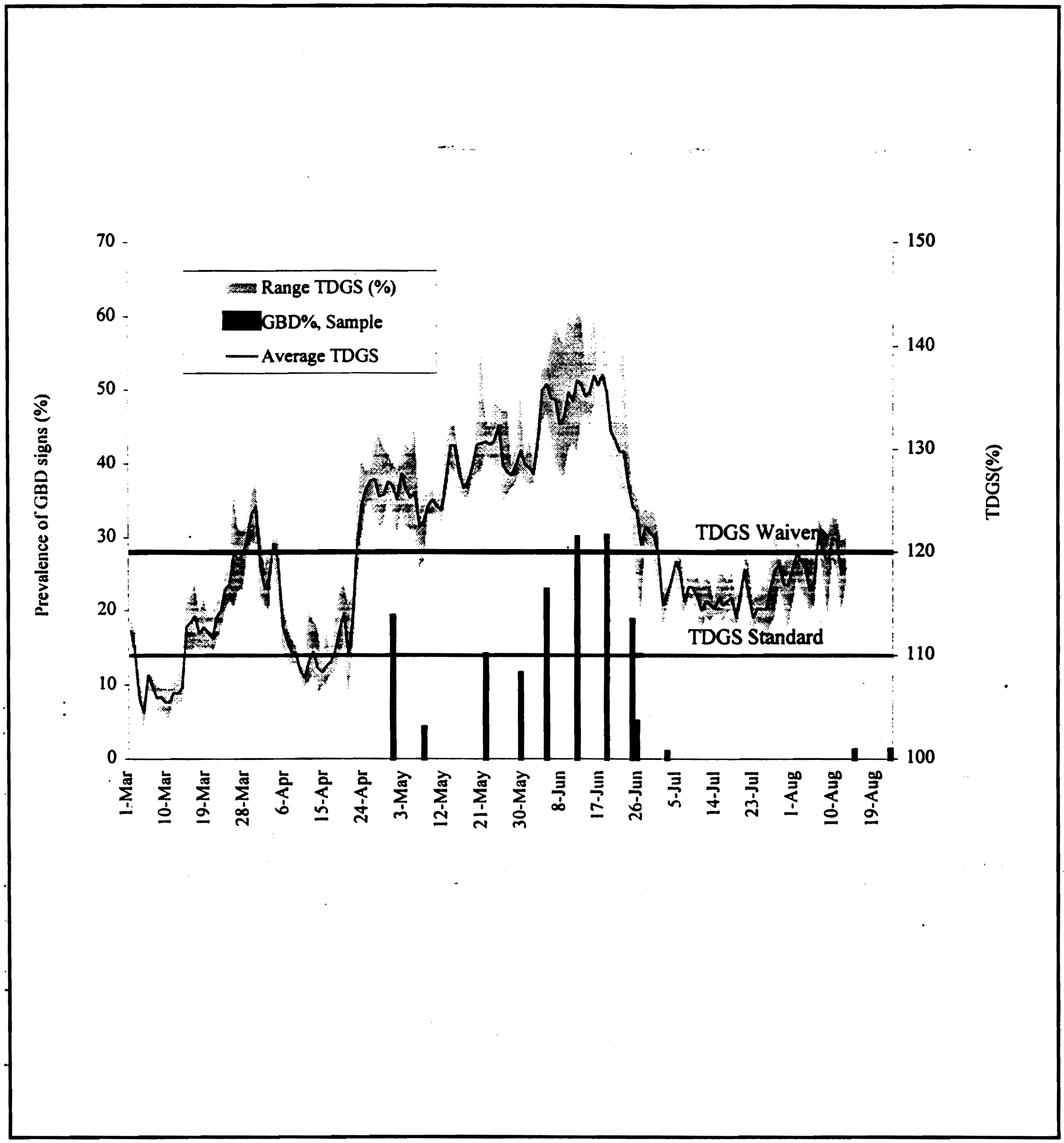
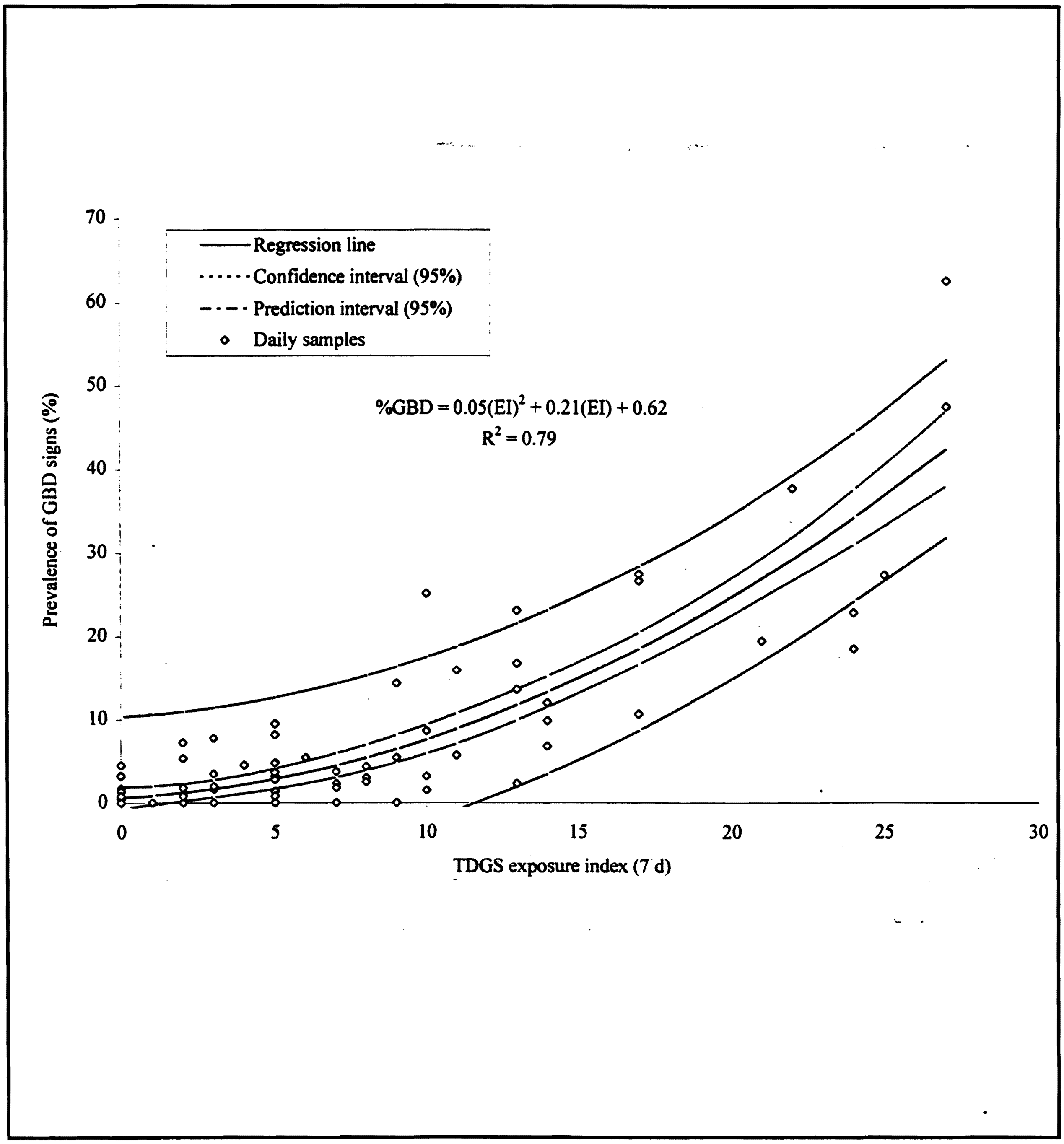
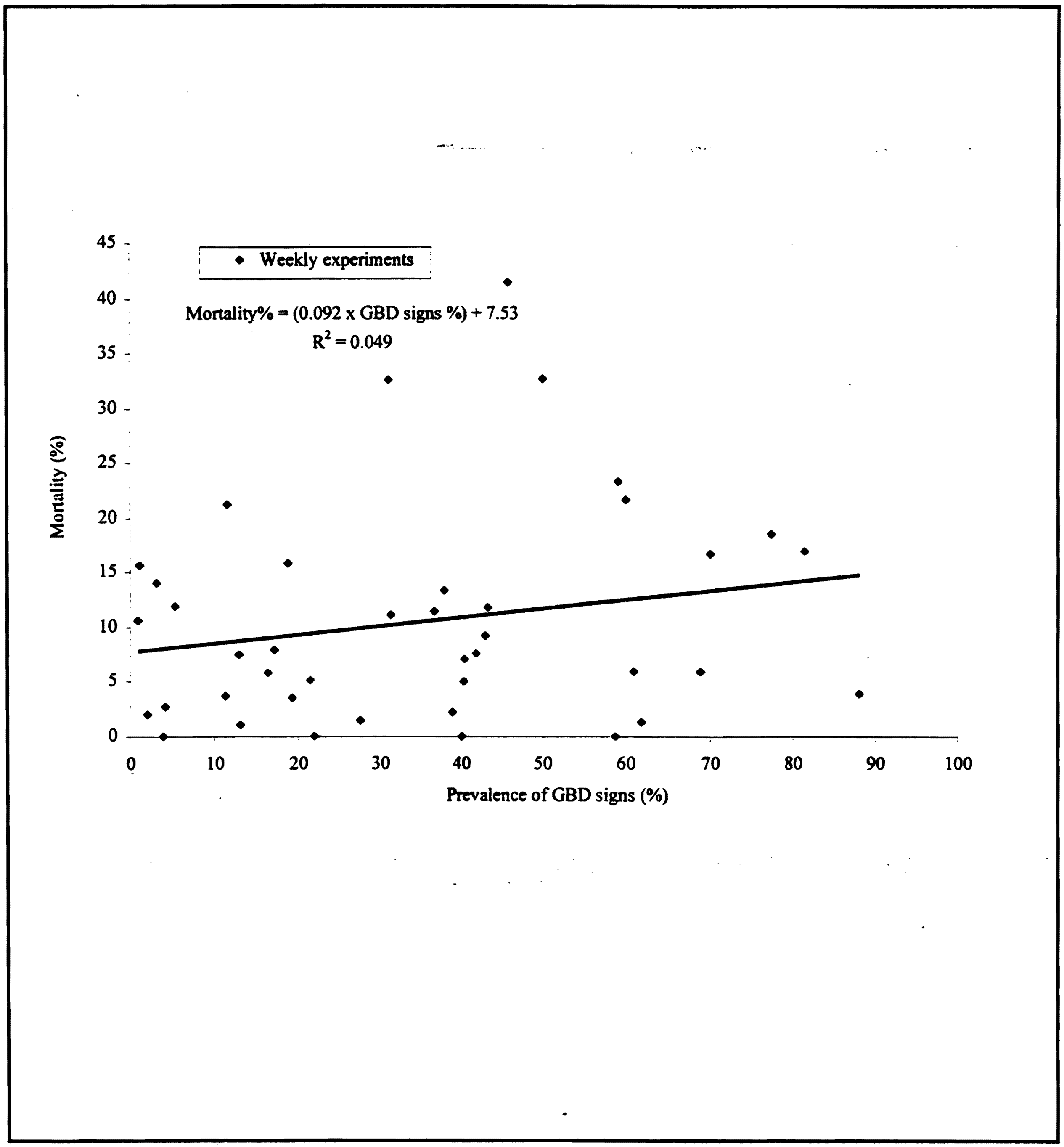

Range TDGS (%)
GBD%, Sample
Average TDGS
Prevalence of GBD signs (%)
TDGS(%)
TDGS Waiver
TDGS Standard
0
10
20
30
40
50
60
70
100
110
120
130
140
150
1-Mar
10-Mar
19-Mar
28-Mar
6-Apr
15-Apr
24-Apr
3-May
12-May
21-May
30-May
8-Jun
17-Jun
26-Jun
5-Jul
14-Jul
23-Jul
1-Aug
10-Aug
19-Aug

Figure 7



Regression line
Confidence interval (95%)
Prediction interval (95%)
Daily samples
%GBD = 0.05(EI)^2 + 0.21(EI) + 0.62
R^2 = 0.79
Prevalence of GBD signs (%)
TDGS exposure index (7 d)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30

Figure 8



Weekly experiments
Mortality% = (0.092 x GBD signs %) + 7.53
$R^2 = 0.049$
Mortality (%)
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
Prevalence of GBD signs (%)