Technical Report 2004-8

IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

MIGRATION DEPTHS OF ADULT SPRING–SUMMER CHINOOK SALMON IN THE LOWER COLUMBIA AND SNAKE RIVERS IN RELATION TO DISSOLVED GAS SUPERSATURATION

Report for project ADS-00-5

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Preface

Most historical studies that have addressed effects of dissolved gas exposure on fish survival and reproductive potential have been conducted in a laboratory setting. An important question yet to be answered is the applicability of using those laboratory results to evaluate in-river conditions experienced by aquatic organisms. Recent advances in radiotelemetry equipment and environmental modeling provided us with the tools to monitor the natural behavior and the environmental conditions encountered by fish. In this report we provide information on the in situ depths of migration for adult spring–summer Chinook salmon migrating through the Lower Columbia and Snake rivers in relation to exposure to and avoidance of gas supersaturated water. Study objectives reported on here relate to RPA's 24, 107, and 115 in Section 9.6.1 of the "Hydrosystem" Biological Option (NMFS 2000).

Acknowledgements

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Abstract

Dissolved gas supersaturation in the Columbia and Snake rivers routinely occurs during the spring and summer freshet as a result of water spilling over dams and can be lethal to fish. Measurable plumes of high dissolved gas extend downstream of dam spillways and create gas supersaturated conditions that do not equilibrate in reservoirs. Based on modeling results, the extent of the dissolved gas plume downstream from Bonneville Dam before dissipating is at least 10 km and the lateral position of the plume is highly dependent on dam powerhouse operation and spill volume.

During the spring and summer of 2000, 228-adult Chinook salmon *Oncorhynchus tshawytscha* were tagged at Bonneville Dam with archival radio data storage transmitters (RDSTs) that recorded depth of migration every 5 s and water temperature every 1 min. Migration depth is instrumental in determining levels of exposure due to the effects of hydrostatic pressure that provides compensation that limits the effects of supersaturation (hydrostatic compensation). We evaluated the swimming depths of 131 fish with RDSTs to determine in situ swimming depths in relation to water with elevated dissolved gas concentrations as they migrated from the Bonneville Dam tailrace upstream to Lower Granite Dam. Migration paths of 54 individual fish were monitored in the tailraces of Bonneville and Ice Harbor dams and collaborated with output from a two-dimensional dissolved gas model to estimate exposure levels.

We found that adult spring–summer Chinook salmon spent a majority of their time at depths deeper than 2 m (providing at least 20% hydrostatic compensation), and only several minutes at a time at depths shallower than 2 m. The most successive time an individual fish was observed shallower than 1 and 2 m deep was 1.3 h and 19.5 h, respectively. These behaviors suggest that adult salmon exposure to elevated levels of dissolved gas should have been minimal in 2000.

Based on analysis of locations of 54 fish and dissolved gas model results downstream of Bonneville and Ice Harbor dams, uncompensated exposure based on modeled dissolved gas levels (typically less than 130% TDGP) was estimated to be 4.1% of the time fish spent in the Bonneville tailrace and 11.9 % of the time spent in the Ice Harbor tailrace. Less than 1% of this exposure was at or higher than 115% which is

considered a conservative level of exposure known to cause GBD and mortality. Adult spring–summer Chinook salmon tended to migrate near the shoreline with approximately equal proportions of fish entering or leaving areas of the river with elevated dissolved gas levels. No significant association existed between crossing the river and the position of the dissolved gas plume downstream of Bonneville Dam. Statistical associations were also weak between dissolved gas concentrations and the percent and duration of time fish occupied near-surface waters.

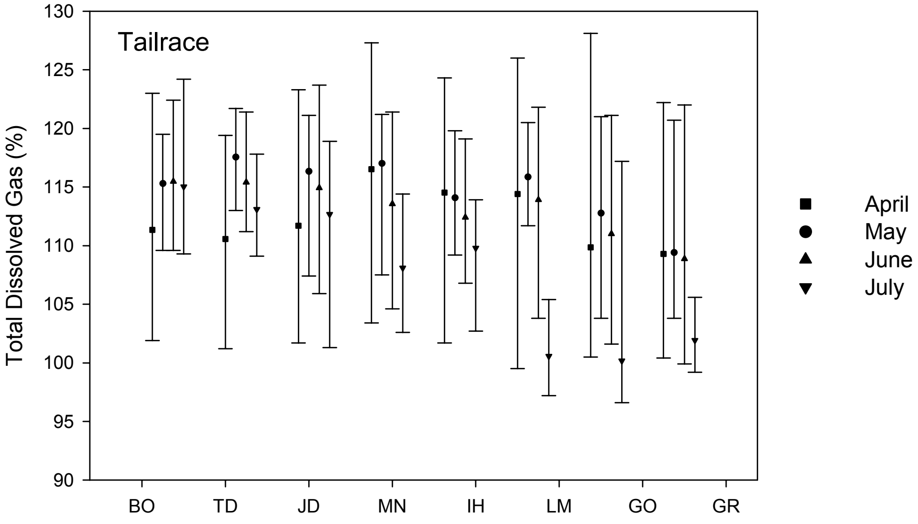
We recommend that efforts should be made to direct higher dissolved gas water from the spillway away form shorelines to minimize the potential for exposure. Additional research is needed to quantify the effects of short but frequent exposure to supersaturated dissolved gas conditions on reproductive potential and survival.

Introduction

Dissolved gas supersaturation in the Columbia and Snake rivers has largely been attributed to spilling water over dam spillways during spring and summer. Spillway discharge at dams causes atmospheric air (mainly nitrogen and oxygen) to be entrained in the spilling basin to depths where pressure is sufficient to produce supersaturation exceeding the water quality standard of 110% TDGP (Shrank et. al 1997; Appendix Figure 1). Supersaturated conditions persist throughout the length of a downstream reservoir in the Lower Columbia and Snake rivers because lack of turbulence does not allow water to equilibrate rapidly (Ebel, 1969; Figure 1). Gas saturation capacity also increases as water temperatures increase, which occurs as water moves downstream through the hydrosystem. Adult exposure is most likely to occur in reservoirs, tailraces and near fishway entrances at dams, and less so inside fishways because adult fish ladders reduce gas supersaturation of the water to levels lower than in the river, typically below 105% saturation in lower portions of fishways (Bouck 1996).

Spilling water at dam spillways has been one management strategy to increase survival of juvenile salmonids *Oncorhynchus spp.* passing Columbia and Snake river dams (Muir et al. 2001; Schoeneman et al. 1961). However, voluntary use of spill poses a potential conflict with the management of adult salmonids because the spill period coincides with the timing of adult spring–summer Chinook salmon *O. tshawytscha* and steelhead *O. mykiss* upstream migration. Supersaturated water conditions can cause gas bubble disease (GBD) or gas bubble trauma (GBT) in fish. Gas bubble disease occurs when tissues and fluids of fish exposed to supersaturated water also become saturated (Weitkamp and Katz 1980). Gases can then come out of solution, resulting in bubble formation (Weitkamp and Katz 1980). Excessive bubble formation can cause potentially lethal vascular and cardiac blockage or hemorrhaging from emboli formation (Weitkamp and Katz 1980). Gas bubble trauma also has been known to increase fish susceptibility to disease and predation, in addition to reducing growth and swimming performance (Dawley and Ebel 1975, Weitkamp and Katz 1980).

The level of dissolved gas supersaturation that salmonids can safely tolerate is variable depending on water temperature, species, body size, exposure duration, general



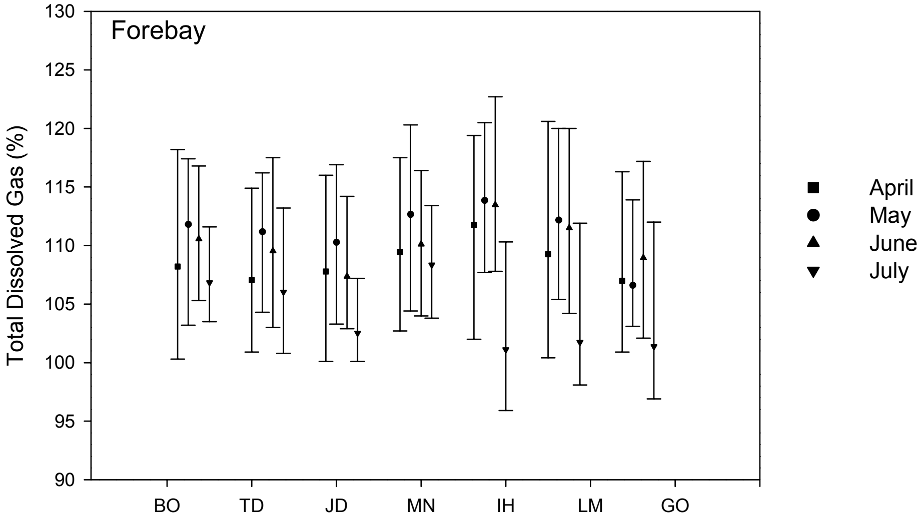


Figure 1. Average hourly total dissolved gas concentrations (%) including maximum to minimum in the Lower Columbia and Snake River dam tailraces and forbays in April, May, June, and July of 2000; B0 = Bonneville Dam, TD = The Dalles Dam, MN = McNary Dam, IH = Ice Harbor Dam, LM = Lower Monumental Dam, GO = Little Goose Dam, GR = Lower Granite Dam (data from U.S. Army Corps of Engineers Technical Management Team http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html).

physical condition, and swimming depth (Ebel et al. 1975). Woods (1968) describes a level of nitrogen at 118% saturation to be detrimental to adult salmonids. Rucker and Tuttle (1948) reported gas supersaturation between 110% and 115% was the critical range for gas bubble formation in adult salmonids. Westgard (1964) reported that adult Chinook salmon held in water at 116% nitrogen saturation developed GBD symptoms. In 1968, supersaturated levels from 123-143% related to construction of John Day Dam resulted in substantial juvenile and adult salmon and steelhead mortalities and signs of GBT (Beiningen and Ebel 1970).

Fish may be able to avoid areas of higher dissolved gas concentrations by either moving laterally to avoid higher saturation where spatial heterogeneity exists, or by sounding to depths where hydrostatic pressure is sufficient to compensate for supersaturation. In general, each meter of depth exerts pressure that increases the solubility of dissolved gas to compensate for approximately 10% saturation (Weitkamp and Katz 1980). Maintaining a single depth where adequate hydrostatic compensation is achieved may not be required to avoid GBD. Intermittent exposure to supersaturated gases through changes in swimming depth and corresponding hydrostatic compensation reduced signs of GBD (Meekin and Turner 1974; Ebel et al. 1975). The time to form emboli leading to mortality or sublethal effects from gas bubble disease is thought to be considerably longer than the 60-90 minutes required for equilibration of the tissues (Beyer et al. 1976).

Studies of fish behavior in relation to dissolved gas vary among species and also within species depending on testing environments. Hydrostatic compensation or lateral movements away from higher dissolved gas concentrations was observed with adult summer and fall Chinook salmon in the Lower Snake River using depth-sensitive tags (Gray and Haynes 1977). Avoidance of gas supersaturated water also was observed in lab experiments with juvenile Chinook salmon (Meekin and Turner 1974; Dawley et al. 1975), juvenile rainbow trout *O. mykiss*, Coho *O. kisutch*, Sockeye *O. nerka* and Chinook salmon (Stevens et al. 1980). However, studies with juvenile steelhead (Blahm et al. 1975; Dawley et al. 1975; Stevens et al. 1980), rainbow trout (Lund and Heggberget 1985) and juvenile Chinook salmon (Ebel 1971) showed no indication of avoidance of gas supersaturated water. Other studies indicate avoidance of only higher levels of gas supersaturation. Carp *Cyprinus carpio* and black bullhead *Ameiurus melas* avoided dissolved gas levels exceeding 145% (Gray et al. 1983), whereas juvenile Coho salmon, Sockeye salmon, Chinook salmon, and rainbow trout avoided levels that exceeded 125%, but not always 115% (Stevens et al. 1980).

Few studies have examined how gas supersaturation affects the upstream migration of adult salmonids in the Columbia and Snake rivers. Our study objectives were: 1) determining migration routes of adult spring–summer Chinook salmon relative to water with higher dissolved gas concentrations, 2) evaluating the depth of migration for adult spring–summer Chinook salmon in gas supersaturated water, and 3) determining the range of dissolved gas exposure. The following objectives relate to reasonable and prudent actions 24, 107, and 115 described in section 9.6.1 of the Biological Option (National Marine Fisheries Service 2000).

Methods

Study Area

The area of interest for this evaluation included the lower Columbia River from release sites at river kilometer (rkm) 225.6 (~9 km downstream from Bonneville Dam) upstream to the Columbia and Snake River confluence (rkm 521.6), and the Snake River from the mouth upstream to Lower Granite Dam (rkm 694.6; Figure 2). Mobile tracking efforts by boats were concentrated in the Bonneville and Ice Harbor Dam tailraces to determine migratory routes and depths of migration relative to dissolved gas plumes.

Bonneville Dam, located at rkm 235.1 on the Columbia River, is the first dam adult salmon encounter during upstream migration from the Pacific Ocean. Based on modeling, a lateral dissolved gas gradient exists during periods of spill that is highly dependant on powerhouse operation (Richmond et al. 1999; Appendix Figure 2). Dissolved gas levels recorded by a fixed monitoring station approximately 6 km downstream from Bonneville Dam (rkm 229.4) ranged from 115-135 % in 1997, an above average discharge year, to 110-125 % in 1998 and 2000, 2 years with near-average discharge (U.S Army Corps of Engineers Technical Management Team http://www.nwdwc.usace.army.mil/TMT/tdg_data/months.html).

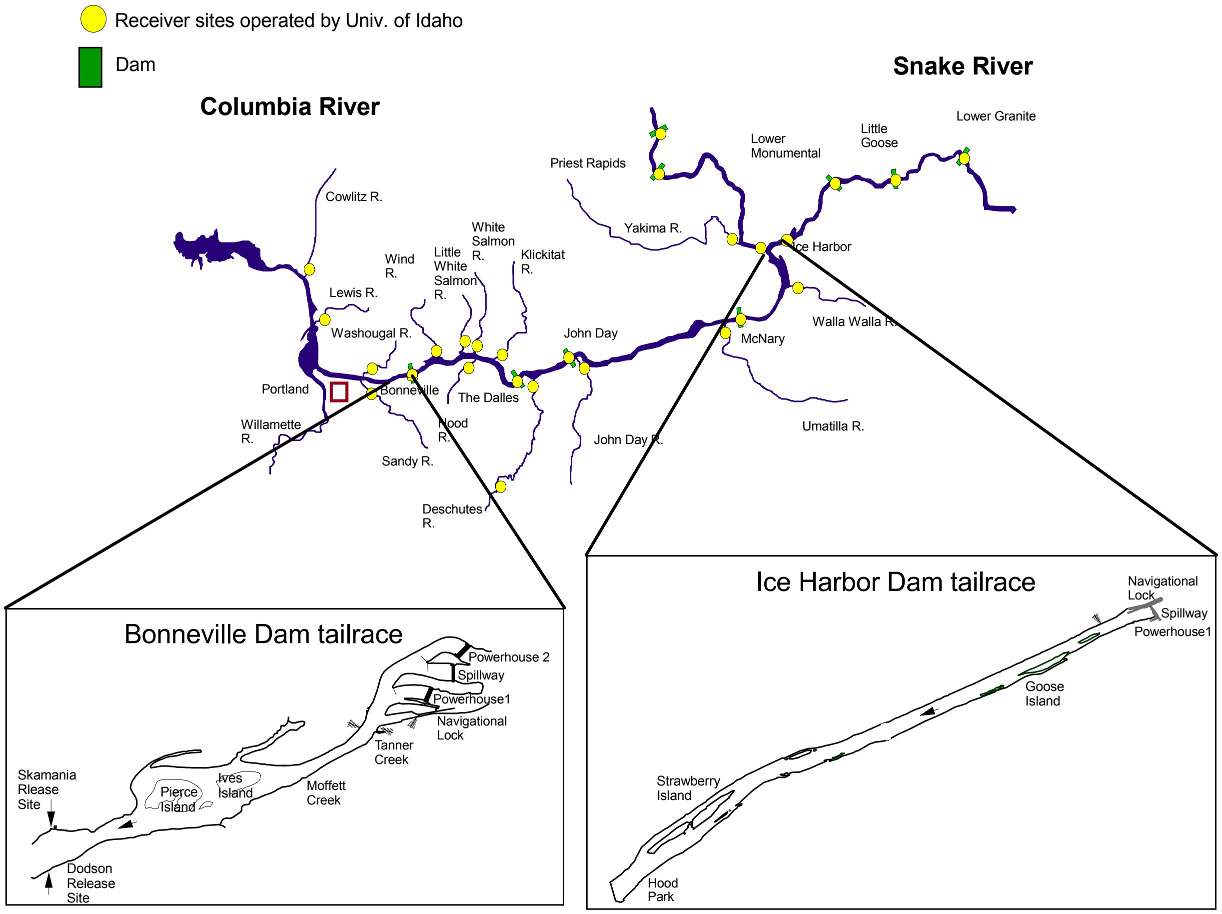


Figure 2. The study area in the Columbia and Snake rivers, where radio tagged adult spring-summer Chinook salmon were monitored during 2000 (enlarged areas indicate sections of more intense boat tracking).

Ice Harbor Dam, located 15.6 km upstream from the mouth of the Snake River, is the first dam adult salmon encounter during migration up the Snake River. Measurements of total dissolved gas in the Ice Harbor Dam tailrace at mid-channel have ranged from 120-135% saturation during above-average discharge years (spring and summer 1996 and 1997) to 110-125% saturation during near-average discharge (spring and summer 1998 and 2000; U.S Army Corps of Engineers Technical Management Team http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html).

Tagging Procedures

As part of a large-scale radio telemetry study of adult salmon and steelhead in the Columbia River Basin, adult fish were trapped and tagged at Bonneville Dam (Bjornn et al. 2000). From 4 April through 31 July 2000, 1,132 adult spring–summer Chinook salmon were tagged intragastrically with either a 7- volt (8 ×1.6 cm; 29 g in air) standard radio transmitter or a 3-volt (9 ×2 cm; 34 g in air) radio data storage transmitter (RDST) at the Adult Fish Facility located adjacent to the Washington shore fishway (Figure 3). Radio data storage transmitters were programmed to record temperature at 1-min intervals and pressure at 5-s intervals during upstream migration, which allowed 40 d of data storage. These transmitters were placed in 228 spring–summer Chinook salmon thought to be of Snake River origin based on passive integrated transponder (PIT) tag codes and adipose fin clips, so that tags could be recovered at Lower Granite Dam. Fish that reached Lower Granite Dam were diverting from the fish ladder into the adult fish trap based on selected PIT tags or coded wire tags. Most (96.7%) fish tagged with a RDST were of hatchery origin. More details on tagging methods and the Adult Fish Facility can be found in Keefer et al. (in press).

Tagged fish were released at two locations downstream from Bonneville Dam, Dodson Landing (rkm 225.6) on the Oregon shore or Skamania Landing (rkm 224.5) on the Washington shore (Figure 2). Radio data storage transmitters were removed from the fish and replaced with a standard radio transmitter at the adult fish trap at Lower Granite Dam to continue monitoring fish migration. Some RDSTs were reused in other fish after tag and data recovery.

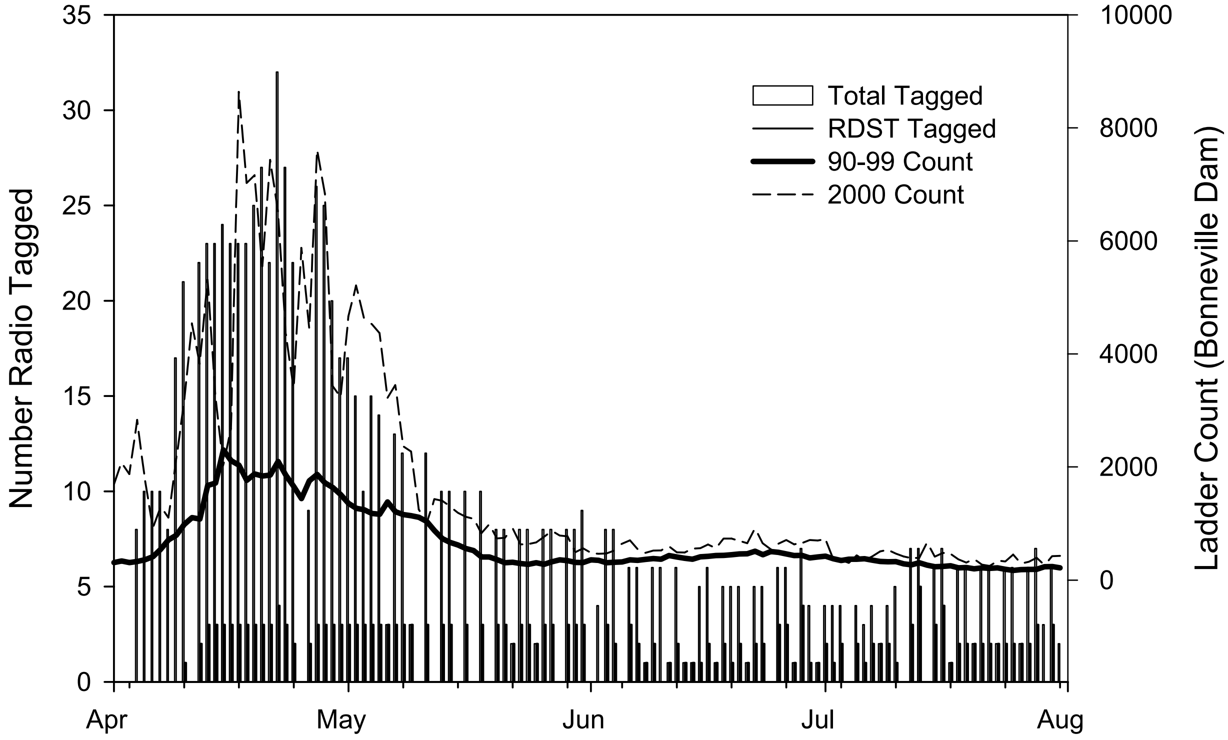


Figure 3. The timing and number of adult spring-summer Chinook salmon radio tagged daily at Bonneville Dam in 2000 (dark bars) relative to the ladder counts at Bonneville Dam during 2000 (solid line). The 10-year average (1990-1999) ladder counts for Chinook salmon are also shown (broken line).

Fine-scale Evaluation of Dissolved Gas Exposure

One factor that adds uncertainty to estimating exposure levels besides knowing the fish's depth is knowing the associated dissolved gas concentration encountered by the fish. The high degree of spatial variability in dissolved gas levels downstream from dams could result in different exposure levels for individual fish using different migration paths (Scheibe and Richmond 2002). Radio tagged adult spring–summer Chinook salmon were mobile tracked to evaluate specific locations and migration routes for fish migrating downstream from dams where horizontal gradients of dissolved gas can occur. Information regarding migration routes and the depth of migration at specific locations was used in coordination with simulated dissolved gas levels (Richmond et al. 1999) to estimate dissolved gas exposure histories for individual fish (Figure 4).

Mobile tracking with boats equipped with six element Yagi antennas and Lotek SRX 400 radio receivers downstream from Bonneville and Ice Harbor dams began in mid-April and continued to September, when spill ceased. Tagged fish were tracked from release sites to the boat-restricted zone downstream from Bonneville Dam, and from the Snake River confluence to the boat-restricted zone downstream from Ice Harbor Dam. Tracking typically consisted of locating fish every 10-20 min during daylight hours as they moved through tailraces. Tracking preference was given to RDST-tagged fish to determine fish locations needed to estimate exposure to dissolved gas. Transmitter identification, location, date, time, and tracking routes were recorded on GIS maps of each area. Logistic regression analysis was used to evaluate associations between release locations, positions of dissolved gas plumes, and fish migration paths. If fish were not tracked at least half the total distance from the release sites to Bonneville Dam, or from the confluence of the Snake River to Ice Harbor Dam, or if an accurate route could not be determined, the data were not included in the analysis.

Output from a two-dimensional depth averaged fluid dynamics model (MASS2; Richmond et al. 1999) was used to estimate dissolved gas concentrations experienced by 35 RDST-tagged adult spring–summer Chinook salmon in the Bonneville tailrace and by 19 salmon in the Snake River downstream from Ice Harbor Dam. Simulations of flow velocities, water temperature, and gas saturation were run for the time each fish was tracked in the Bonneville and Ice Harbor tailraces; simulations provided information at

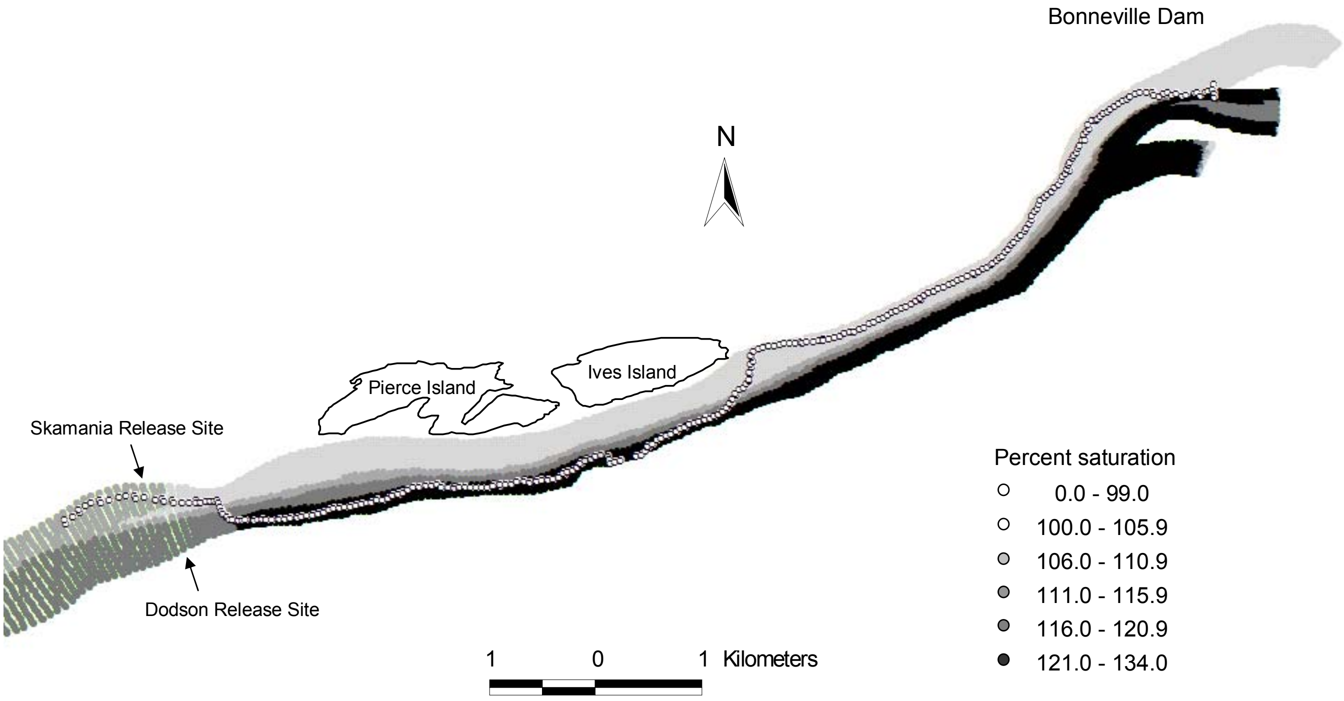


Figure 4. Simulated (MASS2) percent saturation on 24 July 2000 downstream from Bonneville Dam. Circles represent locations for fish (RDST #2435A). The circle color represents the magnitude of post compensation exposure (percent saturation equivalent to what the fish would experience after taking into consideration hydrostatic compensation).

approximately 30 m increments during a fish's track (Figure 4; Richmond et al. 1999). Post compensation exposure levels were estimated using the depth of the fish from RDSTs and the compensation depth (depth that provides complete hydrostatic pressure compensation) determined using total dissolved gas pressure estimated from the MASS2 model output:

$$\textit{Compensation Depth (m)} = [(\textit{Barometric Pressure mm Hg} - \textit{TDG Pressure mm Hg}) / 23] * 0.3048$$

(U.S Army Corps of Engineers Technical Management Team http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html) and

$$\textit{Post Compensation Exposure (\%)} = [(\textit{Compensation Depth m} - \textit{Fish Depth m})]*10 + 100$$

Large-scale Evaluation of Dissolved Gas Exposure

Chinook salmon movements past dams, through reservoirs, and into tributaries were determined using fixed radio receivers (radio receivers connected to aerial antennas or underwater antennas) located at all major tributaries and dams in the Columbia and lower Snake rivers (Figure 2). Aerial antennas were used with sequentially scanning receivers (6 s per frequency) while underwater antennas were used in combination with SRX/DSP receivers capable of simultaneously monitoring several radio transmitter frequencies and antennas (Figure 5). The migration history of each fish was separated into passage segments in reservoirs and dam tailraces. Fish were considered in a tailrace during the time between the last record on Yagi aerial antennas downstream from each dam (the distance downstream varies from dam to dam; Appendix Table 1) and entry into dam fishways based on records from underwater antennas located at fishway entrances, the collection channel or navigation lock. Reservoir passage times were calculated from the last record at the top of a fish ladder to the first record at a tailrace aerial antenna at the next dam upstream. Time fish spent in monitored tributaries was excluded from this analysis. The Wind, Little White Salmon, White Salmon, Klickitat, Hood, Deschutes, and John Day rivers were continually monitored by fixed receivers; Eagle and Herman creeks were monitored on a weekly basis from a boat or truck. Data processing involved assigning various codes to identify fish behavior within and around dams and tributaries. A more detailed explanation of data collection and processing procedures can be found in Bjornn et al. (2000).

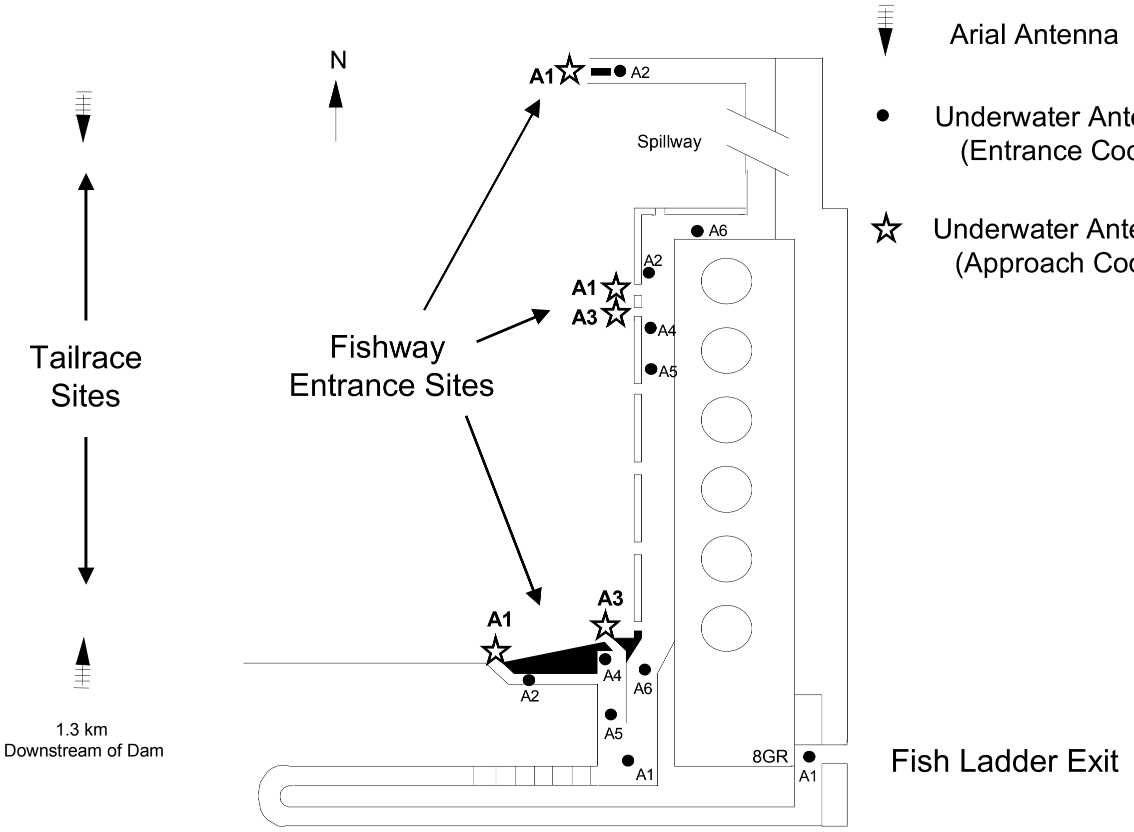


Figure 5. Diagram of Lower Granite Dam with location of aerial tailrace antennas and fixed underwater antennas.

Median migration depth was calculated for fish passing through each reservoir and tailrace in the Lower Columbia and Snake rivers. Medians were used rather than means because depth distributions were asymmetrical and skewed towards deeper depths. Pairwise comparisons of individual fish median migration depths at each dam were performed using analysis of variance (ANOVA) followed by Tukey's post hoc statistic (Zar 1999). Exposure was estimated from the percentage of time fish were observed near the surface (between 0 and 2 m). Exposure duration was determined from the successive depth records shallower than 1 and 2 m. The limited number of dissolved gas monitoring stations in the system made it difficult to determine levels of dissolved gas encountered by fish; therefore, we evaluated the depth of migration that would provide a level of hydrostatic compensation at 10% and at 20% TDGP through hydrostatic compensation. We believe maintaining a depth deeper than 2 m would have provided complete hydrostatic compensation under most saturation and temperature conditions during the study. Maintaining a depth deeper than 1 m would also have provided adequate compensation most of the time based on total dissolved gas concentrations measured in tailraces and forebays during 2000 (U.S Army Corps of Engineers Technical Management Team http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html).

Linear regression was used to evaluate relationships between water supersaturation and migration depth during passage through reservoirs and tailraces. The average dissolved gas percentage weighted by the period of time an individual fish was observed in a reservoir or tailrace was the independent variable used in this regression model. Dissolved gas concentrations were measured hourly at fixed monitoring stations located in the forebays and tailraces of Columbia and Snake river dams (Figure 6). The percentage of time adult spring–summer Chinook salmon were observed deeper than 1 and 2 m, and the continuous amount of time shallower than 1 and 2 m at each dam, were dependant variables in the linear regression models. A $\sin^{-1} \sqrt{}$ transformation was applied to the percentage of time deeper than 1 and 2 m and a $\log_e$ transformation was applied to continuous duration of time shallower than 1 and 2 m to improve homogeneity of variances and normality of residuals (Zar 1999).

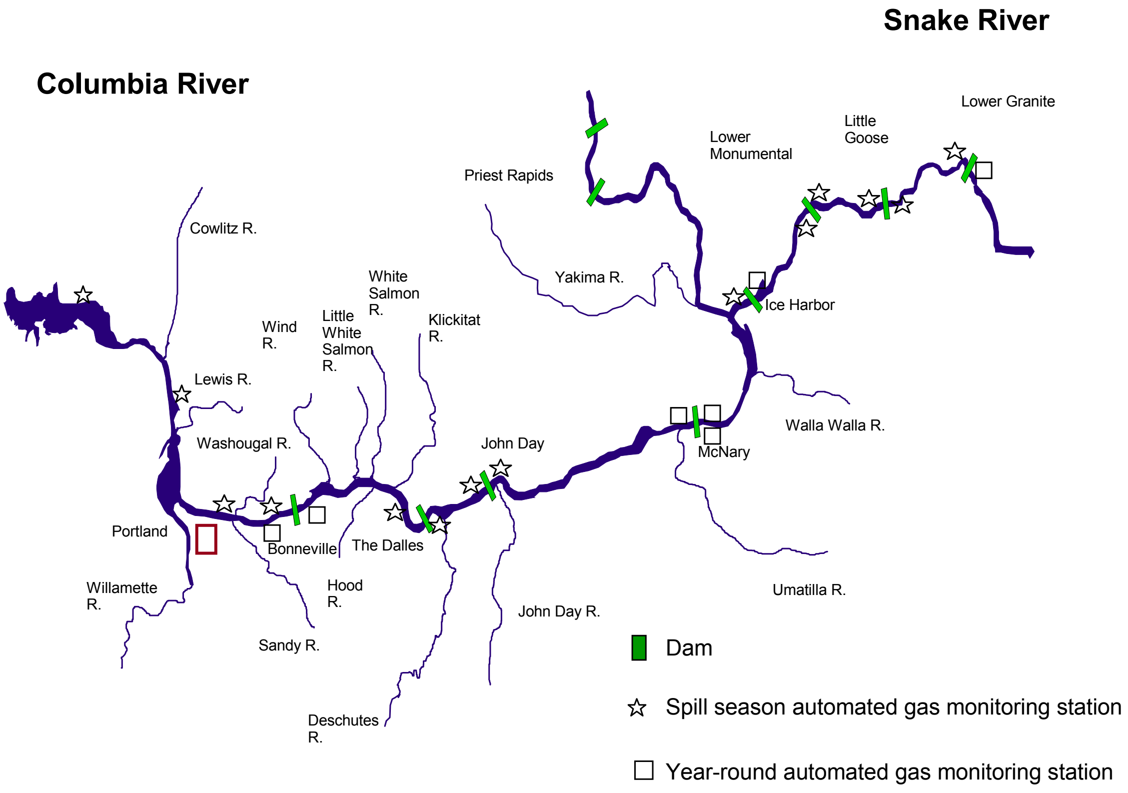


Figure 6. Locations of dissolved gas monitoring stations in the Lower Columbia and Snake rivers.

Results

Fine-scale Evaluation of Dissolved Gas Exposure

Of the 1,132 adult spring–summer Chinook salmon released with transmitters downstream from Bonneville Dam during the study period, 72 (combination of RDST and standard transmitters) salmon were tracked sufficiently to summarize migratory routes relative to the position of the dissolved gas plume downstream from Bonneville Dam. Of the tracked salmon, approximately equal proportions were released on the WA (51.4%) and OR shores (48.6%). Forty-nine adult spring–summer Chinook salmon (68% of 72) were monitored migrating when the higher dissolved gas plume was positioned mid-river, a condition that occurs during spill with approximately equal discharge from powerhouse 1 and powerhouse 2 (Figure 7; Appendix Figure 2). Thirteen fish (18%) were tracked when the higher dissolved gas plume was located along the Washington shore which occurs when the majority of discharge is from powerhouse 1 (Figure 8; Appendix Figure 2). Ten fish (14%) were tracked with the higher dissolved gas plume along the Oregon shore; with the majority of discharge from powerhouse 2 (Figure 9; Appendix Figure 2).

Generally, fish migrated in close proximity to shorelines (usually within 50 m) with little time spent mid-river except to cross between shorelines. We found neither an association between crossing events and release location (logistic regression, df = 1, P = 0.408) nor between crossing events and the location of the dissolved gas plume (logistic regression, df = 1, P = 0.547). We observed more fish crossed the river into water with elevated gas levels (7 of 12 or 58%) than were leaving water with elevated gas levels (5 of 12 or 42%). Furthermore, adult spring–summer Chinook salmon in the Bonneville tailrace migrated near the shoreline of release (58.3% or 42 fish did not cross) with approximately equal proportions of salmon crossing from the Washington shore to the Oregon shore (17 of 30 or 56.7%) as from the Oregon shore to the Washington shore (13 of 30 or 43.3%).

Eighty-six adult spring–summer Chinook salmon were partially tracked from the confluence of the Snake River to Ice Harbor Dam. Based on model simulations the position of the dissolved gas plume downstream from Ice Harbor Dam changed frequently throughout the day making it unfeasible to accurately determine if fish were

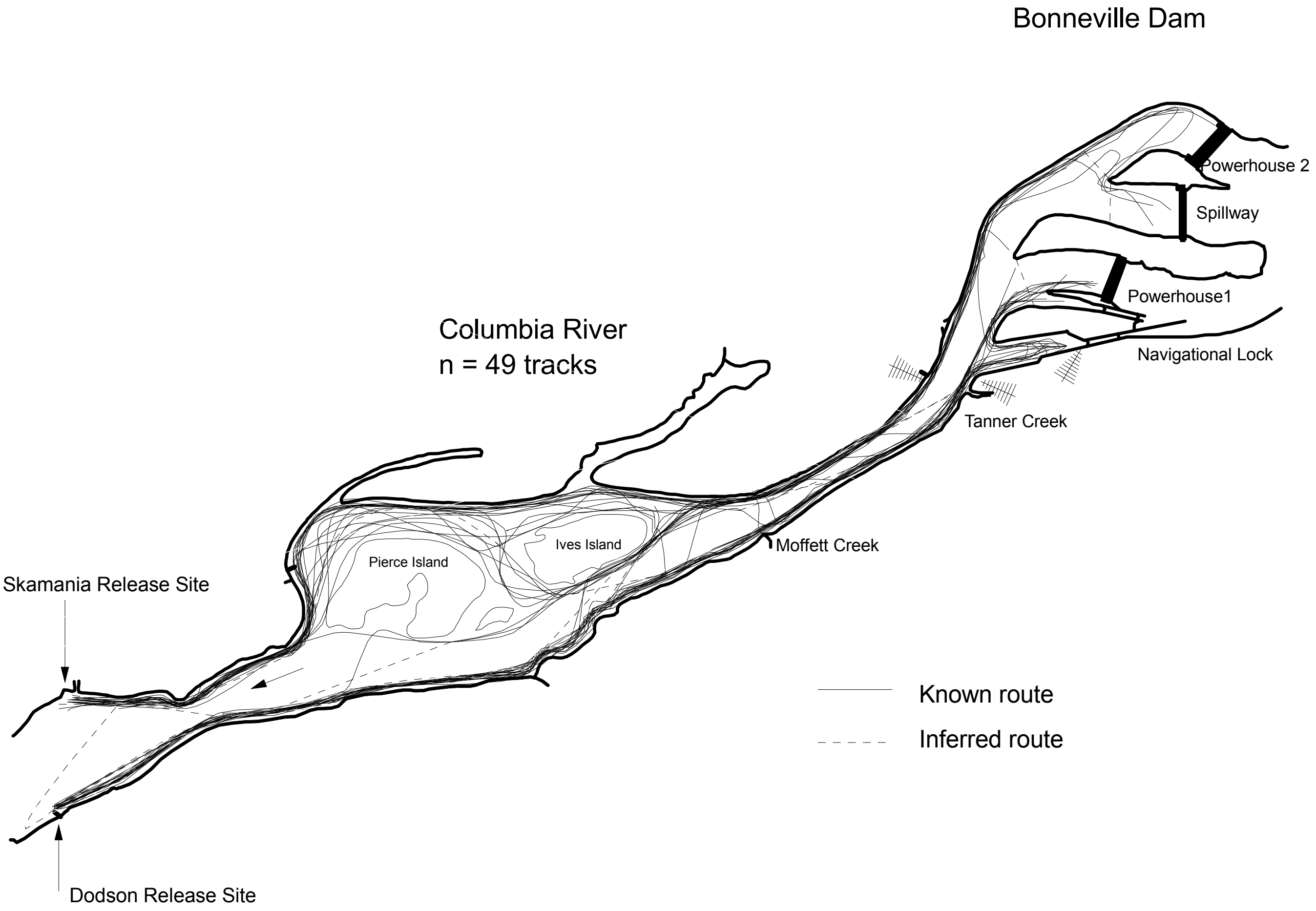


Figure 7. Migration routes for adult spring-summer Chinook salmon in the Bonneville Dam tailrace during 2000 with discharge from powerhouse 1, powerhouse 2, and spill (Middle River Dissolved Gas Plume).

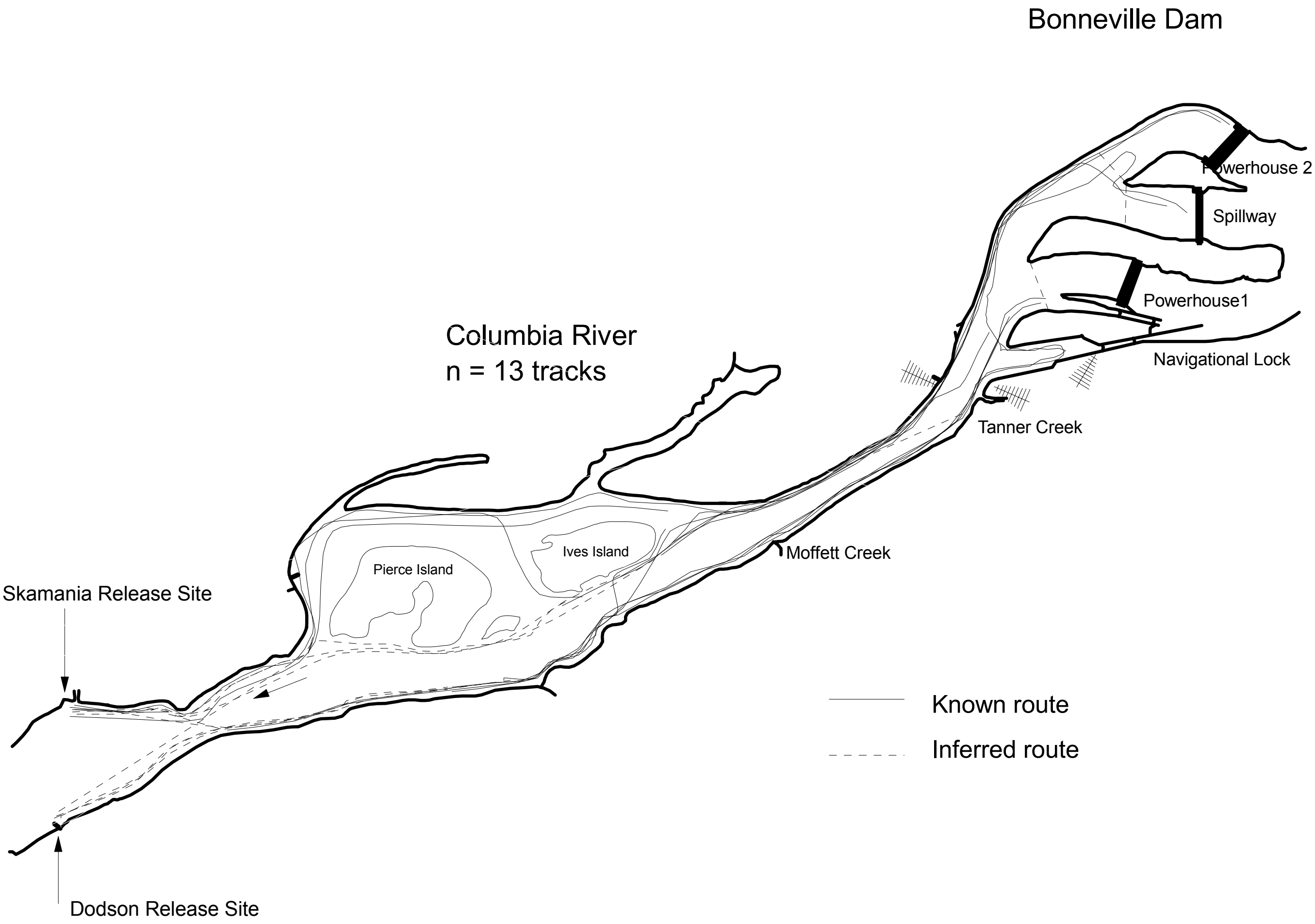


Figure 8. Migration routes for adult spring-summer Chinook salmon in the Bonneville Dam tailrace during 2000 with spill and discharge from powerhouse 1 only (Washington Shore Dissolved Gas Plume).

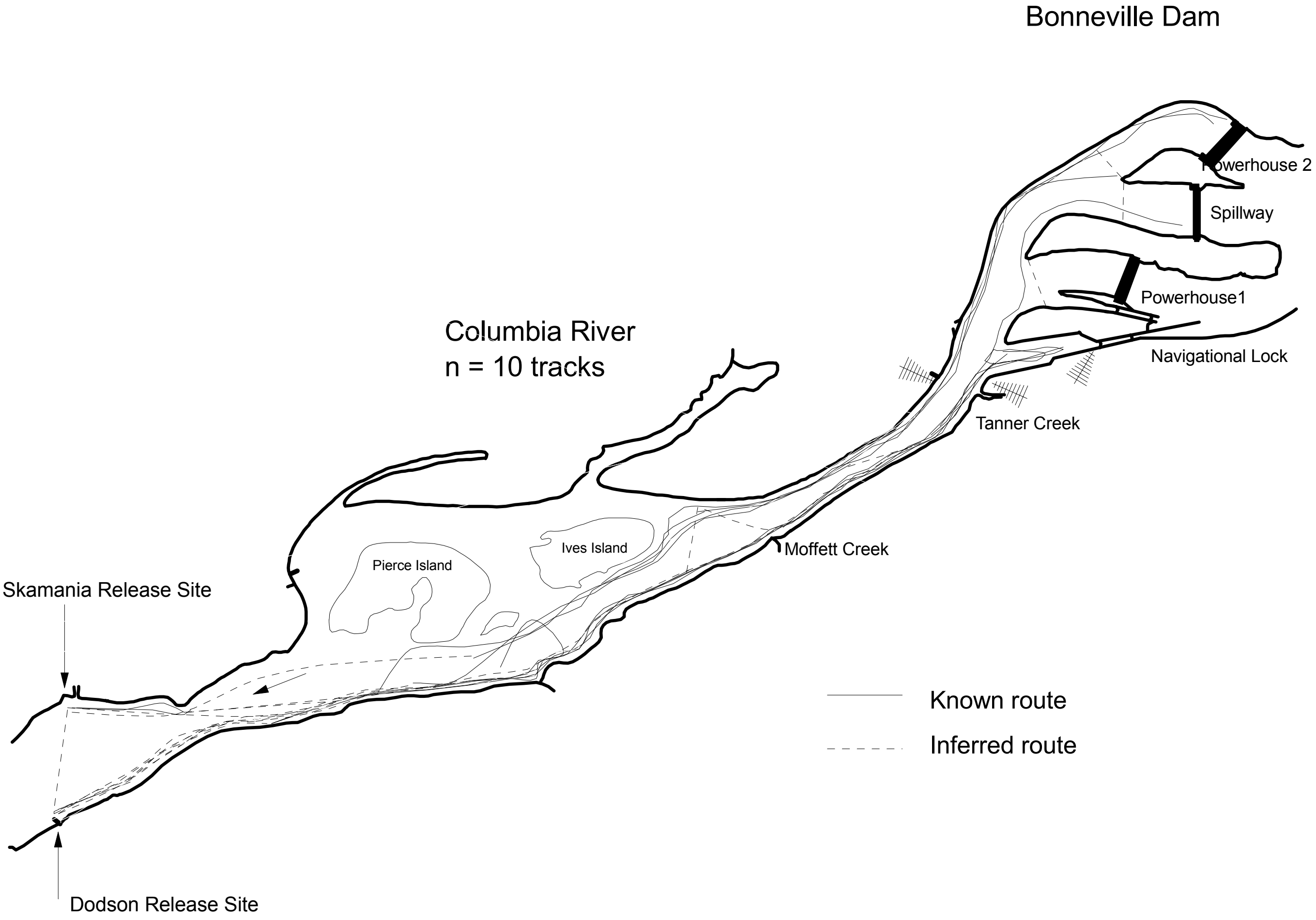


Figure 9. Migration routes for adult spring-summer Chinook salmon in the Bonneville Dam tailrace during 2000 with spill and discharge from powerhouse 2 only (Oregon Shore Dissolved Gas Plume).

avoiding the dissolved gas plume. Generally, migration behavior of fish in the Ice Harbor tailrace was similar to fish downstream from Bonneville Dam with respect to near-shore orientation (Figures 10 and 11). Fish observed migrating in the Ice Harbor tailrace after water levels dropped in mid to late June showed a strong tendency to migrate up the shipping channel along the north shore (Figure 10). Migration routes were more evenly split between the north and south shorelines before water levels dropped (Figure 11).

Archived data were retrieved from 35 adult spring–summer Chinook salmon mobile tracked downstream from Bonneville Dam and from 19 salmon mobile tracked downstream from Ice Harbor Dam. We observed that these fish were sufficiently deep in the water column to receive complete hydrostatic compensation 95.9% of the time spent in the Bonneville tailrace and 88.1% of the time in the Ice Harbor tailrace based on dissolved gas levels estimated from MASS2 model simulations and corresponding fish locations and depth records (Figure 12). Conversely, we estimated adult spring–summer Chinook salmon were exposed to supersaturated dissolved gas levels because of inadequate hydrostatic pressure compensation 4.1% of the time in the Bonneville tailrace; 1.2% of the uncompensated exposure was equivalent to a level of dissolved gas supersaturation between 101-105%, 1.8% to a level between 106-110%, 0.8% to a level between 111-115%, and 0.3% to a level between 116 and 120%. In the Ice Harbor tailrace, adult spring–summer Chinook salmon were exposed to elevated dissolved gas saturation as a result of inadequate hydrostatic pressure compensation 11.9% of the time with 11.6% of the uncompensated exposure equivalent to a level of dissolved gas supersaturation between 101 -105%, and 0.3% to a level between 106 -110%.

Adult spring–summer Chinook salmon encountered water with gas saturation levels between 105-115% in the Bonneville tailrace and between 110-115% in the Ice Harbor tailrace, 74.1% and 85% of the time, respectively (Figure 13). When the gas saturation of the water downstream from Bonneville Dam exceeded 115%, we found an increase in the percentage of time fish were exposed to a level of saturation due to inadequate hydrostatic pressure compensation (Figure 13). At dissolved gas saturation levels between 125-130% uncompensated exposure to a level of supersaturation was estimated to be 70.7% of the time (Figure 13).

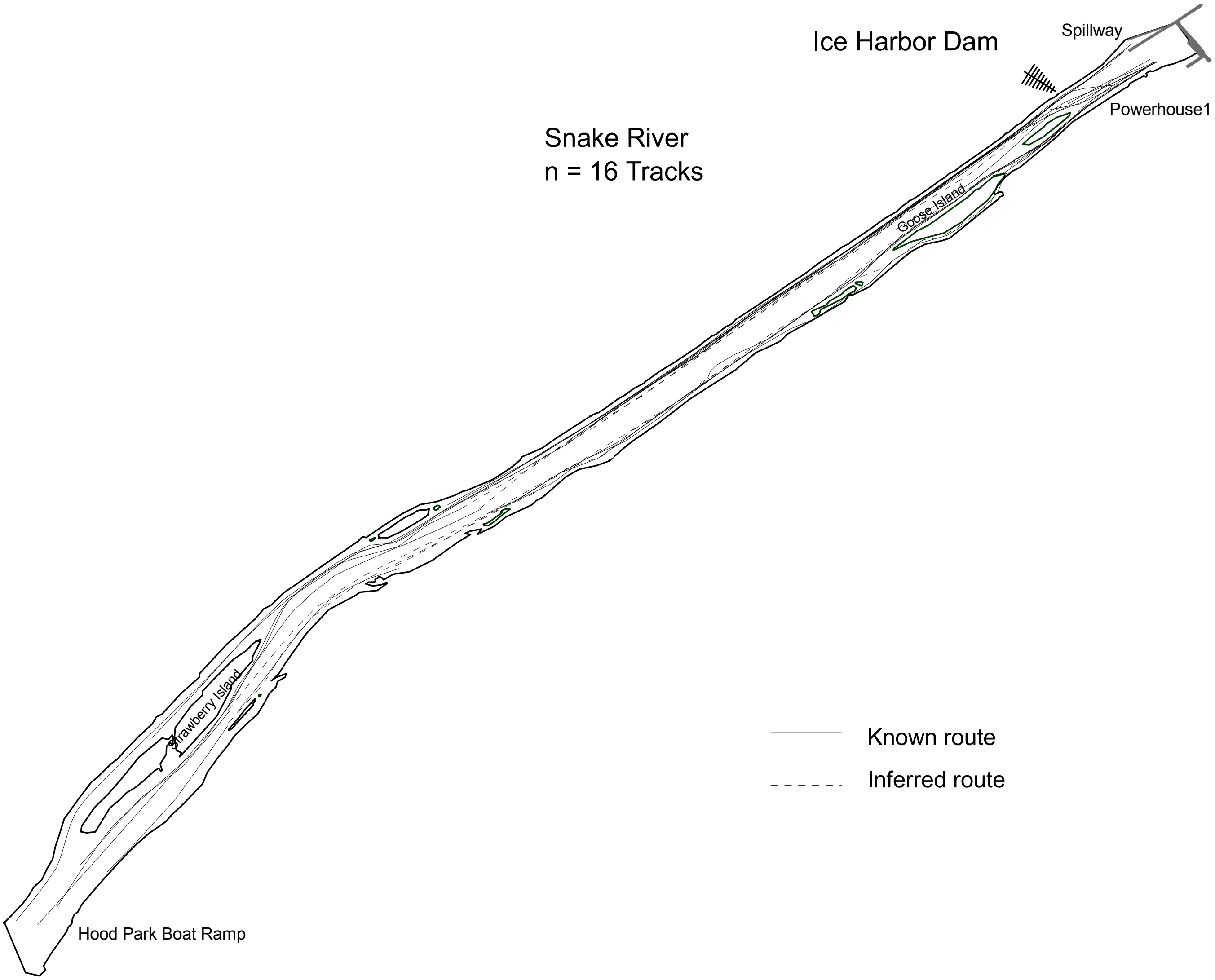
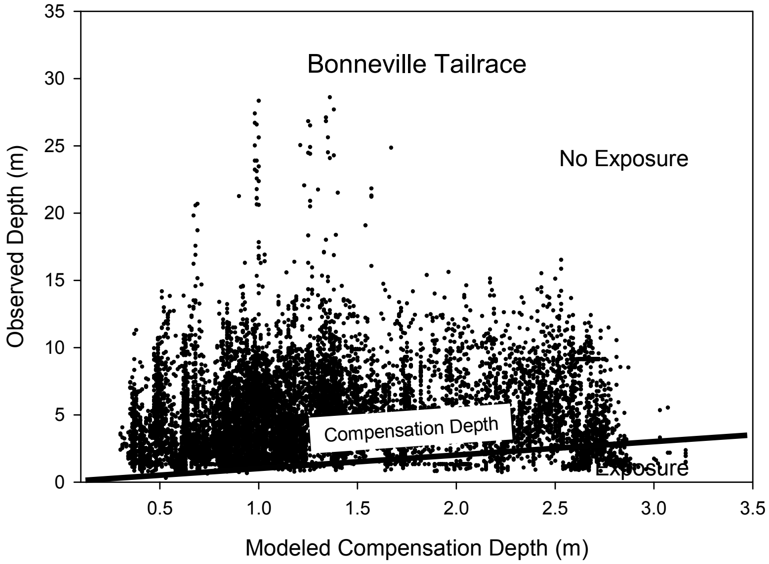


Figure 10. Migration routes for adult spring Chinook salmon in the Ice Harbor Dam tailrace during 2000.

Figure 11. Migration routes for adult summer Chinook salmon in the Ice Harbor Dam tailrace during 2000.



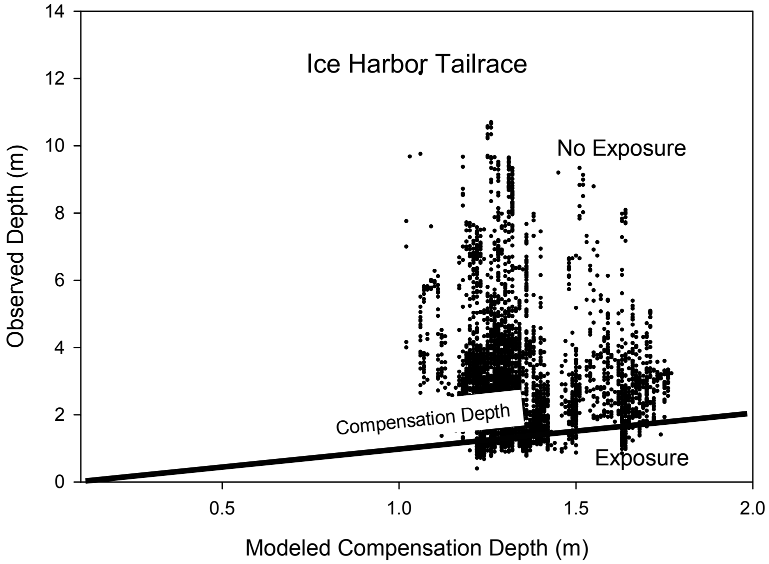
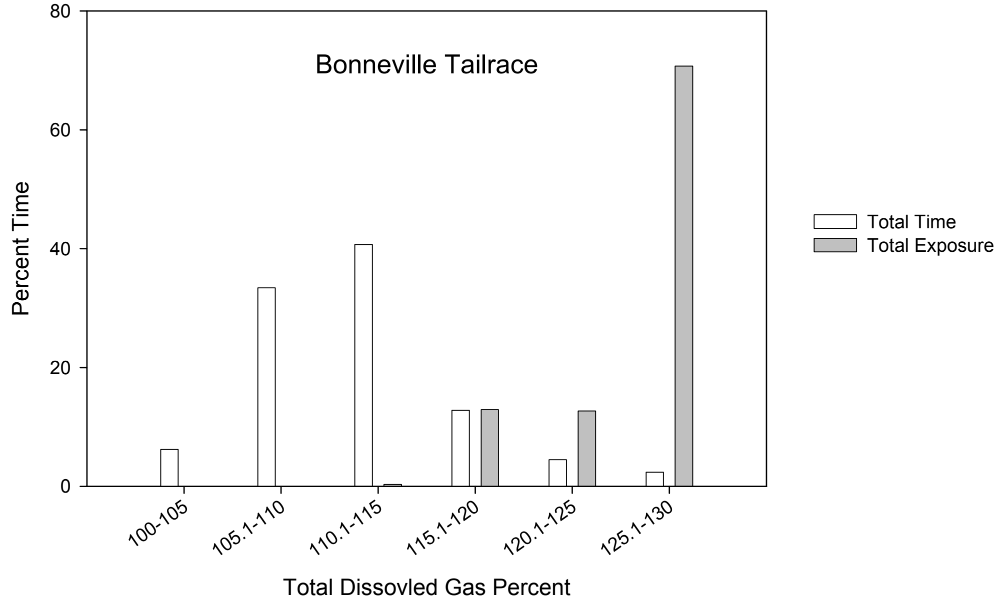


Figure 12. Relationship between the MASS2 modeled compensation depth (depth where there is complete hydrostatic compensation) relative to the actual recorded depth of adult spring-summer Chinook salmon in the Bonneville Dam tailrace (top) and the Ice Harbor Dam tailrace (bottom) during the spring and summer of 2000.



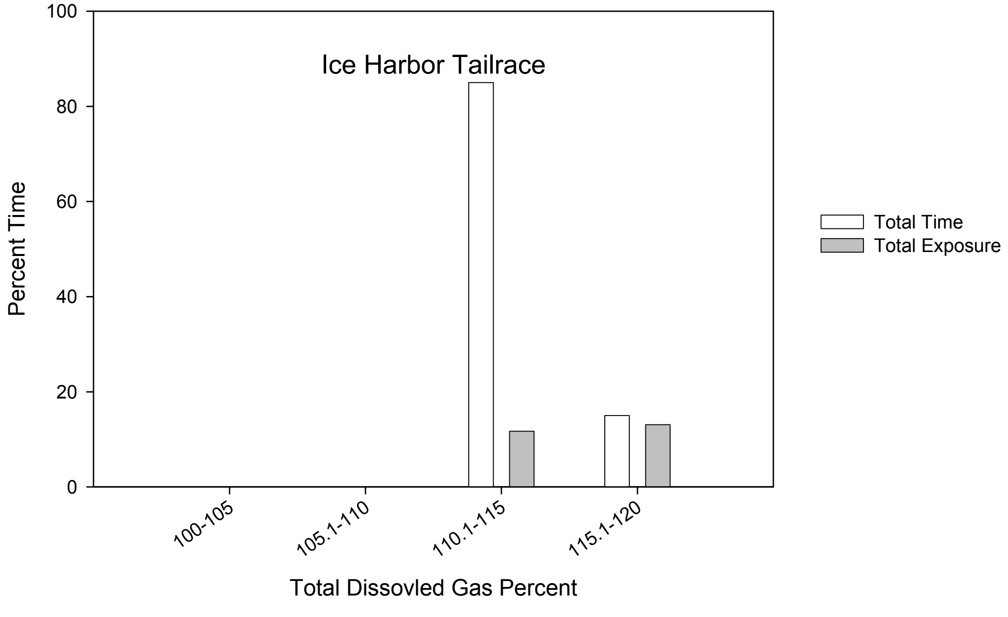


Figure 13. Total exposure relative to the amount of time at various categories of dissolved gas supersaturation.

Large-scale Evaluation of Exposure

Of the 228 adult spring–summer Chinook salmon outfitted with RDSTs, 137 tags were returned (60% return rate) and 131 were used to evaluate depth of migration. Six RDSTs were unusable due to a malfunctioning pressure sensor or improper tag set-up. The majority of the fish tagged with RDSTs (53%) were recaptured at Lower Granite Dam adult trap and provided an extensive history of fish migration depths through the Columbia and Lower Snake rivers. Hatcheries (21%), tribal and sport fishery (16%), spawning grounds and weirs (10%) accounted for most of the remaining RDSTs returned (Appendix Table 2).

Median migration depths of adult spring-summer Chinook salmon were significantly deeper at Bonneville and The Dalles reservoirs than at upstream reservoirs (ANOVA df = 6, F = 22.3, $p < 0.0001$, Figure 14). Similarly, median depths in tailraces were greater at most lower Columbia than Snake rivers dams (ANOVA df = 7, F = 18.2, $p < 0.0001$, Figures 15). In the Snake River tailraces, the median migration depths were generally shallower than Columbia River tailraces with the exception of Little Goose and Lower Granite tailraces, which were statistically similar to The Dalles and McNary tailraces (Figure 15). Median migration depths were the shallowest in the Ice Harbor and Lower Monumental tailraces (Figure 15).

Adult spring–summer Chinook salmon swam at depths deeper than 2 m a majority of the time when migrating through reservoirs and tailraces in the Lower Columbia and Snake rivers. The percentage of time that RDST fish were at least 2 m below the surface (providing at least 20% hydrostatic pressure compensation) during migration through a reservoir ranged from 66% at Ice Harbor to 85.1% at Bonneville (Figure 16). Fish were deeper than 1 m (providing at least 10% hydrostatic pressure compensation) ranging from 90.7% of the time in the Little Goose Reservoir to 97% of time in the Bonneville Reservoir (Figure 16). The relationship between the dissolved gas saturation and the percentage of time fish were deeper than 2 m in the water column was significantly positive though weak for Bonneville (ANOVA, df = 124, $P < 0.001$, $r^2 = 0.177$) and The Dalles reservoirs (ANOVA, df = 116, $P < 0.001$, $r^2 = 0.117$; Appendix Figure 3). Significant but weak positive correlations ($r^2 = 0.059$ to 0.108; Appendix Figure 4) were observed between the total dissolved gas saturation of the water and the percentage of

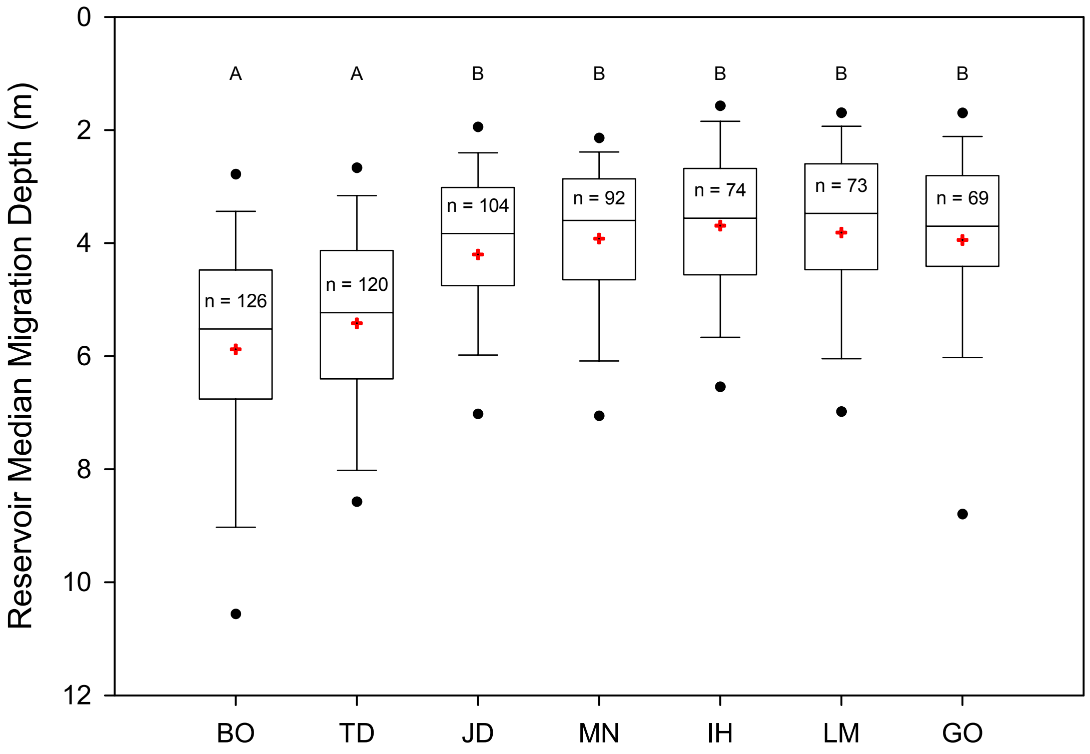


Figure 14. Average (cross), median (bar) and 5th, 25th, 75th, and 95th percentiles of migration depths for adult spring-summer Chinook salmon during migration through the four Lower Columbia and three Lower Snake River reservoirs in 2000 (BO = Bonneville, TD = The Dalles, JD = John Day, MN = McNary, IH = Ice Harbor, LM = Lower Monumental, and GO = Little Goose). Medians significantly different at $p = 0.05$ indicated by different letters (Tukey's post hoc test).

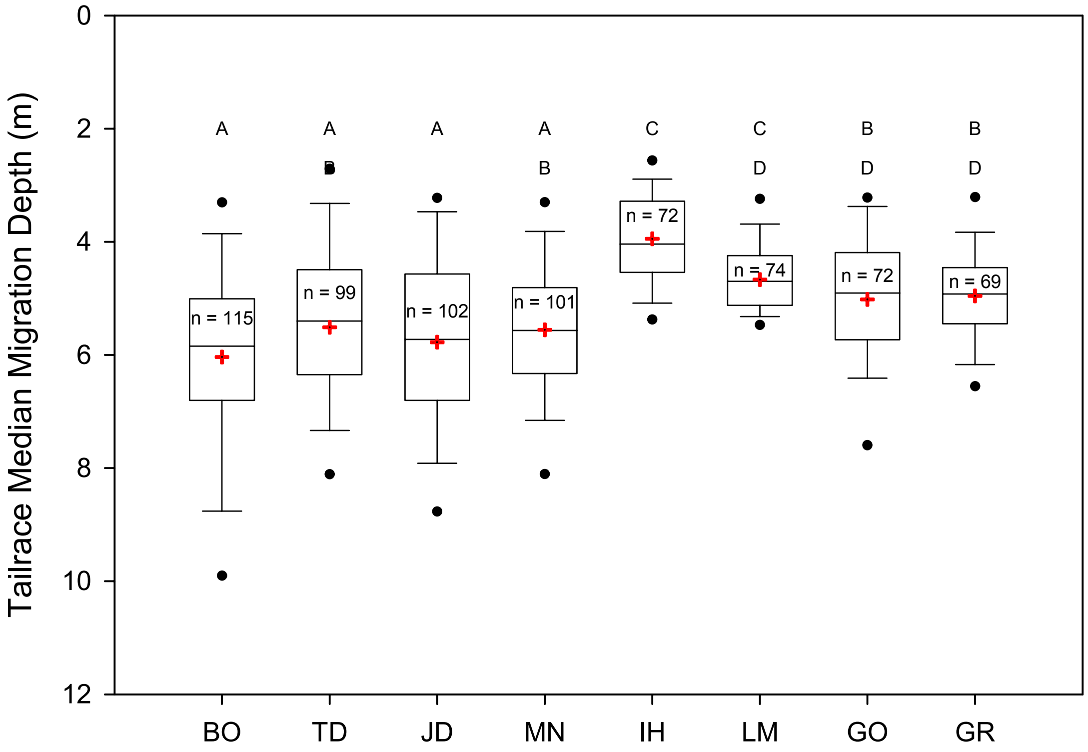
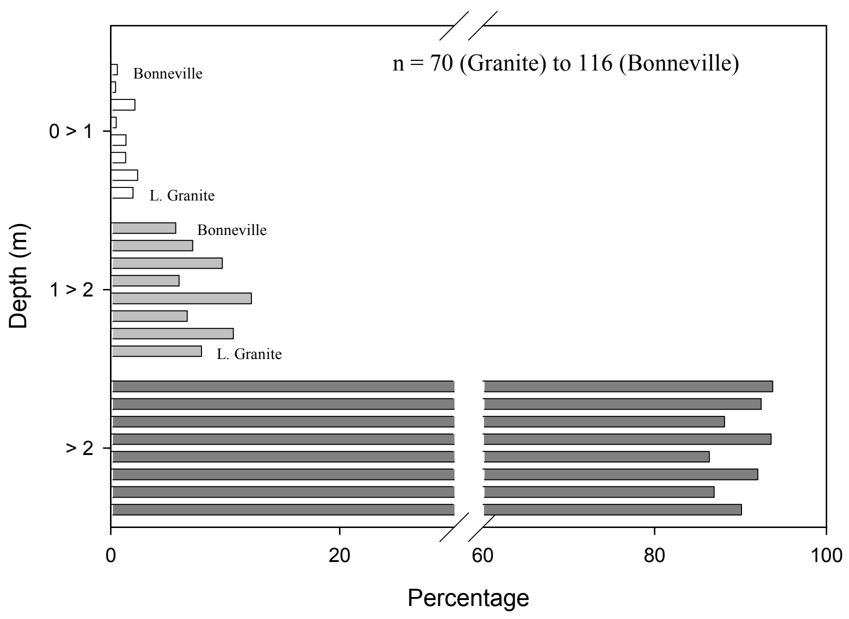
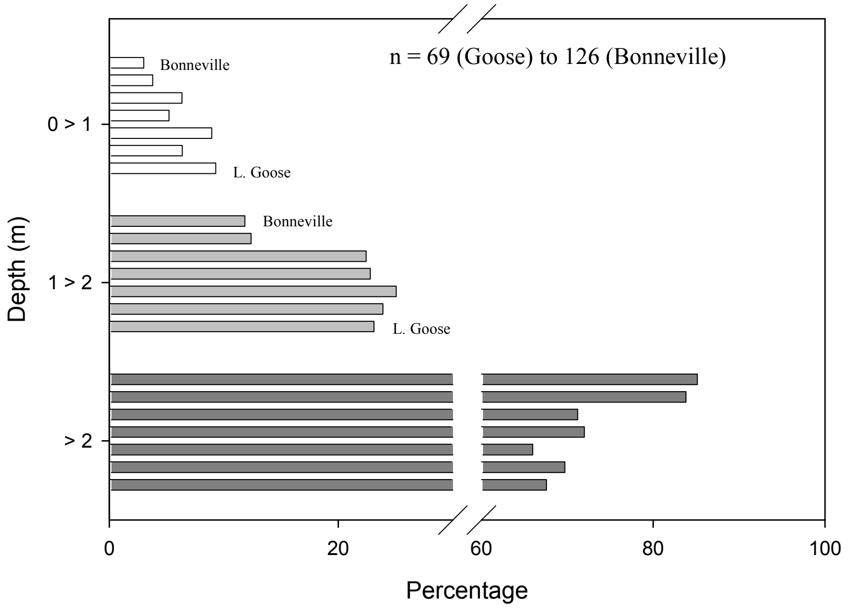


Figure 15. Average (cross), median (bar) and 5th, 25th, 75th, and 95th percentiles of median migration depths for adult spring-summer Chinook salmon in the tailrace sections of the four Lower Columbia River dams and four Lower Snake River dams in 2000 (BO = Bonneville, TD = The Dalles, JD = John Day, MN = McNary, IH = Ice Harbor, LM = Lower Monumental, GO = Little Goose, and GR = Lower Granite). Medians significantly different at p = 0.05 indicated by different letters (Tukey's post hoc test).



Columbia and Snake River Tailraces



Columbia and Snake River Reservoirs

Figure 16. Percentage of time spent between the surface and 2 m by adult spring-summer Chinook salmon tagged with radio data storage tags (RDSTs) during migration through tailraces (top panel) and reservoirs (bottom panel) in the Columbia and Snake rivers.

time fish were deeper than 1 m in Columbia River reservoirs but not in Lower Snake River reservoirs.

Adult spring–summer Chinook salmon generally migrated deeper in tailraces than in reservoirs. The percentage of time spent at least 2 m below the surface during migration through a tailrace ranged from 86.4% at Ice Harbor to 93.7% at Bonneville (Figure 16). The percentage of time deeper than 1 m ranged from 97.7% in the Little Goose tailrace to 99.6% in The Dalles tailrace (Figure 16). The relationship between dissolved gas concentrations and the percentage of time fish were deeper than 2 m was significantly positive but weak in all but the Bonneville tailrace with r^2 value ranging between 0.062 at Lower Granite to 0.196 at McNary (Appendix Figure 5). Significant positive correlations existed between total dissolved gas saturation and the percentage of time deeper than 1 m in the John Day tailrace (ANOVA, df = 99, F = 5.47, $P = 0.021$, $r^2 = 0.05$) and McNary tailrace (ANOVA, df = 99, F = 4.24, $P = 0.042$, $r^2 = 0.04$; Appendix Figure 6).

Duration of Exposure

Adult spring-summer Chinook salmon frequently altered their depth, and rarely spent long periods at depths shallower than 2 m (Figure 17). The duration of time adult Chinook salmon typically occupied surface waters ranged from minutes at a time at depths < 2 m to seconds at depths < 1 m (Figure 17 and 18). The maximum successive time < 1 and < 2 m experienced by an individual fish outfitted with a RDST during migration through a reservoir was 1.3 h and 19.5 h, respectively (Figure 19).

Although we found durations of time near the surface were short, we found that adult spring-summer Chinook salmon frequently re-ascended to surface waters. The median duration of time > 2 m deep in the water column before re-ascending to a depth < 2 m ranged from 2.1 min in the Ice Harbor Reservoir to 3.4 min in The Dalles Reservoir (Figure 17). The median duration of time > 1 m deep in the water column before re-ascending to a depth < 1 m ranged from 6.6 min in the Little Goose Reservoir to 33.5 min in the Bonneville Reservoir (Figure 18).

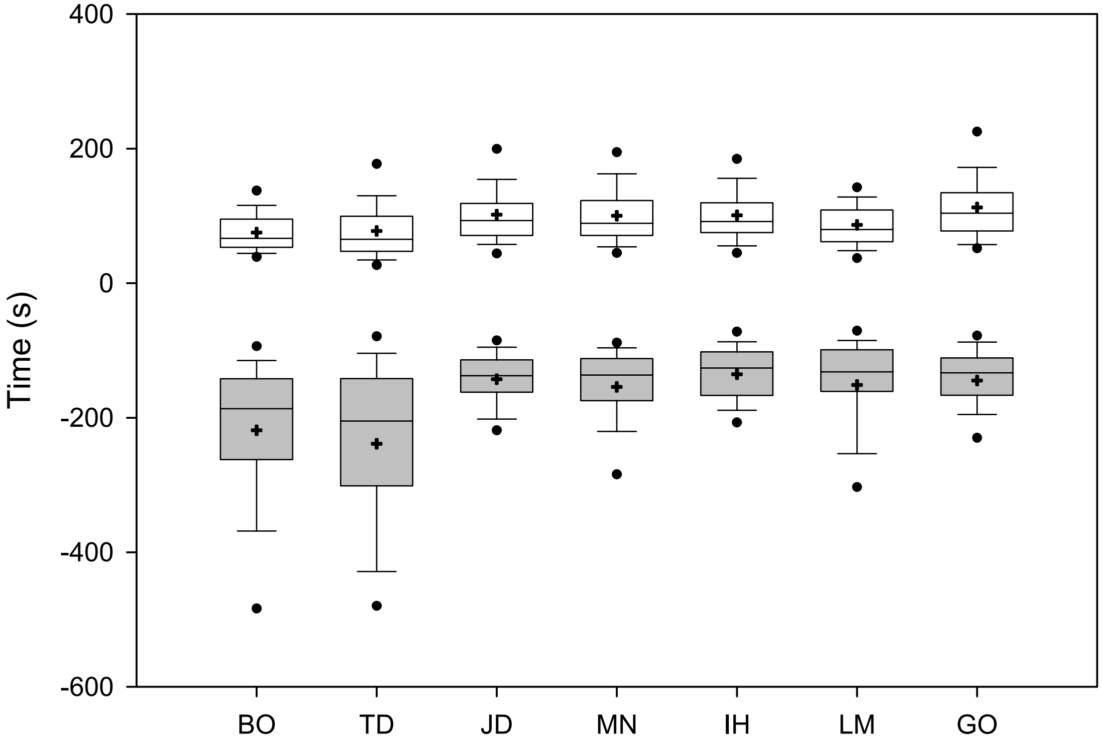
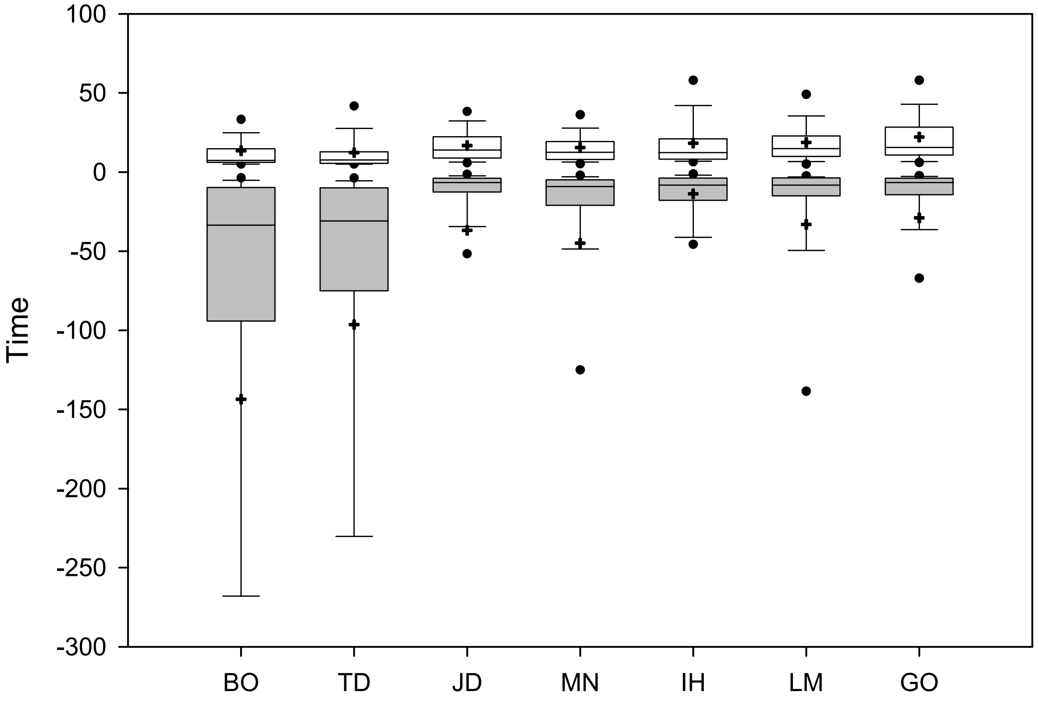


Figure 17. Average (cross), median (bar), and 5th, 25th, 75th, and 95th percentiles for average consecutive time (s) < 2 m (white) and > 2 m (gray) by adult spring-summer Chinook salmon during migration through the four Lower Columbia and three Lower Snake River reservoirs. BO = Bonneville (n = 126), TD = The Dalles (n = 120), JD = John Day (n = 104), MN = McNary (n = 92), IH = Ice Harbor (n = 74), LM = Lower Monumental (n = 73), and GO = Little Goose (n = 69).



* negative time values measured in minutes and positive time values measured in seconds.

Figure 18. Average (cross), median (bar), and 5th, 25th, 75th, and 95th percentiles for average consecutive time (s) < 1 m (white) and > 1 m (gray) by adult spring-summer Chinook salmon during migration through the four Lower Columbia and three Lower Snake River reservoirs. BO = Bonneville (n = 126), TD = The Dalles (n = 120), JD = John Day (n = 104), MN = McNary (n = 92), IH = Ice Harbor (n = 74), LM = Lower Monumental (n = 73), and GO = Little Goose (n = 69).

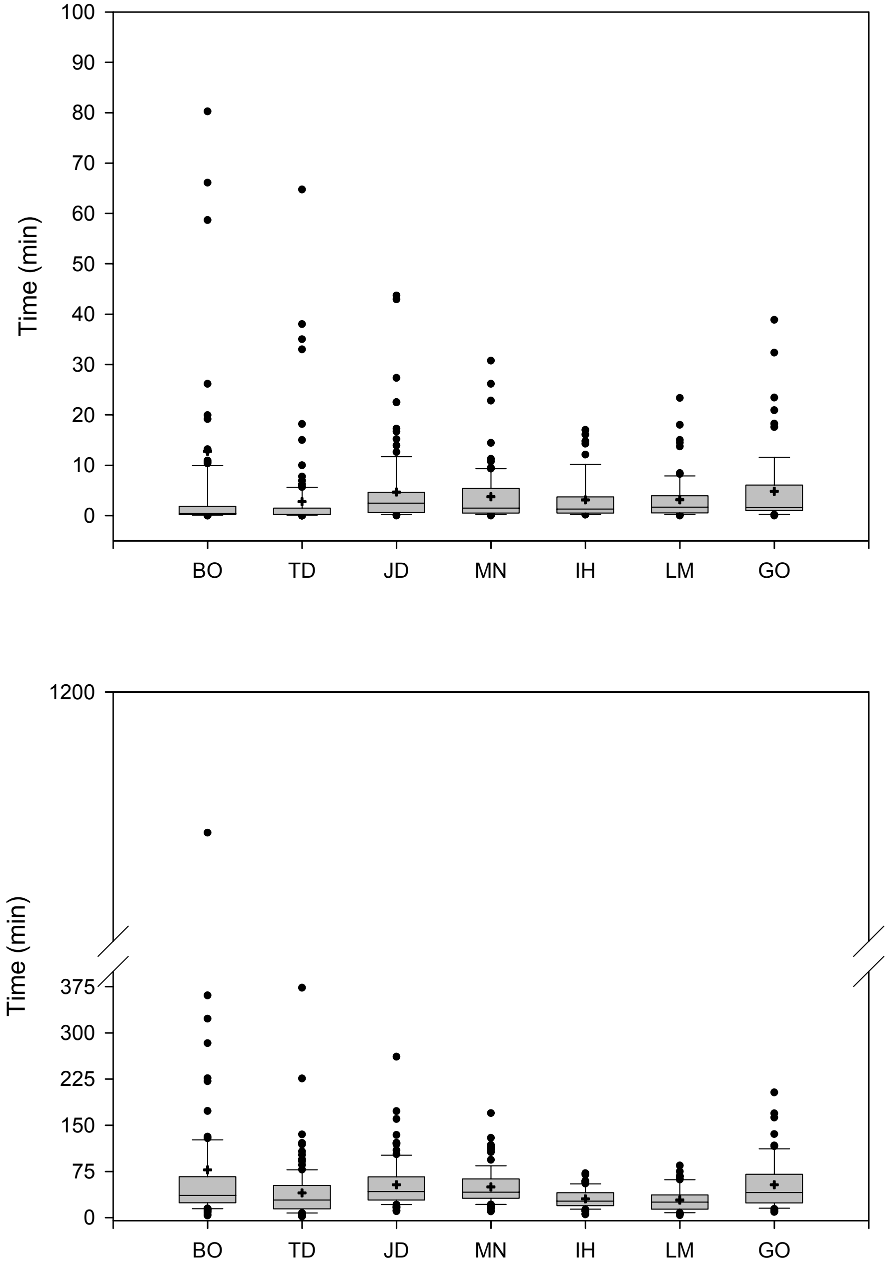


Figure 19. Average (cross), median (bar) and 5th, 25th, 75th, and 95th percentiles for maximum consecutive time (min) < 1 m (top panel) and < 2 m (bottom panel) by adult spring-summer Chinook salmon during migration through the four Lower Columbia and three Lower Snake River reservoirs. BO = Bonneville (n = 126), TD = The Dalles (n = 120), JD = John Day (n = 104), MN = McNary (n = 92), IH = Ice Harbor (n = 74), LM = Lower Monumental (n = 73), and GO = Little Goose (n = 69).

No significant relationships existed between dissolved gas levels and the average continuous time fish spent shallower than 2 m in the water column during migration through a reservoir (Appendix Figure 7). Significant but weak negative relationships existed between the average continuous time < 1 m in the water column and the dissolved gas concentration of the water in the Bonneville Reservoir (ANOVA, df = 122, F = 7.5, $P = 0.007$, $r^2 = 0.058$) and John Day Reservoirs (ANOVA, df = 101, F = 8.4, $P = 0.005$, $r^2 = 0.077$; Appendix Figure 8).

Discussion

Fine-scale Evaluation of Dissolved Gas Exposure

Results indicate that adult spring–summer Chinook salmon did not move laterally to avoid higher dissolved gas concentrations (>120% TDG). Approximately equal proportions of fish entered higher dissolved gas water as compared to fish that left areas of the river with elevated dissolved gas levels. These results conflict with lab tests in shallow tanks where juvenile Chinook salmon actively avoided 120% and 130% nitrogen supersaturated water (Meekin and Turner 1974; Dawley et al. 1975). Since we monitored migration paths of adult fish migrating in-river, we were unable to account for effects of hydrostatic compensation making our results difficult to compare to laboratory studies. Fish migrating in areas of the river with elevated gas concentrations were not confined to surface waters and probably received adequate compensation through vertical positioning.

Adult spring–summer Chinook salmon oriented near shorelines during upstream migration. The location of fish being tracked could only be estimated, due to variability in transmitter signal strength that varied according to the fish's depth. However, we were confident that we were able to estimate fish distance from shore to within approximately 10 m. Migration in close proximity to shorelines has been previously documented for adult Chinook salmon downstream and upstream from Bonneville Dam (Bjornn et al. 2000, Reischel and Bjornn 2003) and steelhead in the Snake River (Monan et al. 1970). A possible explanation for shoreline orientation is that it may be an energy-conserving behavior as fish seek slower water velocities near shore. Migrating close to shore may also put fish in better position to detect chemical cues from the natal tributaries, thus reducing the likelihood of straying. Adult spring–summer Chinook salmon were generally observed mid-river only when crossing between shorelines. We observed that crossing was more frequent where a tributary flowed into the river from the opposite shoreline, or where a shallow shelf extending into the river directed fish to the opposite shoreline.

Uncertainty in the depth of migration for adult salmon and lack of understanding in the spatial distribution of dissolved gas levels are two factors that limit our ability to evaluate dissolved gas exposures. Results from models of dissolved gas supersaturation relative to migration depth of adult spring–summer Chinook salmon downstream from Bonneville and Ice Harbor dams indicate that exposure to gas supersaturation as a result of inadequate hydrostatic compensation was minimal (less than 12%) during 2000. Most of the exposure that did occur based on the modeled dissolved gas concentrations and migration depth data was equivalent to a level of saturation between 100%-110% TDG in the Bonneville tailrace and 100%-105% TDG in the Ice Harbor tailrace. These exposure levels are lower than those generally considered lethal even with prolonged exposure (Ebel et al. 1975; Nebeker 1973). The higher percentage of exposure observed in the Ice Harbor tailrace probably was related to the shallowness of the river downstream from Ice Harbor Dam. Shrank et al. (1997) observed that GBD was prevalent in juvenile resident nonsalmonids downstream from Ice Harbor Dam but was rare in other reaches of the Columbia and Snake rivers.

Model results and corresponding migration depths indicated that occurrences of exposure to dissolved gas increased for adult Chinook salmon when saturation levels exceeded 115%. Adult Chinook salmon where observed migrating in water with saturation levels ranging from 100–115% the majority of the time. However, when saturation levels of the water exceed 115% we found an increase in the proportion of uncompensated exposure relative to the amount of time spent at these elevated levels. Although estimates of dissolved gas exposures of Chinook salmon during 2000 were lower than levels known to cause GBD and mortality, dissolved gas levels above 120 – 125% can occur and extended exposure at these levels can be dangerous, particularly in shallow areas of the river where the ability to hydrostatically compensate is limited.

Signs of GBD and mortality have been observed with adult Chinook salmon in the Columbia River when saturation levels ranged between 123%-143% (Beiningen and Ebel 1970). Ebel et al. (1975) found that even when adult salmon were allowed the choice to hydrostatically compensate, substantial mortality occurs when gas saturation levels exceed 120% for more than 20 d due to inadequate compensation.

Our estimates of dissolved gas exposure histories for adult migrants were probably conservative because of the tendency for the model to overestimate saturation levels (Richmond et al. 1999). Model verification results indicated that the MASS2 model simulations accurately modeled the spatial variability in dissolved gas concentrations, but the estimated total dissolved gas concentrations were consistently 2-5% higher than those observed in the field, with some estimates being as much as 15-20% higher than actual (Richmond et al. 1999). Accuracy of the pressure sensor in the RDST was approximately +/- 0.5 m, which, may have accounted for an additional +/- 5% error in estimating exposure levels based on the 10% compensation per meter depth rule.

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Large-scale Evaluation of Dissolved Gas Exposure

Few studies have examined migration depths for adult spring–summer Chinook salmon in the Lower Columbia and Snake rivers. We found that adults migrating through reservoirs and tailraces in the Lower Columbia and Snake rivers spent a majority of their time at depths (deeper than 1 to 2 m) that provided adequate hydrostatic compensation for supersaturated conditions encountered during 2000. Using a cutoff depth of 2 m represents a conservative estimate of compensation depth based on dissolved gas levels recorded in 2000. Dissolved gas levels recorded during the spring and summer of 2000 were typically lower than the 5-year average at most hydroelectric projects, and rarely exceeded 125% based on hourly records at fixed monitoring stations (Appendix Figure 1).

Adult spring–summer Chinook salmon tended to migrate deeper in tailraces than in reservoirs. This may be because steep gradient shorelines are common in the dam tailraces, creating increased depths near shore. Alternatively, differences in water velocity, temperature, or dissolved gas levels between tailrace and reservoir reaches of the rivers may have been responsible. Results on depth use between the surface and 2 m were consistent with those of Gray and Haynes (1977) who found that adult spring Chinook salmon spent approximately 89% of their time at least 2 m below the surface in the Snake River downstream from Little Goose Dam when gas saturation levels were below 130% TDGP. We observed that tagged fish were > 2 m in the tailrace of Little Goose Dam about 87% of the time under similar saturation levels. The highest percentage of time recorded near the surface was in the Lower Snake River downstream from Ice Harbor Dam, an area that is shallow relative to other tailraces: water depth is typically < 2-3 m along the south shoreline or > 10 m along the north shore, where the shipping channel is located. Shrank et al. (1997) observed GBD was prevalent in fish downstream of Ice Harbor Dam but was rare in other reaches of the Columbia and Snake rivers.

Based on median reservoir passage times of up to 2 d, adult Chinook salmon could potentially be exposed to gas supersaturation for relatively long periods (Bjornn et al. 2000). However, although adult spring–summer Chinook salmon frequently entered the upper 2 m of the water column, excursions to these shallow depths were brief, ranging from seconds for depths less than 1 m to minutes for depths less than 2 m (Figures 20). These vertical movements may have been related to orientation (Ruggerone et al. 1990). Effects of short but frequent exposure patterns that we observed in adult spring–summer Chinook salmon on the prevalence of GBD and mortality are unknown. Based on previous literature, we speculate that the continuous change of migration depth observed in adult spring–summer Chinook salmon would provide adequate compensation to gas supersaturated water. Beyer et al. (1976) suggest that equilibrium of gas pressures in fish requires 60-90 min, which would enable a fish to spend a considerable amount of time near the surface without developing gas bubble disease. Dawley et al. (1975) reported similar vertical movement behavior in juvenile steelhead in a deep (10 m) aquarium and observed no mortality within 7 d at total dissolved gas levels of 130%. Continuous exposure to gas supersaturated water, 45 h at 114% TDGS and 10 hr 125% TDGS had no effect on reproductive performance (i.e. fecundity, egg diameter, fertilization success, and embryo survival) of adult female Chinook salmon (Gale et al. 2001). Ebel et al. (1975) reported that 25 d continuous exposure was needed to cause substantial mortality in both juvenile and adult salmon at a saturation level of 115%

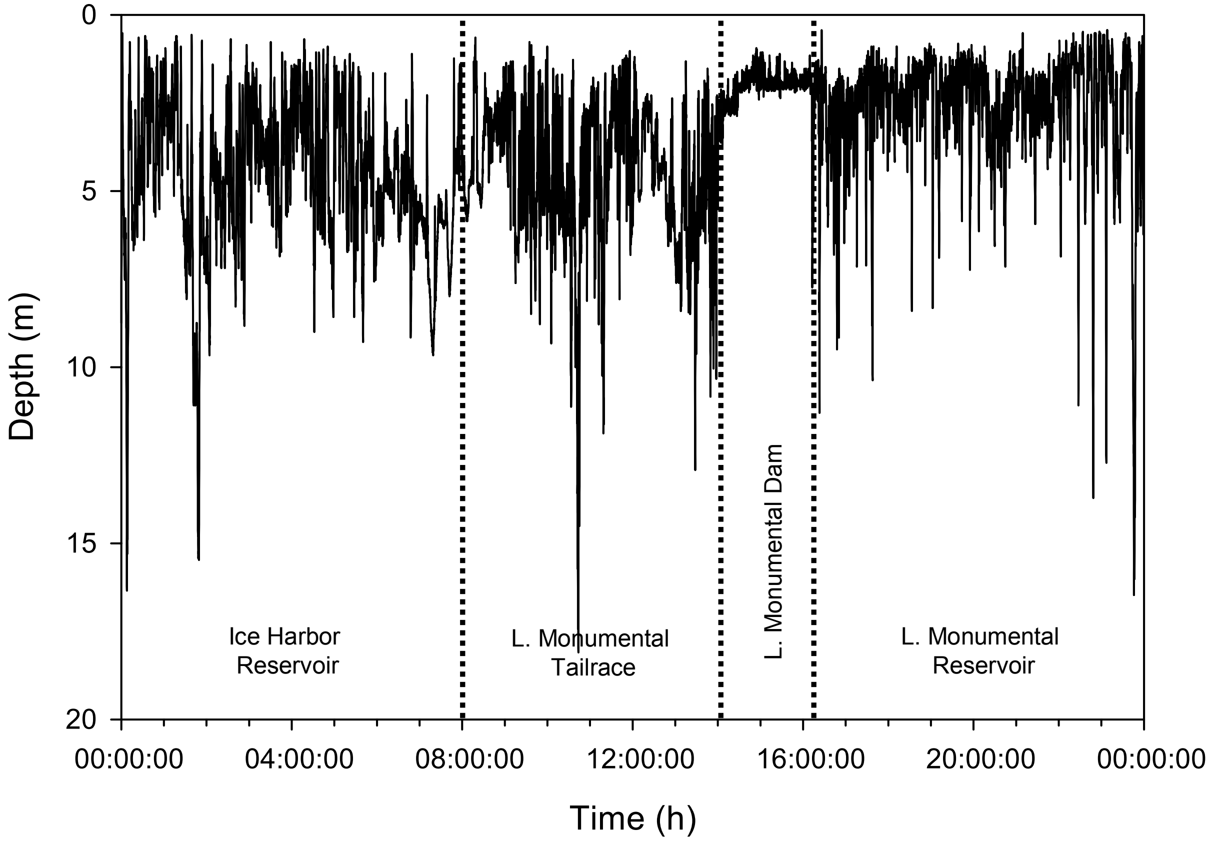

Figure 20. Swimming depth at 5 sec intervals for adult Chinook salmon (RDST #2480B on 3 June 2000.

TDGS. Nebeker (1973) indicated that the lethal time that results in death of one-half of the exposed population (LT50) for adult Chinook salmon at 125% TDGS was approximately 17 h. Hence, even the longest continuous time recorded by an adult spring–summer Chinook salmon at depths < 1 and 2 m (1.3 and 19.5 h, respectively) would probably be insufficient to affect reproductive success or cause severe GBD symptoms or mortality based on gas levels observed during 2000.

We found no strong relationships or trends between dissolved gas concentrations and the proportion of time fish spent near the surface. Stronger vertical avoidance responses to dissolved gas saturation may occur only at saturation levels higher than those occurring in the Columbia and Snake rivers in 2000 (Gray et al. 1983; Gray and Haynes 1977; Stevens et al. 1980). Logistic constraints on our experimental design and relatively low spill conditions could have contributed to the lack of relationship observed between migration depth and dissolved gas concentrations, and additional research over a broader range of dissolved gas conditions is needed to quantify the effects of short but frequent durations of exposure to high dissolved gas conditions on survival and reproductive potential.

Management Implications

Given the tendency for adult spring–summer Chinook salmon to migrate near shorelines during upstream migration, operational changes at dams that could direct the dissolved gas plume mid-river would reduce the risk of adult migrants encountering water with higher dissolved gas conditions. The frequent vertical movement into and out of the surface layer by adult spring–summer Chinook salmon suggests a need for additional research to identify effects of frequent but short durations of dissolved gas exposure on long-term survival and reproductive potential.

Summary

- During the spring and summer of 2000, adult Chinook salmon (*Oncorynchus tshawytscha*) were tagged with archival radio data storage transmitters (RDSTs) at Bonneville Dam. Fish with RDSTs were used to determine in situ swimming depth in supersaturated water at they progressed through tailraces and reservoirs from Bonneville Dam to Lower Granite Dam.

- Migration paths of individual fish were monitored in the Bonneville Dam and Ice Harbor Dam tailraces. Migration depths at specific locations were compared with dissolved gas concentrations generated from a model (MASS2) to estimate exposure to supersaturated water.

- Dissolved gas levels were moderate and adult spring–summer Chinook salmon exposure to supersaturated water was minimal in 2000. Exposure that did occur based on estimated levels of dissolved gas was generally less than levels known to cause signs of GBD and mortality for adult salmonids.

- Evaluation of adult spring-summer Chinook migration depth indicates that a majority of the time was spent at depths that provided adequate hydrostatic compensation for supersaturated conditions recorded during 2000.

- We did not observe strong associations between migration routes or migration depth and the dissolved gas concentration of the water.

- Fish entered surface waters (< 2 m) frequently, but the time spent there was usually brief. Additional research is needed to quantify the effects of such exposure regimes on reproductive success and survival.

- We observed that adult spring–summer Chinook salmon tend to migrate near shorelines. Dam operations to direct dissolved gas plumes mid-river may decrease the potential for fish to encounter supersaturated water.

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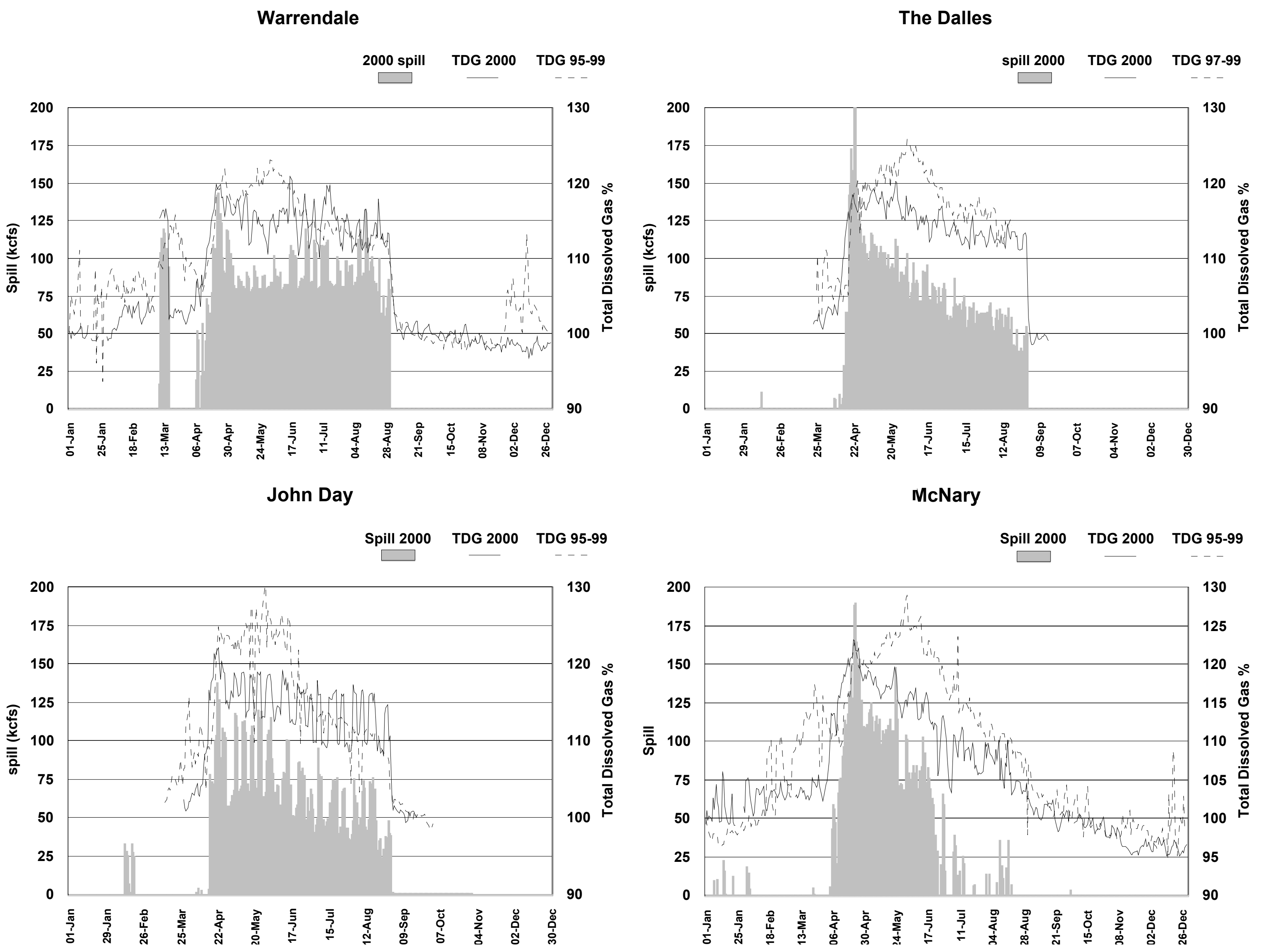
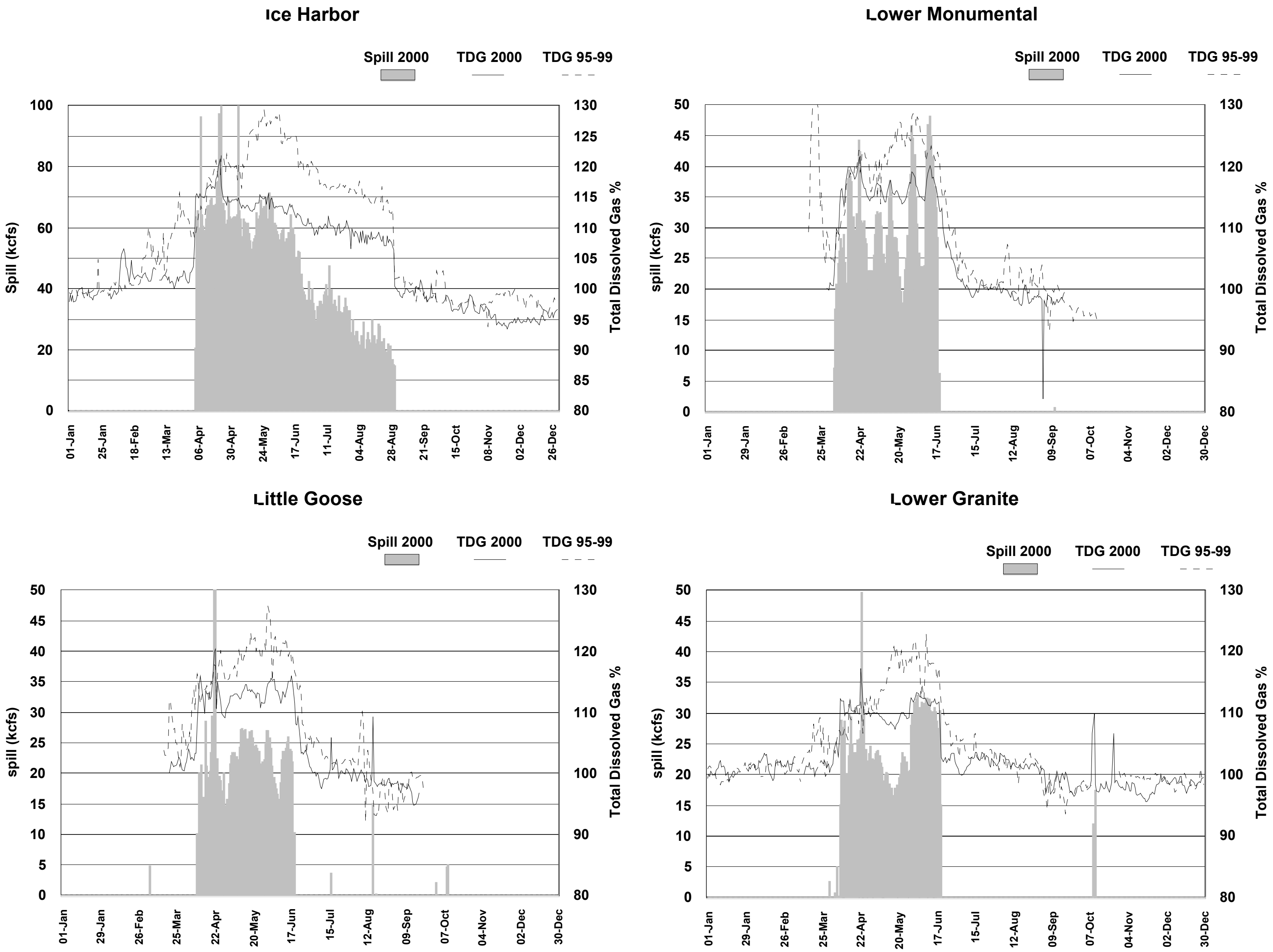
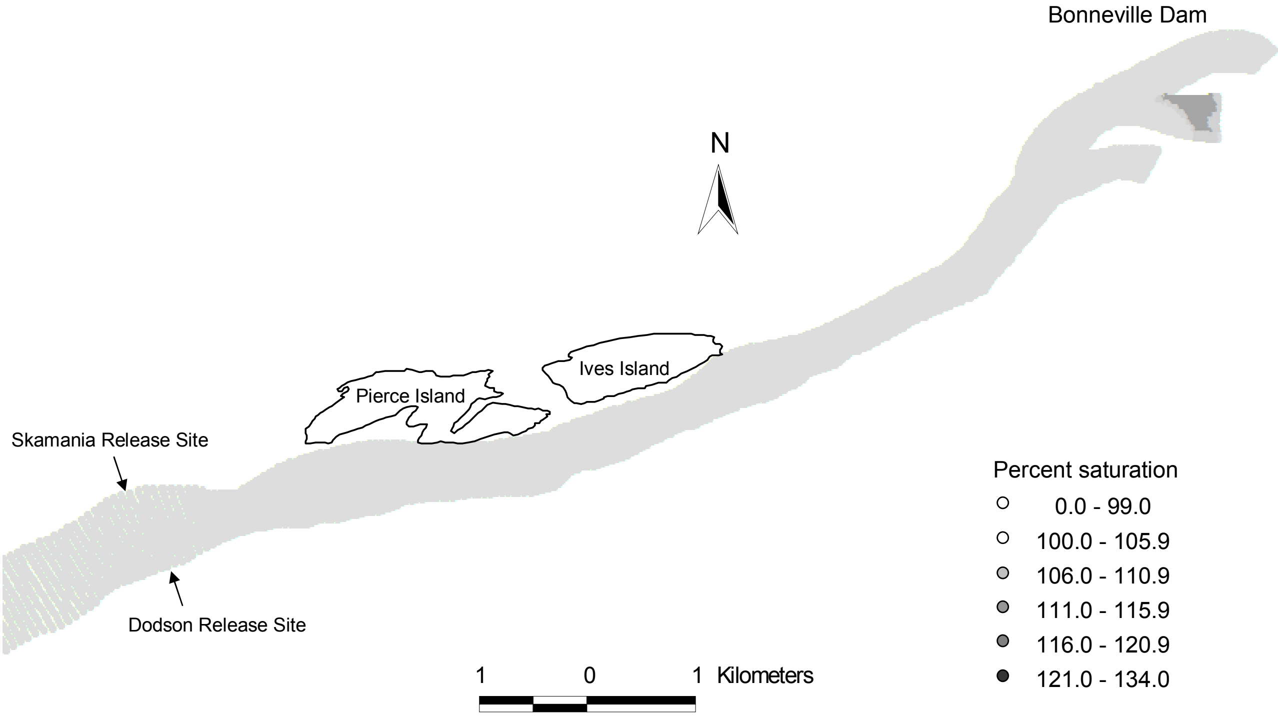


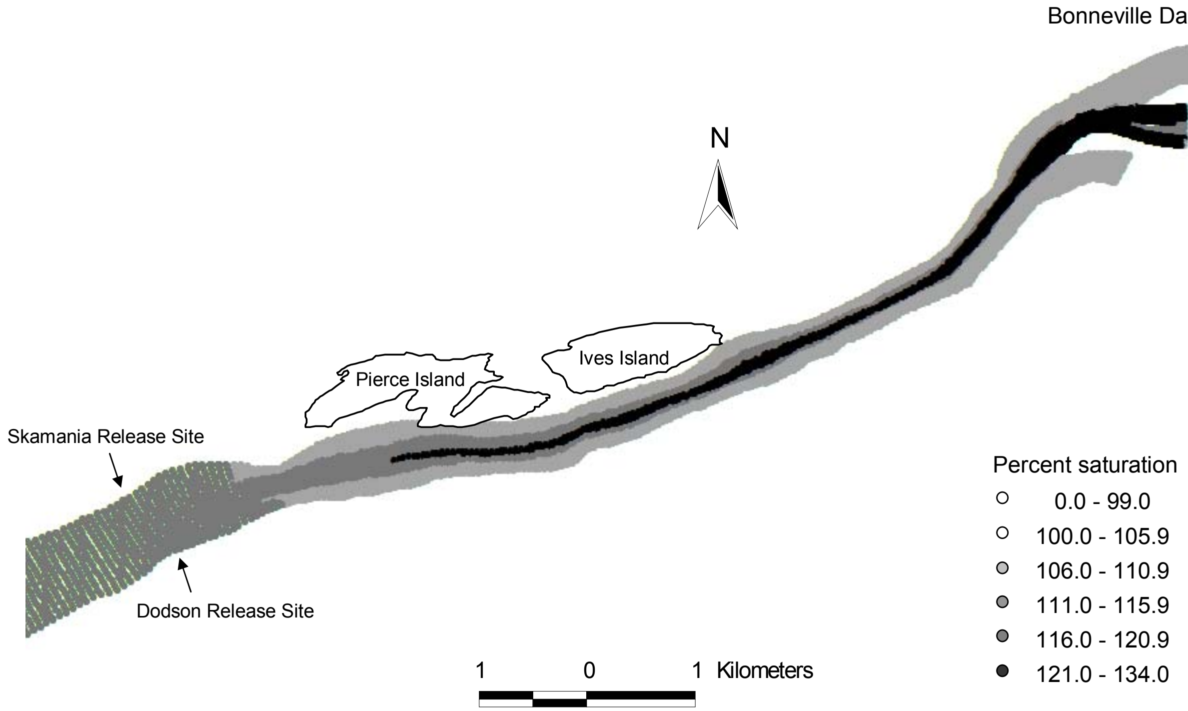
Appendix Figure 1. Daily total dissolved gas saturation and spill volume recorded in the tailrace during 2000 relative to the 5-year average.



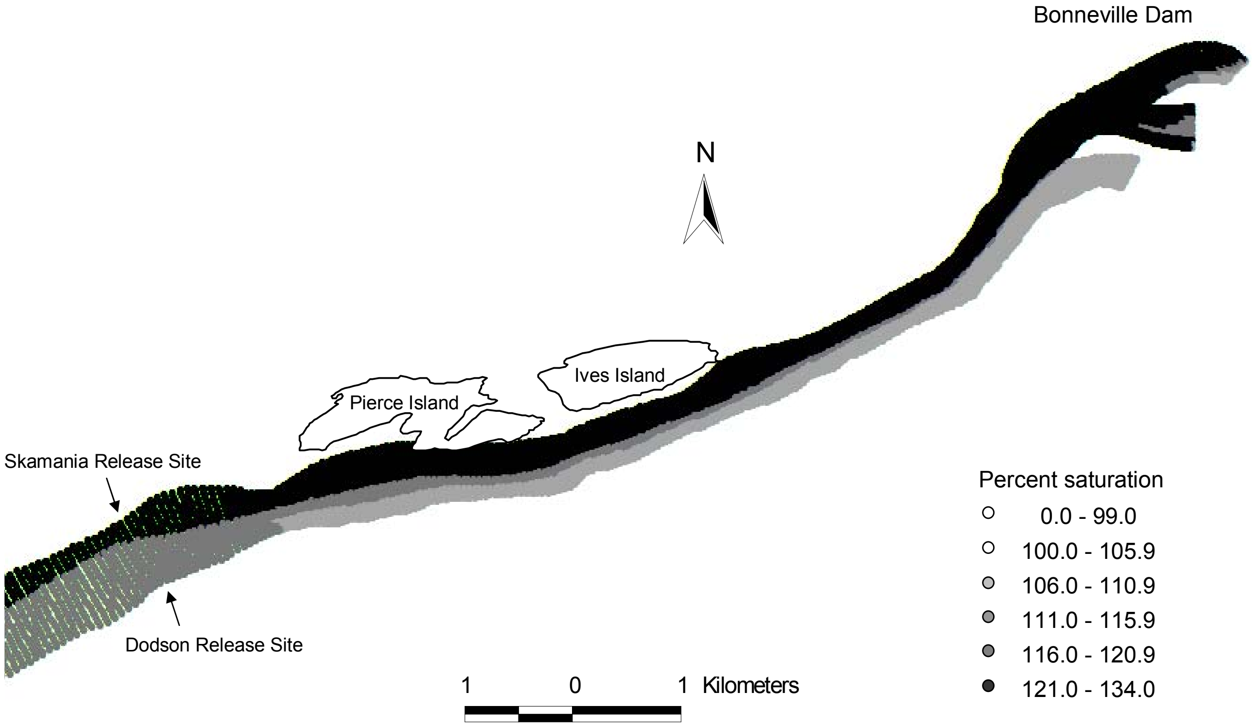
Appendix Figure 1. Continued.



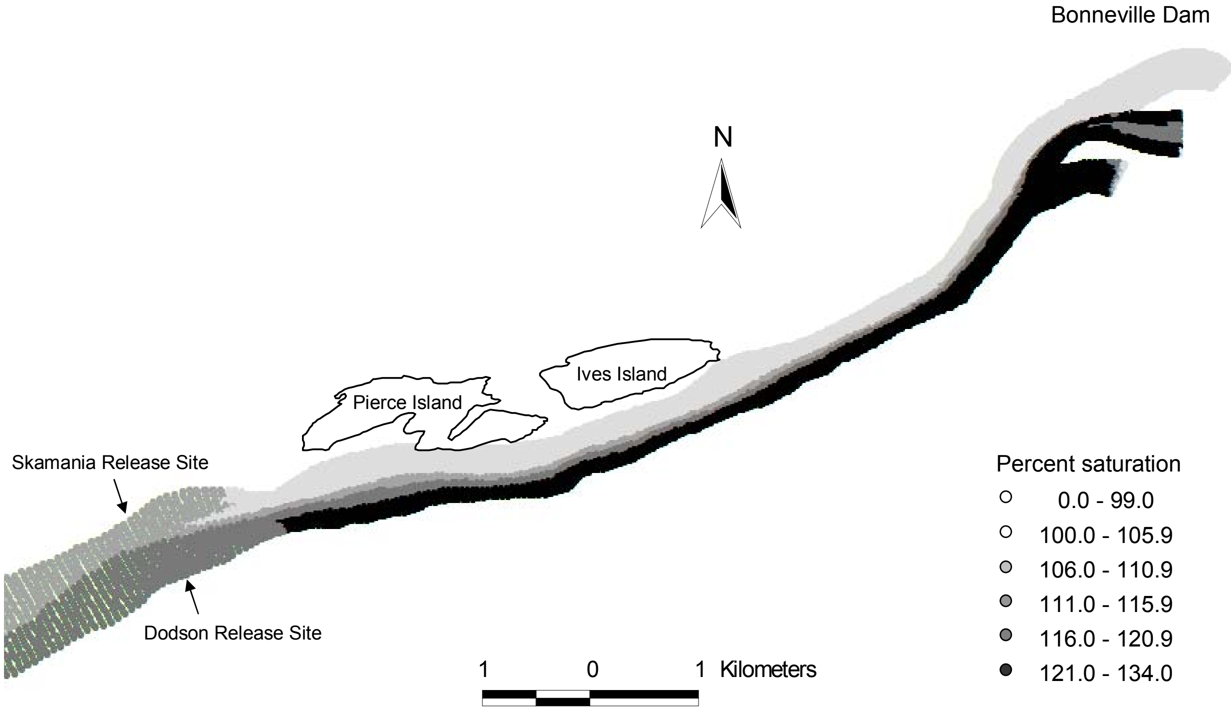
Appendix Figure 2. MASS2 simulated dissolved gas saturation downstream of Bonneville Dam on 12 April 00 during no spill conditions, powerhouse 1 discharge (100,000 cfs) and powerhouse 2 discharge (129,854 cfs).



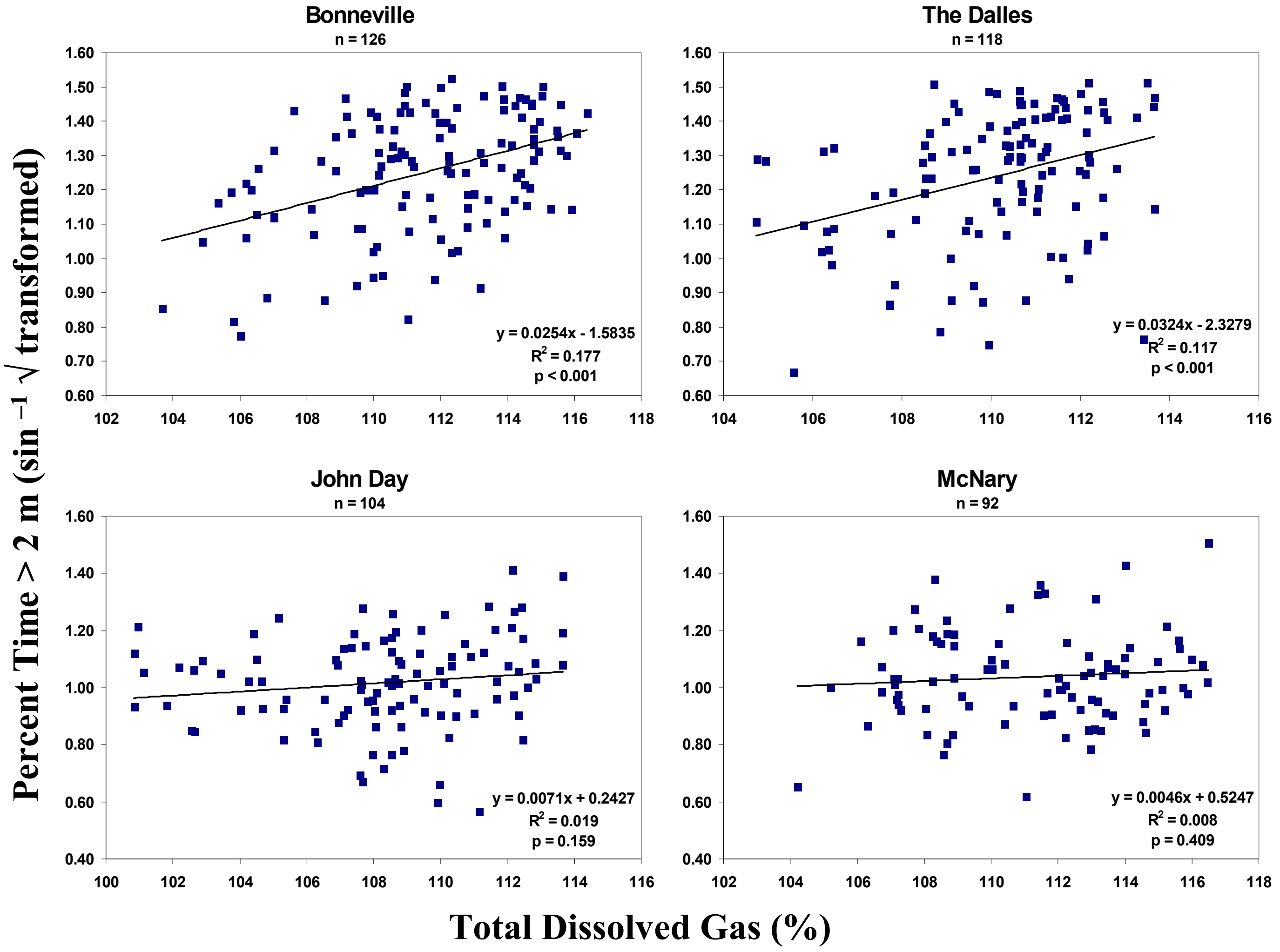
Appendix Figure 2 (continued). MASS2 simulated dissolved gas saturation downstream of Bonneville Dam on 29 April 00 during spill (119,000 cfs), discharge from powerhouse 1 (100,000 cfs) and discharge from powerhouse 2 (88,887 cfs).



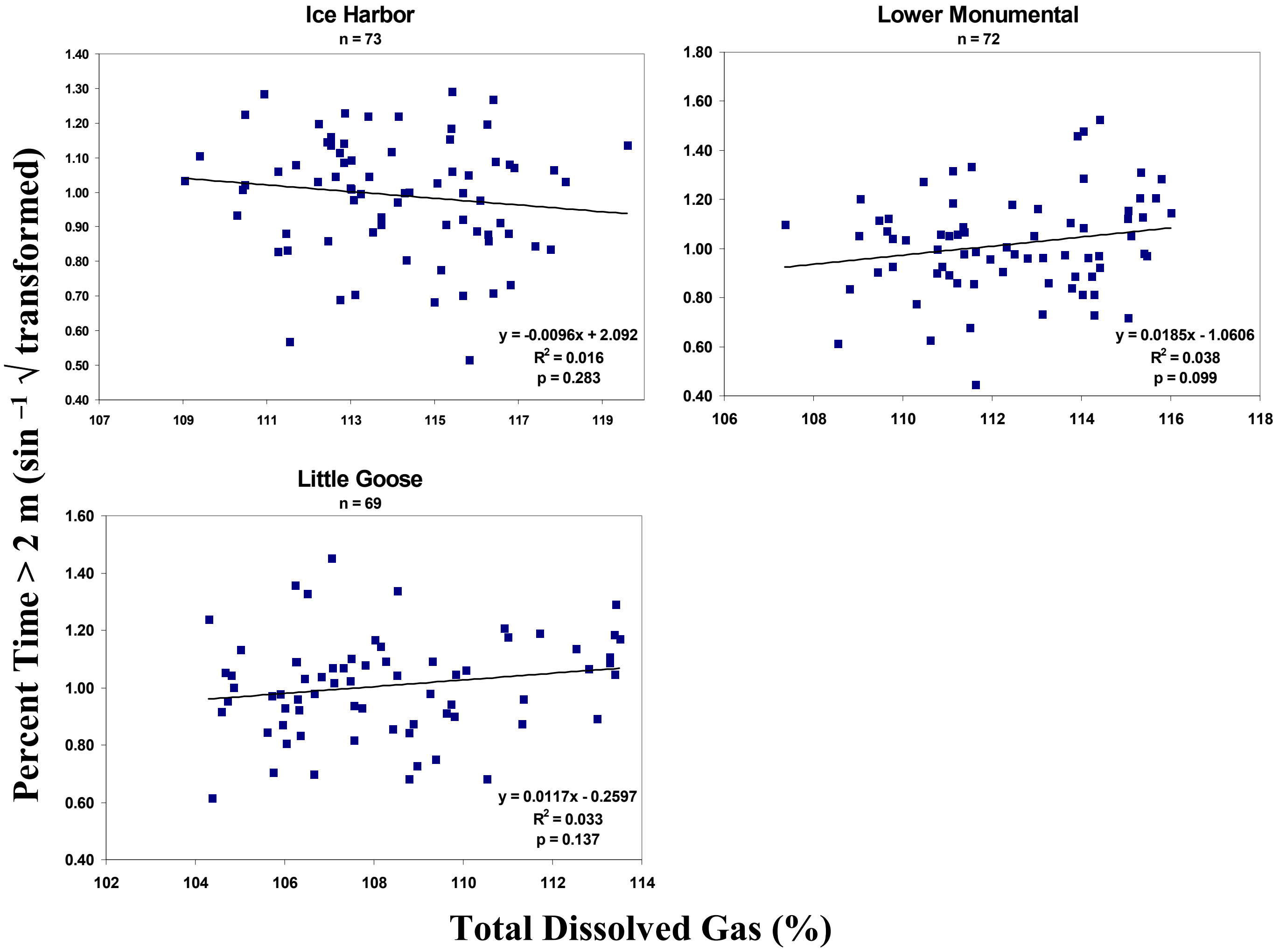
Appendix Figure 2 (continued). MASS2 simulated dissolved gas saturation downstream of Bonneville Dam on 4 June 00 during spill (102,000 cfs), discharge from powerhouse 1 (97,350 cfs) and discharge from powerhouse 2 (6,758 cfs).



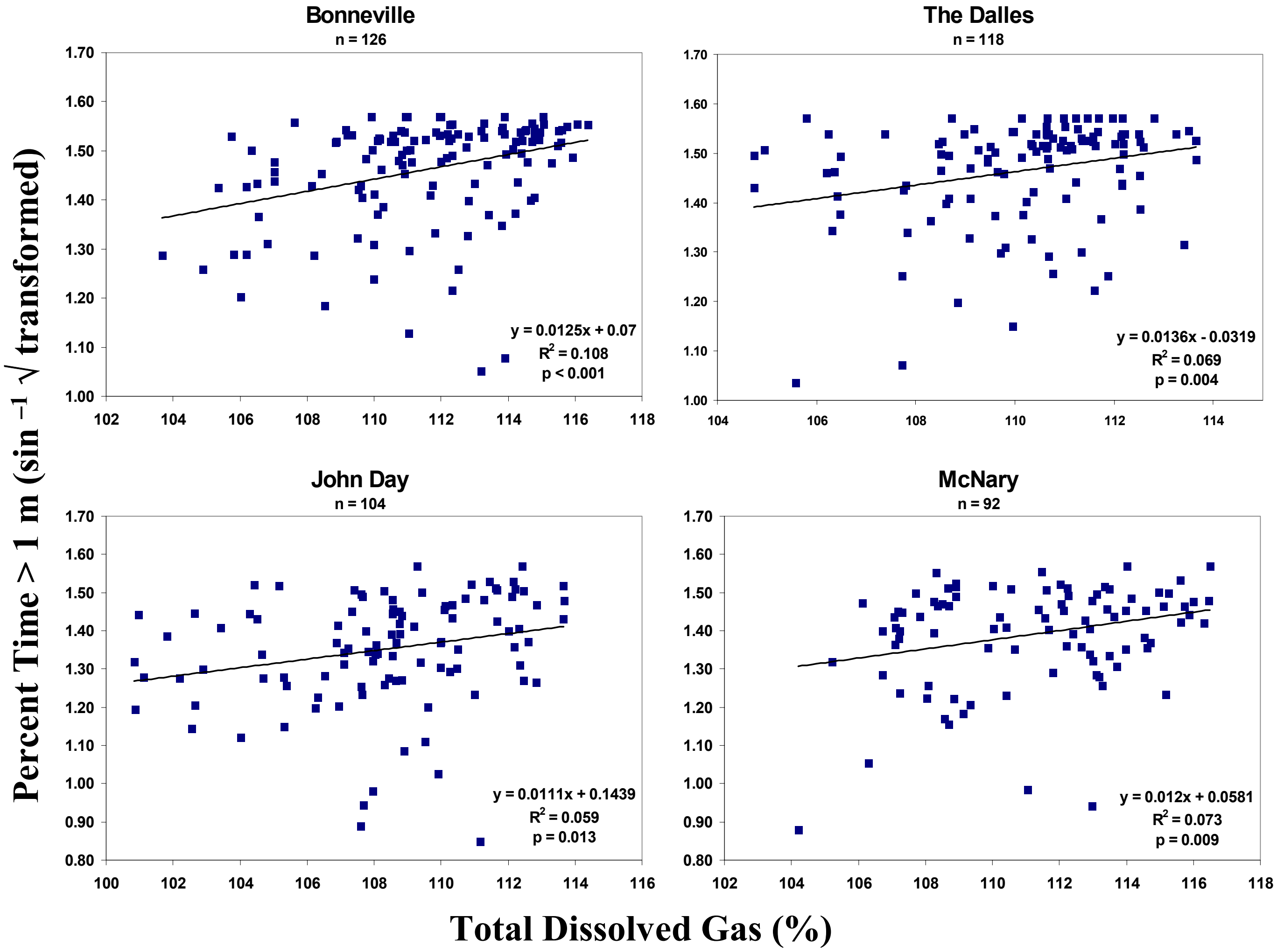
Appendix Figure 2 (continued). MASS2 simulated dissolved gas saturation downstream of Bonneville Dam on 24 July 00 during spill (91,900 cfs) and discharge from powerhouse 2 (81,941 cfs).



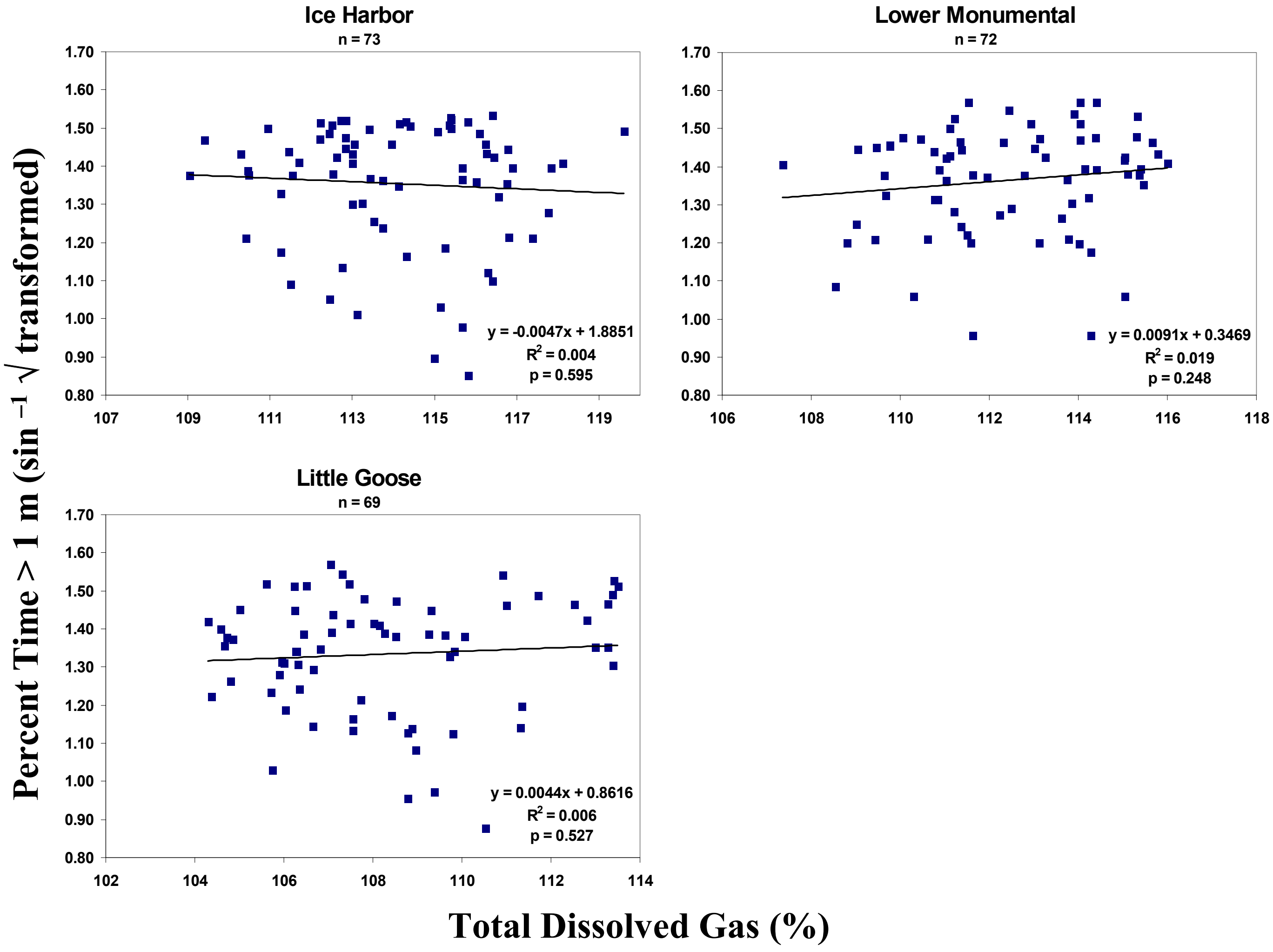
Appendix Figure 3. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, and Little Goose reservoirs and the percentage of time adult spring-summer Chinook salmon spent deeper than 2 m ($\sin^{-1} \sqrt{}$ transformed) in 2000.



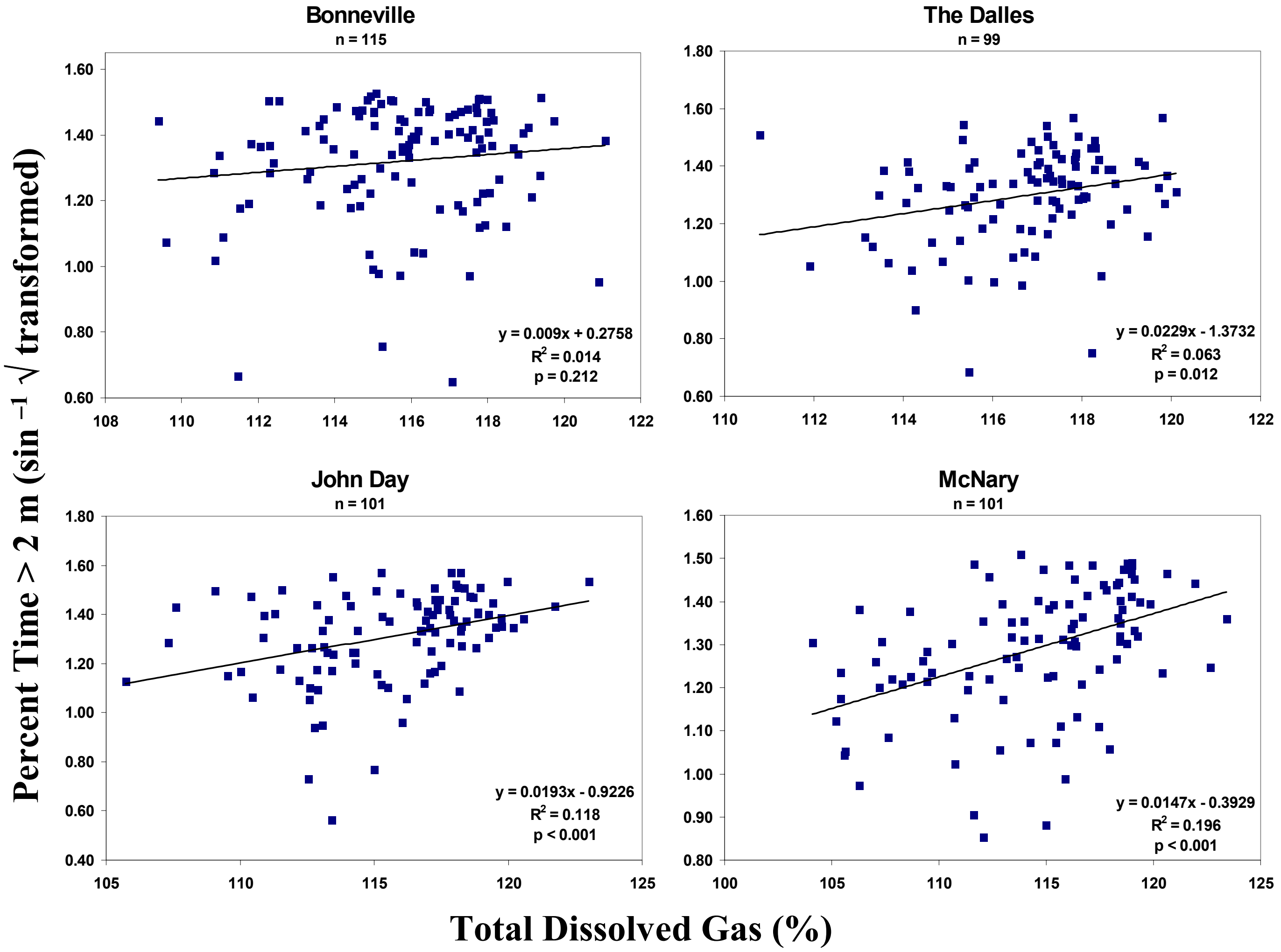
Appendix Figure 3. Continued.



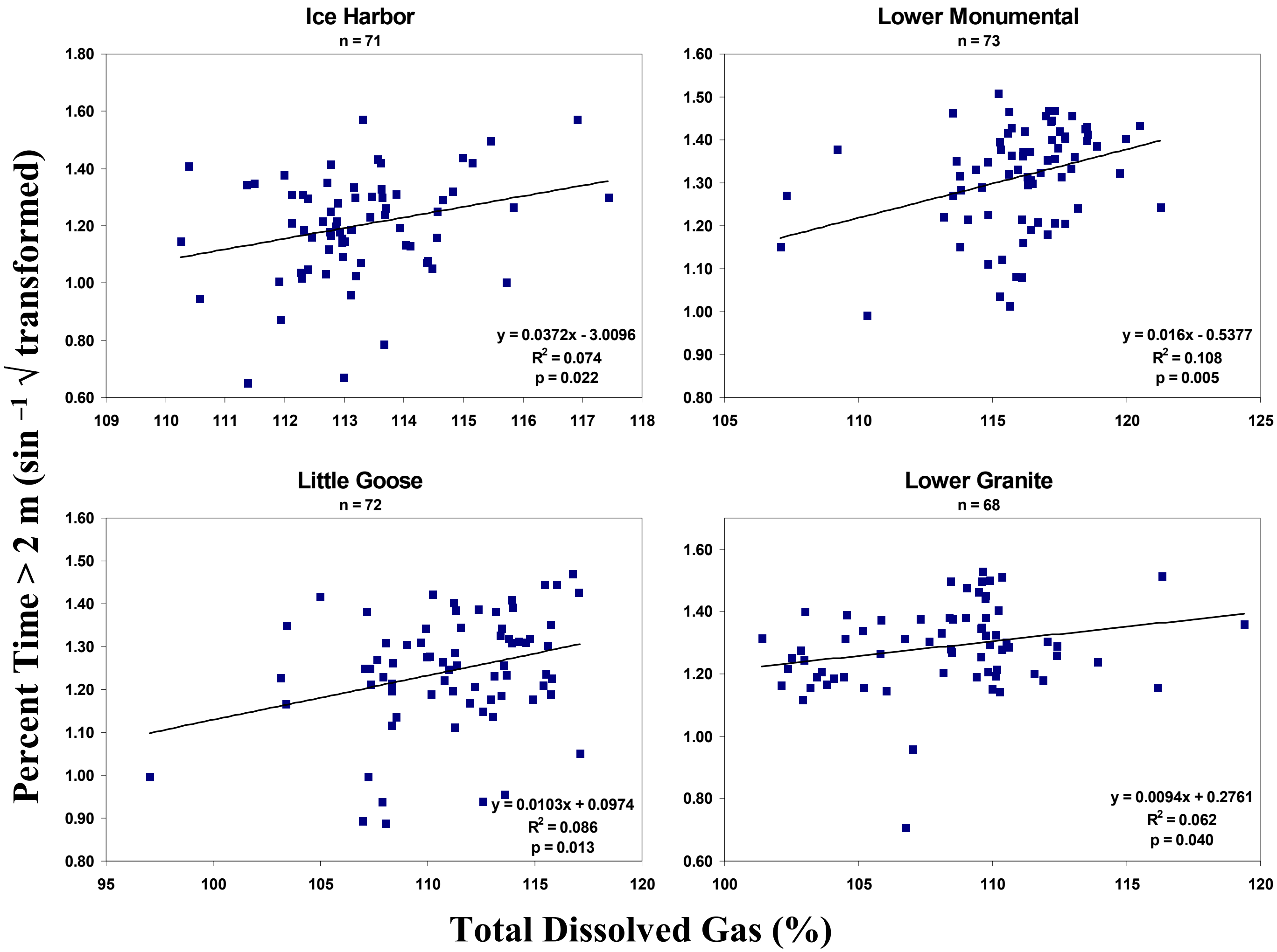
Appendix Figure 4. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, and Little Goose reservoirs and the percentage of time adult spring-summer Chinook salmon spent deeper than 1 m ($\sin^{-1} \sqrt{}$ transformed) in 2000.



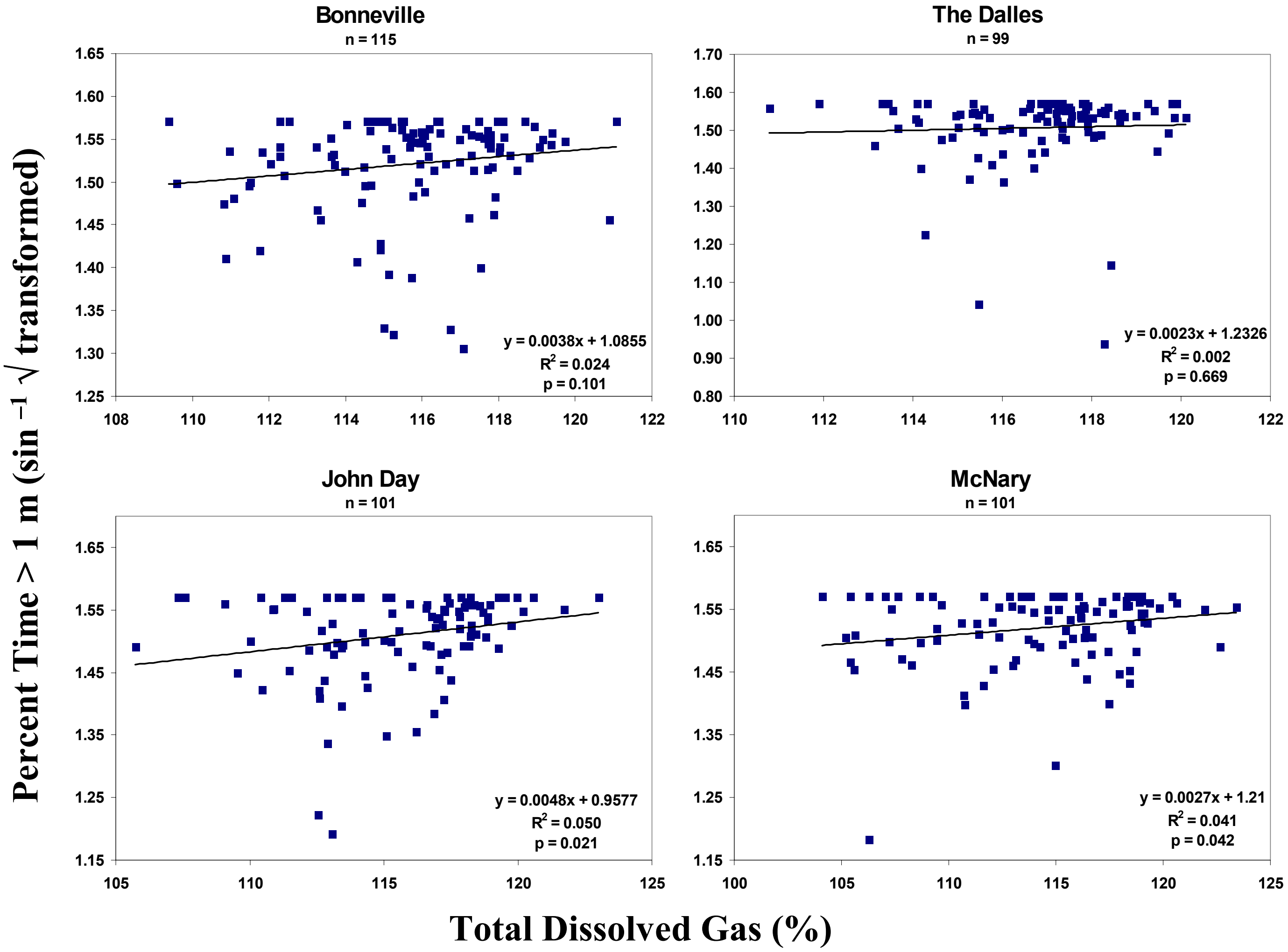
Appendix Figure 4. Continued.



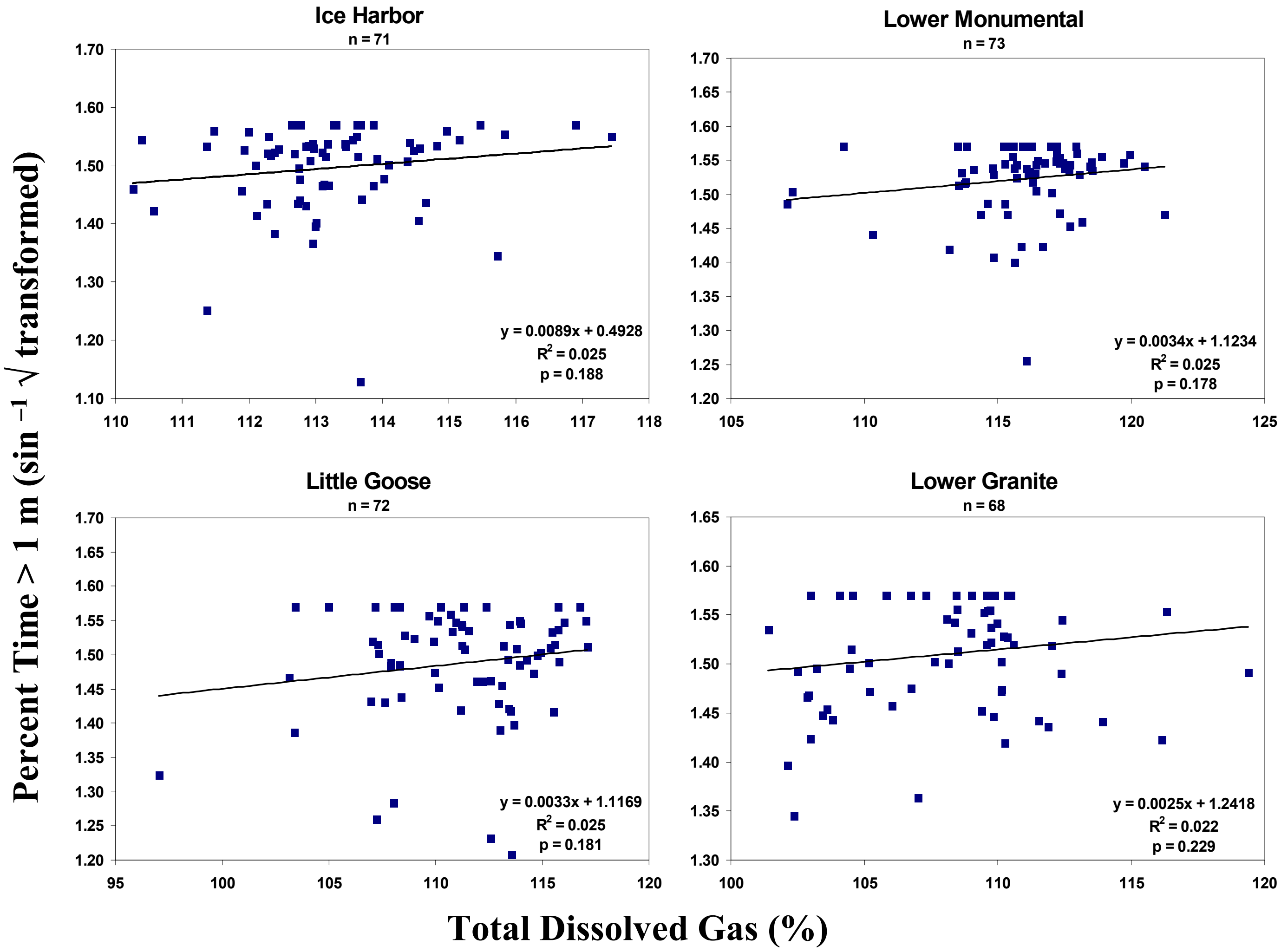
Appendix Figure 5. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose and Lower Granite tailraces and the percentage of time adult spring-summer Chinook salmon spent deeper than 2 m ($\sin^{-1}\sqrt{}$ transformed) in 2000.



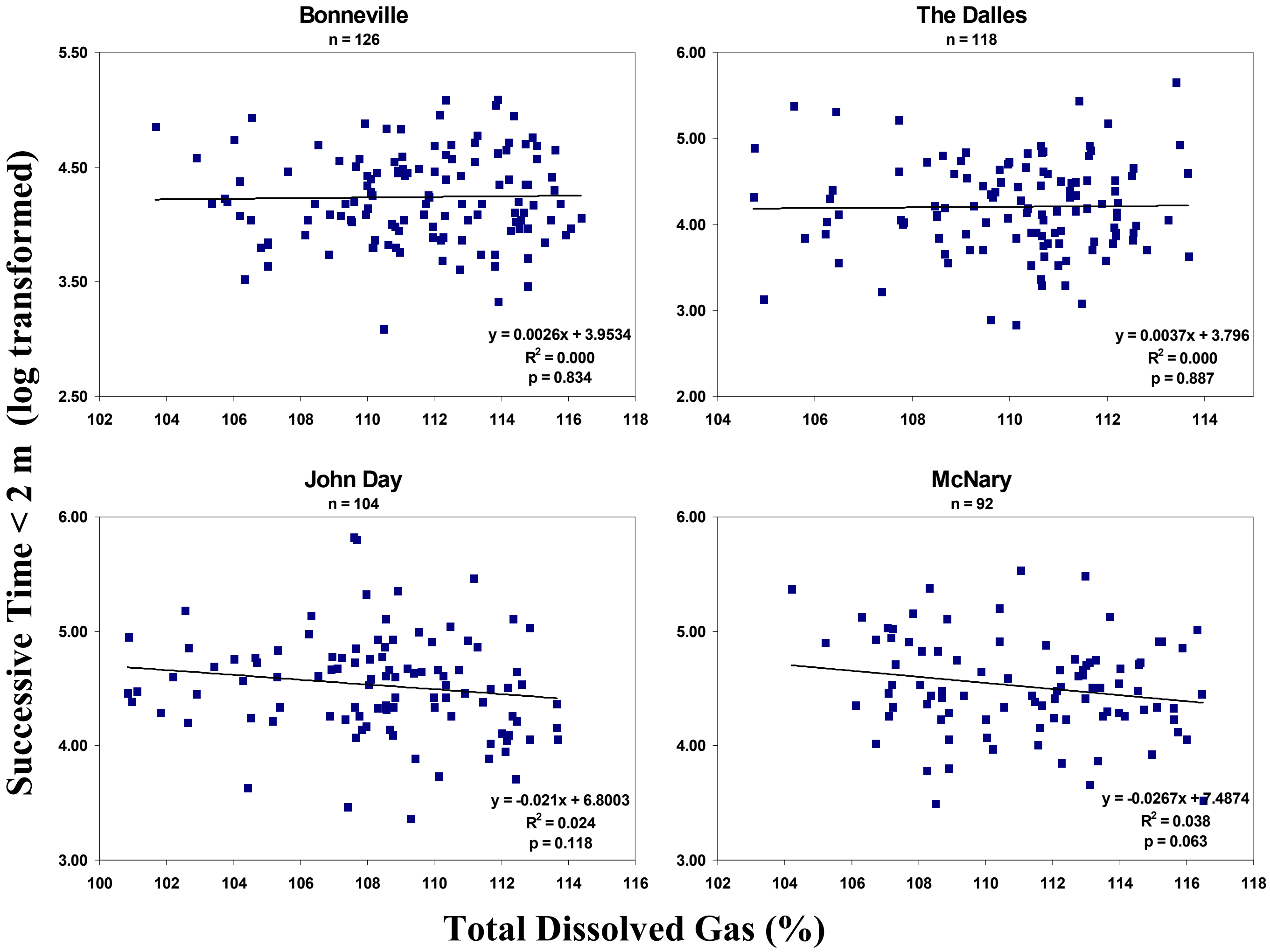
Appendix Figure 5. Continued.



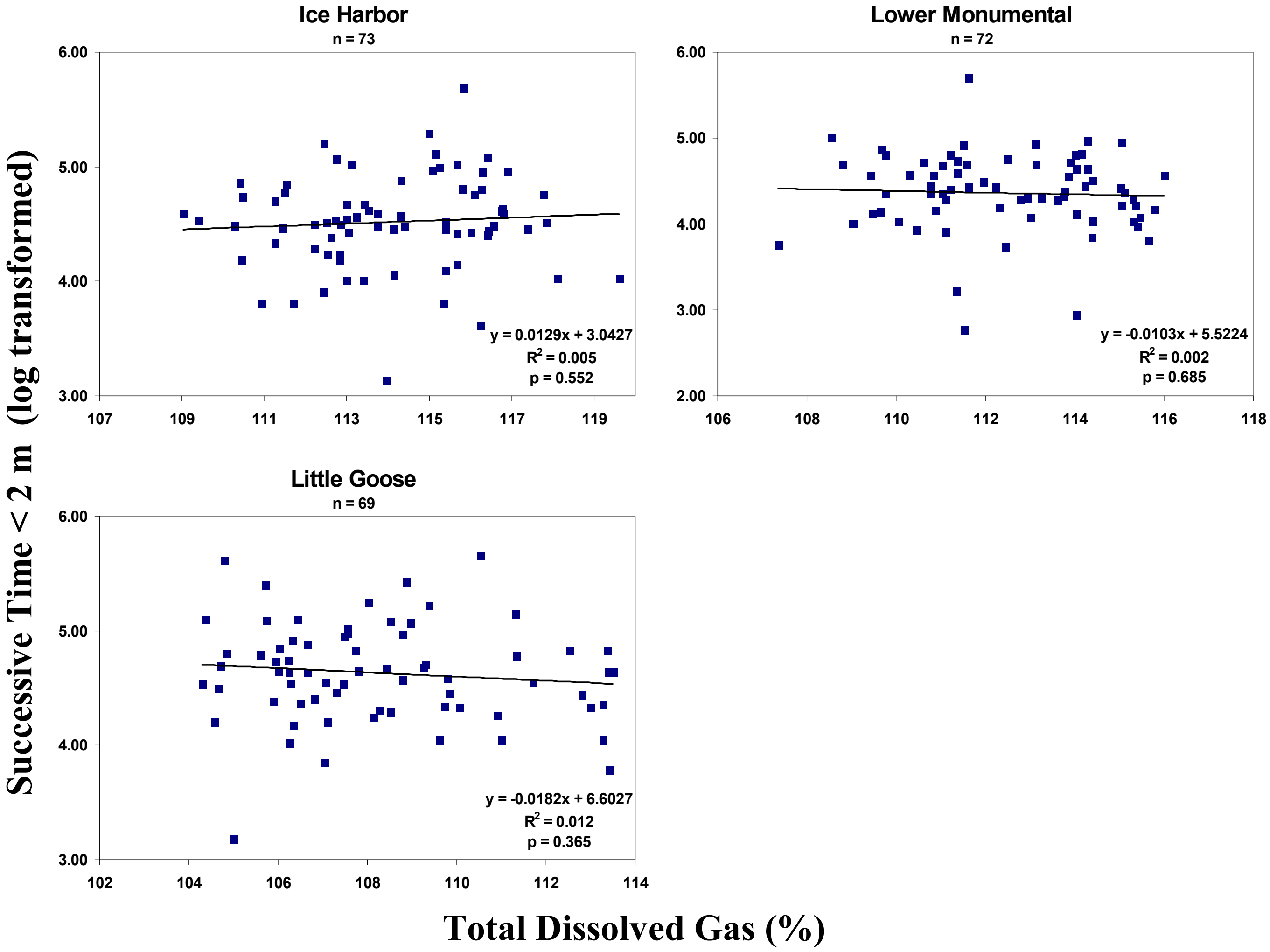
Appendix Figure 6. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose and Lower Granite tailraces and the percentage of time adult spring-summer Chinook salmon spent deeper than 1 m ($\sin^{-1} \sqrt{}$ transformed) in 2000.



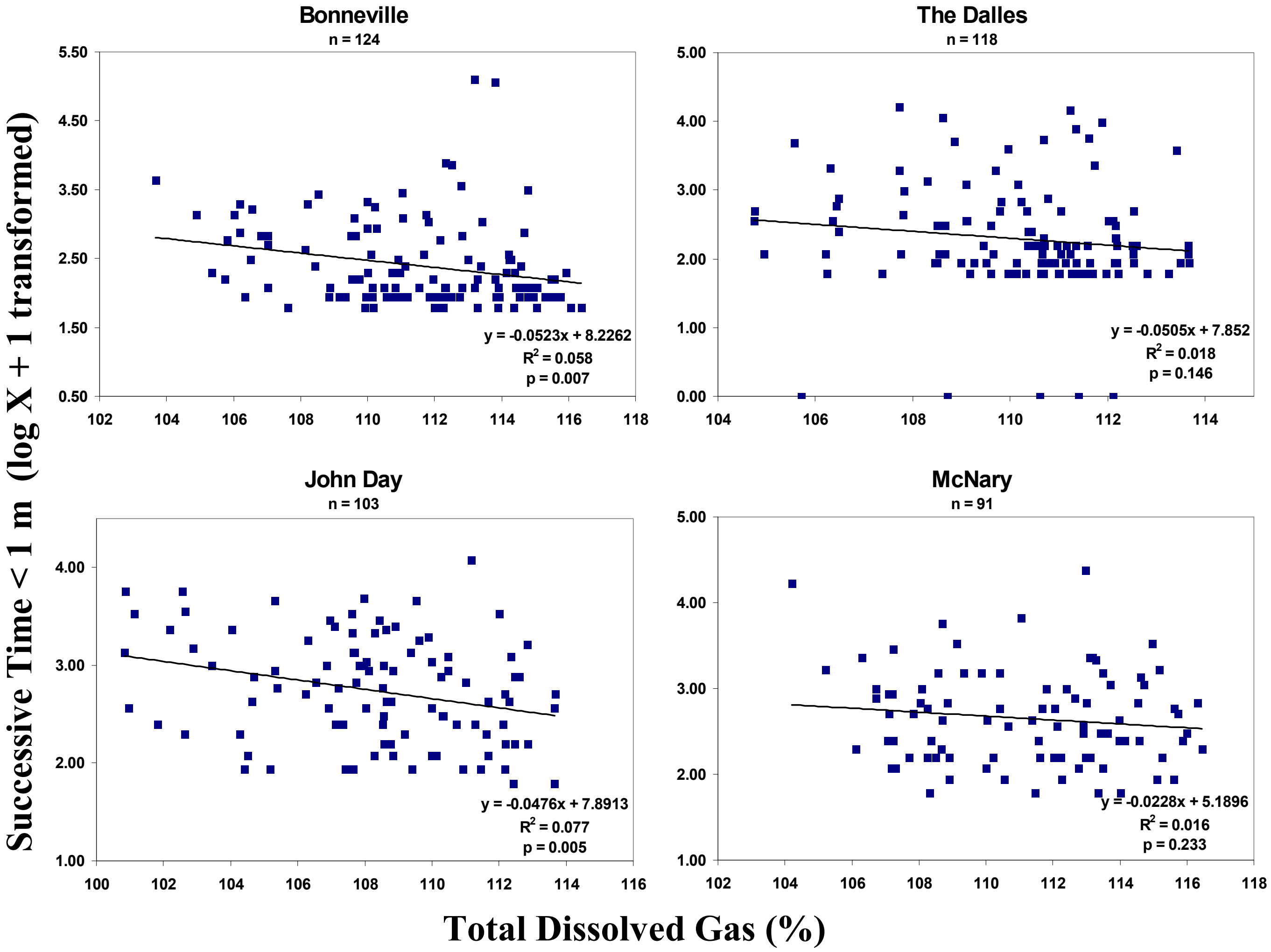
Appendix Figure 6. Continued



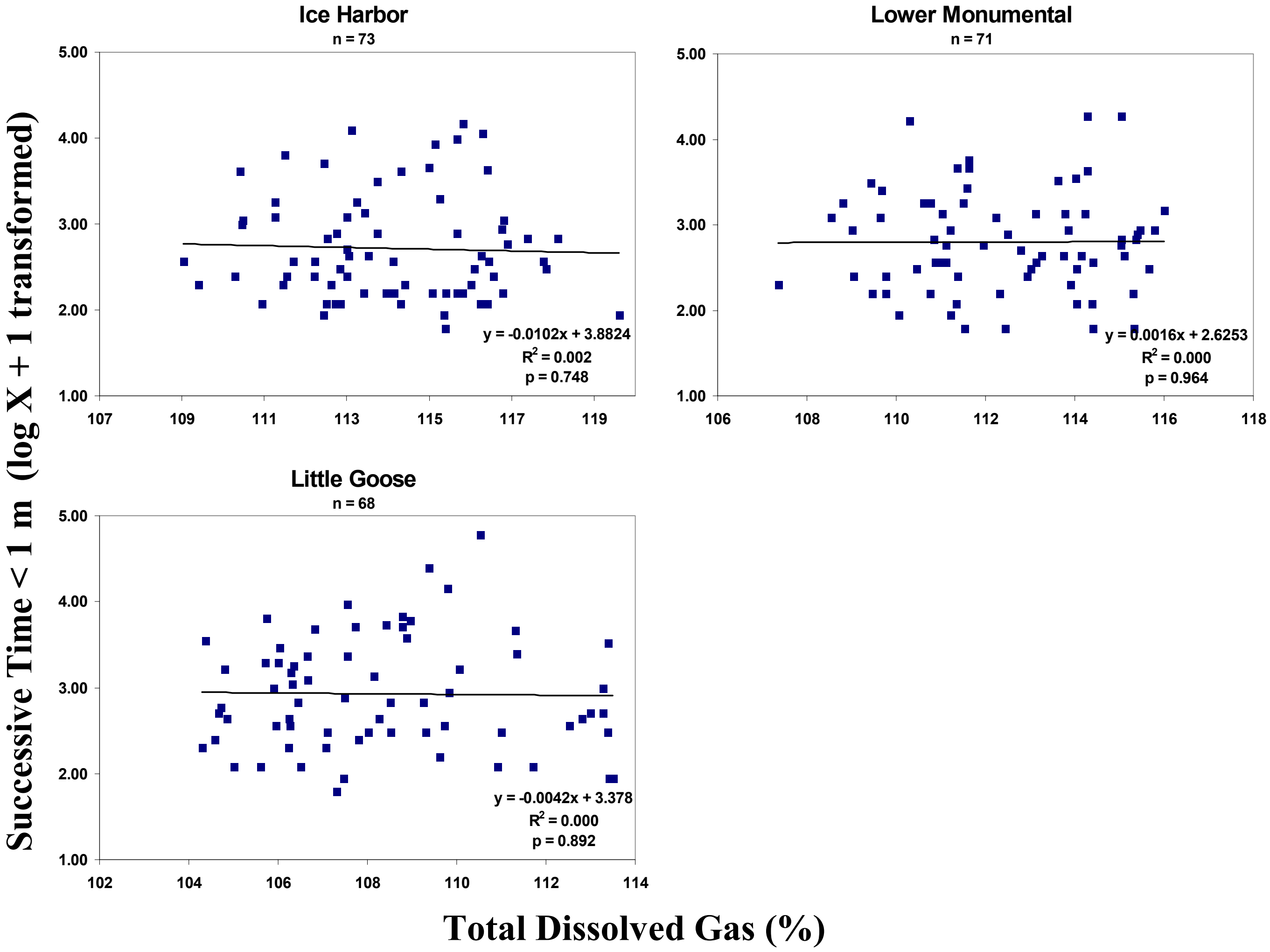
Appendix Figure 7. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, and Little Goose reservoirs and the average consecutive time adult spring-summer Chinook salmon spent shallower than 2 m ($\log_e$ X transformed) during 2000.



Appendix Figure 7. Continued.



Appendix Figure 8. Relationship between the total dissolved gas concentration of the water in the Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, and Little Goose reservoirs and the average consecutive time adult spring-summer Chinook salmon spent shallower than 1 m ($\log_e$ X+1 transformed) in 2000.



Appendix Figure 8. Continued.

Appendix Table 1. Distance between the tailrace antenna and dam.

Dam	Distance (rkm)
Bonneville	2.8
The Dalles	3.2
John Day	1.9
McNary	2.5
Ice Harbor	0.6
Lower Monumental	1.0
Little Goose	0.5
Lower Granite	0.8

Appendix Table 2. Recapture location for adult spring-summer Chinook salmon tagged with RDSTs in 2000.

Recapture Location	Number	RKM	Recapture Location	Number	RKM
Lower Granite Dam Adult Trap	73	694.6	Methow River	1	843.0
Mainstem Columbia River	15		Wenatchee River	1	753.7
Warm Springs National Fish Hatchery	8	477.7	Similkameen River	1	977.6
Wells Hatchery	7	829.6	Imnaha River	1	909.8
Okanogan River	3	858.4	Little White Salmon National Fish Hatchery	1	262.5
Pelton Reregulating Dam (Deschutes River)	3	493.6	North Fork Clearwater River	1	810.9
Mainstem Deschutes River	3	328.4	Powell Weir (Lochsa River)	1	1015.5
Entiat National Fish Hatchery	2	789.5	Rapid River Trap	1	980.7
Klickitat River	2	290.3	South Fork of Salmon Weir	1	1156.4
Leavenworth National Fish Hatchery	2	797.4	Sherars Falls (Deschutes River)	1	396.3
Icicle River	2	794.8	Downstream of Bonneville Dam (Skamania)	1	225.7
Wells Dam (Upper Columbia River)	2	829.6	Tucannon River	1	621.7
Dryden Dam (Wenatchee River)	1	782.1	Unknown	2	