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[Article]

Influence of the Hyporheic Zone on Supersaturated Gas Exposure to Incubating Chum Salmon

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Abstract.—Hydroelectric dam operation causes total dissolved gas (TDG) to be seasonally elevated in the lower Columbia River, as surface water concentrations approach 120%. Federally protected chum salmon *Oncorhynchus keta* embryos incubating in nearby spawning areas could be affected if depth-compensated TDG concentrations within the hyporheic zone exceed 103%. The objective of this study was to determine whether TDG of the hyporheic zone in two chum salmon spawning areas—one in a side channel near Ives Island, Washington, and another on the main-stem Columbia River near Multnomah Falls, Oregon—was affected by the elevated TDG of the surface water. Depth-compensated hyporheic TDG did not exceed 103% at the Multnomah Falls site. However, in the Ives Island area, chum salmon redds were exposed to TDG greater than 103% for more than 300 h. In response to river depth fluctuations, TDG varied significantly in the Ives Island area, suggesting increased interaction between the hyporheic zone and surface water at that site. We conclude from this study that the interaction between surface water and the hyporheic zone affects the concentration of TDG within the hyporheic zone directly via physical mixing and indirectly by altering water chemistry and thus dissolved gas solubility. Consideration of these interactions is important when estimating TDG exposure within egg pocket environments and will enable resource managers to optimize recovery strategies.

Water exchange within the hyporheic zone has an important impact on the structure and function of aquatic ecosystems (Stanford and Ward 1993; Arntzen et al. 2006; Malcolm et al. 2008). This exchange is controlled by changes in channel morphology across a range of spatial scales, surface water fluctuations, and variations in the underlying geology (Brunke and Gonser 1997; Geist and Dauble 1998; Malcolm et al. 2003; Hanrahan et al. 2005; Arntzen et al. 2006; Wondzell 2006; Tonina and Buffington 2007). Consequently, hydraulic gradients and the extent of hyporheic exchange can vary over small spatial scales (Geist and Dauble 1998; Arntzen et al. 2006; Wondzell 2006; Malcolm et al. 2008). The nature of this exchange can impact fish during early life stages when they incubate within the hyporheic zone. For example, incubating salmonids depend on adequate hyporheic water exchange for a sufficient supply of dissolved oxygen (DO; Chapman 1988; Bjornn and Reiser 1991). If the hyporheic exchange is insufficient or if the exchange occurs with oxygen-depleted groundwater, survival to emergence can be reduced (Sowden and Power 1985; Malcolm et al. 2003; Youngson et al. 2004; Hanrahan et al. 2005). Dissolved oxygen and other atmospheric gases can also become supersaturated, thereby causing mortality of incubating salmonids (Harvey and Cooper 1962; Rucker and Kangas 1974; Nebeker et al. 1978). Supersaturated total dissolved gas (TDG) is created in groundwater or surface water by (1) physical processes that cause changes in temperature or pressure or (2) biological processes, such as photosynthesis and microbial respiration (Fidler and Miller 1997). One of the most widespread anthropogenic sources of supersaturated TDG is the spill of water through dams, which traps air bubbles in water under sufficient pressure to force the air into solution and causes

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supersaturated gas within surface water downstream (Fidler and Miller 1997).

Gas supersaturation caused by spill from dams on the Columbia River was first acknowledged as an environmental concern in the mid-1960s (Ebel and Raymond 1976). Several studies monitored dissolved gas levels and investigated occurrence of gas bubble disease (GBD) in the Columbia River during 1966 through 1969, reporting dissolved gas saturation levels ranging from 120% to 143% and associated signs of GBD and mortality for both juvenile and adult salmonids *Oncorhynchus* spp. (Ebel 1969; Beiningen and Ebel 1970, 1971; Meekin and Allen 1974). The U.S. Environmental Protection Agency (USEPA) set a national water quality standard for TDG saturation at 110% in 1972, and this standard remains in effect (NAS and NAE 1973; USEPA 1987). Beginning in the early 1990s, water quality agencies issued limited waivers on water quality to facilitate spill for downstream migration of juvenile salmonids, permitting up to 120% TDG in dam tailraces where flows from spillways were separated from those of powerhouse discharge (NOAA 1995).

Considerable research has been conducted on the effects of gas supersaturation on aquatic life (including postemergent juvenile and adult salmonids) in the lower Columbia River (Toner and Dawley 1995; Ryan and Dawley 1998; Backman and Evans 2002; Backman et al. 2002). However, little research has been conducted on the effects of gas supersaturation on incubating and larval stages of salmonids. Exposure estimates of TDG from this environment are heretofore not available, representing an important data gap because water quality in the shallow subsurface beneath a streambed can vary widely from that of the overlying surface water (Geist et al. 2002, 2008; Malcolm et al. 2003; Arntzen et al. 2006; Fritz and Arntzen 2007). This difference in water quality often is related to groundwater–surface water interaction, which commonly results from upwelling subsurface water in locations selected by chum salmon *O. keta* for spawning (Tautz and Groot 1975; Hale et al. 1985; Leman 1993), including the Ives Island (Ives), Washington, area of the Columbia River (Geist et al. 2002, 2008).

Chum salmon that spawn and incubate downstream from Bonneville Dam near Ives and at an associated Columbia River site near Multnomah Falls (MF), Oregon, collectively represent one of two remaining populations of the lower Columbia River evolutionarily significant unit, which is listed as threatened under the Endangered Species Act (ESA) of 1973 (NMFS 2004). Recently, there has been concern about whether powerhouse and spill operations at Bonneville Dam have the potential to elevate dissolved gas levels within these spawning areas. Several specific spill operations occur at Bonneville Dam prior to mid-May, when chum salmon emergence is completed (FPC 2007). These include spill operations during March, which are used to assist with the release of juvenile fall Chinook salmon *O. tshawytscha* from the Spring Creek National Fish Hatchery (U.S. Fish and Wildlife Service). During mid-April through September, water is spilled at a rate of approximately 2,830 m^3/s to help pass Chinook salmon, coho salmon *O. kisutch*, sockeye salmon *O. nerka*, and steelhead *O. mykiss* at Bonneville Dam. Additionally, a surface flow bypass channel (termed the Bonneville Second Powerhouse Corner Collector) operates during March through early April to assist with steelhead kelt passage and during early April through September to assist with downstream smolt passage, in both cases spilling water at a rate of 142 m^3/s. The ratio of spilled water to total flow at Bonneville Dam varies widely. Generally, the volume spilled comprises less than 50% of the total river volume. During low flow conditions, as hydropower operators attempt to maintain sufficient spill rates to assist with juvenile passage, spilled water can comprise up to approximately 75% of the total river volume.

Typically, TDG is depth compensated to evaluate potential impacts on aquatic organisms. Depth compensation adjusts TDG measurements based on the hydrostatic pressure at the point of measurement such that for each meter of increased water depth, the effective TDG decreases by approximately 10% (Knittel et al. 1980). The guideline used by managers to protect pre-emergent chum salmon fry has been to limit TDG to 105% after allowing for depth compensation (NMFS 2004). However, GBD has been observed in hatchery sac fry at TDG levels as low as 103% (Wood 1979). When TDG is elevated and Columbia River discharge is insufficient to provide adequate depth compensation, concerns about the effects of TDG on pre-emergent chum salmon fry have forced operators to choose between providing spill to improve juvenile fish passage and limiting spill to protect incubating chum salmon. However, no field measurements of TDG have been collected previously from the egg pocket environment (chum salmon typically create an egg pocket with a ceiling approximately 20 cm below the surrounding riverbed; Peterson and Quinn 1996). This lack of data precludes informed spill management decisions at Bonneville Dam (McGrath et al. 2006).

The objectives of this study were to (1) determine the water quality of the hyporheic zone and river at two chum salmon spawning sites; (2) estimate how fluctuations of river stage affect TDG, DO, and temperature within the egg pocket environment; and (3) estimate exposure of TDG to embryos by extrapolating empirical measurements to redd locations based on redd elevations.

Methods

Hyporheic water quality at chum salmon spawning locations.—Two chum salmon spawning sites were selected for monitoring. One site was a side channel downstream from Bonneville Dam on the right bank, north of Ives at river kilometer (rkm) 230 (rkm 0 = mouth of the Columbia River), 4.3 km downstream from Bonneville Dam (Figure 1). The other site was on the left bank near MF at rkm 220, 14.8 km downstream from Bonneville Dam (Figure 1). The Ives site has been described in detail previously (Geist et al. 2002, 2008). At each site, several monitoring locations were established within recently used chum salmon spawning habitat (Figure 1).

At each monitoring location, we emplaced one river piezometer and one hyporheic piezometer (Figure 2). All piezometers consisted of 5.08-cm-diameter galvanized pipe with a built-in 30-cm-long screen to allow water to flow through. We used a gasoline-powered jackhammer to drive the piezometers into the riverbed with an internal drive rod (Geist et al. 1998). River piezometers were driven until the bottom of the screen was approximately 10 cm above the riverbed and the screen was exposed to the river. Hyporheic piezometers were driven until the top of the screen was approximately 10–20 cm below the riverbed and the screen was exposed at egg pocket depth. After piezometers

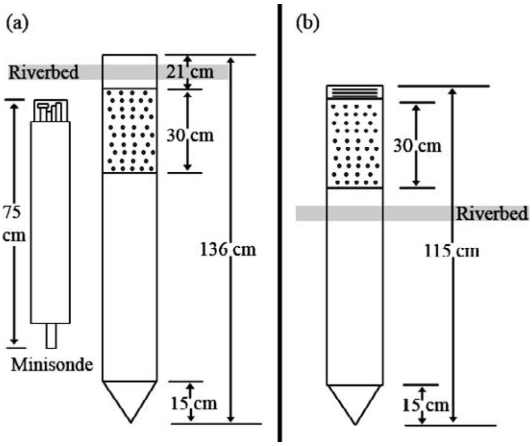

FIGURE 2.—Specifications of piezometers used at Ives Island and Multnomah Falls monitoring locations on the Columbia River: **(a)** screened to the riverbed and **(b)** screened to the river.

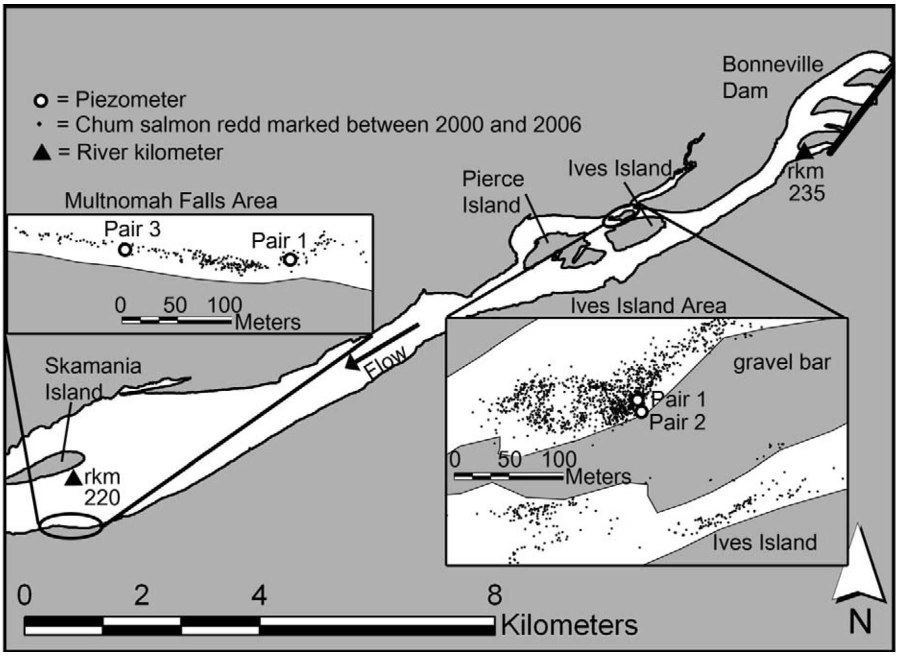

FIGURE 1.—Piezometer locations (white circles) on the Columbia River near Ives Island, Washington, and Multnomah Falls (MF), Oregon. Black circles represent chum salmon redd locations recorded from spawning years 2000–2006.

were installed, they were developed by removing fines with a hand pump.

The locations of the piezometers were recorded with a Trimble Pro XR Global Positioning System receiver (Trimble Navigation Limited, Sunnyvale, California). Sensors were accessed via snorkeling or scuba divers.

Hydrolab Minisonde 5 sensors (Hach Environmental, Loveland, Colorado) were used to monitor water quality. Parameters measured by the Hydrolab sensors (with stated accuracies in parentheses) were TDG (1.5 mm Hg), DO (0.2 mg/L), specific conductance (2 μS/cm), depth (5 cm), and temperature (0.1°C). Sensors generally were equipped with mechanical stirrers, which operated for 1 min prior to each hourly data collection and allowed us to remove air bubbles that could otherwise interfere with TDG readings. During a typical deployment, onboard sensor power lasted approximately 20 d. Sensors were recovered, downloaded, calibrated, and redeployed over intervals ranging from 14 to 23 d during February 28–May 15, 2007. Monitoring was conducted during this period because of overlap between chum salmon sac fry incubation, which is generally completed by mid-May (FPC 2007), and spill operations, which occurred during March–May in 2007.

The accuracy of TDG readings was ensured by collecting postdeployment data adjacent to a freshly calibrated unit. In addition, TDG sensors were evaluated at each recovery using a pressure calibrator certified to 10.34-Pa accuracy (Druck, Inc., Houston, Texas). Total dissolved gas pressure sensor accuracy was checked at 100, 200, and 300 mm Hg above ambient conditions. If the pressure reading was off by more than 1 mm Hg, the unit was recalibrated. To calibrate TDG pressure sensors relative to ambient barometric pressure, we obtained a barometric pressure reading from the Hanford Meteorological Station (located near Richland, Washington) within 1 d of performing pressure calibrations (HMS 2007). This value was used to calibrate a portable barometer (Garmin Vista, Olathe, Kansas) used to transfer barometric data with an accuracy of 0.3 mm Hg from Richland to our field site in the Columbia River gorge. After deployments, each TDG membrane was tested for functionality using soda water and elevated pressure as outlined by Tanner and Johnston (2001). Total dissolved gas readings were converted from ΔP (difference between dissolved gas pressure and atmospheric pressure) to percentage supersaturation of TDG using hourly barometric data obtained from the U.S. Army Corps of Engineers (USACE) Bonneville Dam monitoring station (USACE 2007). Data from a given deployment were omitted if postdeployment membrane tests failed. Prior to each deployment, other water quality sensors were calibrated according to the manufacturer's specifications (Hach Environmental).

Effect of fluctuating river stage on total dissolved gas, dissolved oxygen, and temperature.—All of our sampling locations experienced similar changes in river stage fluctuation during February 28–May 15, 2007. To evaluate whether hyporheic water quality responded differently to changes in river stage, we calculated the range, mean, and SD of hourly water quality data collected at each monitoring site. The total number of hours available for sampling during our study period was 1,832. The net number of hours sampled at each location ranged from 1,449 to 1,694. We looked for statistical differences between mean values from different monitoring locations using unpaired, two-sample t-tests with Bonferroni-adjusted probabilities. To determine whether to use a two-sample t-test assuming equal or unequal variances, F-tests were run prior to each t-test. To reduce temporal autocorrelation associated with 12- and 24-h diel and dam operation cycles, we conducted unpaired t-tests on a randomly selected subset of each overall data set. One data point per hour was randomly selected within every 12-h period to facilitate these tests. After randomization, our sample size was reduced by roughly 1/12 (n ranged from 120 to 142). However, at the Ives 2 hyporheic piezometer (Figure 1), fewer data were available (n = 797 hourly measurements, and n = 65 after randomization). The lack of data resulted from mechanical problems and from data that were deemed unreliable because of questions about membrane function. Based on both the box plots and the time series plots, the remaining TDG data at Ives 2 hyporheic did not show evidence of any trend with time and were therefore deemed representative and appropriate for use in statistical analyses even though they did not cover the full period sampled at the other locations.

Estimated exposure of chum salmon redds to total dissolved gas.—The exposure of chum salmon redds to potentially harmful TDG levels ultimately is controlled by the TDG concentration of water surrounding the egg pocket, the extent to which TDG can be depth compensated (which depends on the elevation of the redd and the water level of the river), and the length of time for which embryos are exposed to harmful levels of TDG. The spatial distribution of chum salmon redds and estimated emergence timing were provided by the Oregon Department of Fish and Wildlife (ODFW) for spawning year 2006 (ODFW, unpublished data). We assigned vertical elevations to chum salmon redds using bathymetry data collected previously (Tiffan et al. 2004). Redd locations were combined with vertical elevations using ArcMap (Environmental Systems Research Institute, Inc., Redlands, California). The elevation of water level recorders was surveyed using a Leica NA730 optical transit (Leica Geosystems AG, Heerbrugg, Switzerland) so that water level measurements could be related to chum salmon redd elevations. We used hourly water surface elevation to estimate the water depth at each redd during incubation year 2007.

To evaluate how differences in connectivity between the hyporheic zone and surface water affect estimates of chum salmon sac fry exposure to TDG, we estimated TDG exposure using data from the Ives 2 hyporheic piezometer (emplaced at a location where there was very little interaction with surface water), the Ives 1 hyporheic piezometer (emplaced at a location with significant interaction between surface water and the hyporheic zone), and the Ives 1 river piezometer. In each case, TDG monitoring results (from either the hyporheic zone or from surface water) were applied to individual redds so that exposure histories over time could be compiled for each redd. The number of hours that depth-compensated TDG exceeded 100, 103, and 105% was tallied for each redd, allowing for comparisons between redd elevation and exposure time at various depth-compensated TDG concentrations above which our literature review suggested negative impacts could occur. During periods of redd dewatering, TDG was not counted toward total exposure time for any of the tested levels. Thus, high-elevation redds often showed lower exposure times to given TDG levels due to the increased time of dewatering.

In the MF spawning area, elevations of individual redds were unavailable. However, the riverbed is relatively uniform there, and little range in the elevation distribution was expected. Given that our sensors were installed at a representative elevation and that depth-compensated TDG never exceeded 100% saturation, we expected there to be little chance that chum salmon redds were negatively affected by TDG.

If water depth is greater than the compensation depth, sufficient hydrostatic pressure prevents bubble formation in fish tissues and the subsequent onset of GBD (Tanner and Johnston 2001). However, if the water depth is less than the compensation depth, gas bubbles begin to form, potentially causing intracranial hemorrhaging, subcutaneous bubble formation, and increased mortality (Harvey and Cooper 1962; Rucker and Kangas 1974; Krise and Herman 1989). When this occurs, hydrostatic pressure still reduces the impact to biota, but the effective TDG is not fully reduced to 100%. We computed the percentage reduction (compensation) in supersaturation using an equation modified from Knittel et al. (1980):

$$\text{Compensation} = 100(P_w/P_b),$$

where P_w is the pressure due to the water column where TDG was measured and P_b is the barometric pressure.

Results

Hyporheic Water Quality at Chum Salmon Spawning Locations

The percentage of TDG saturation was higher within the hyporheic zone at Ives than at MF ($P < 0.001$; Figure 3). River TDG was greater than hyporheic TDG at both sites ($P < 0.001$). However, there was no difference in river TDG between Ives and MF ($P > 0.10$; Figure 3). Total dissolved gas within the hyporheic zone was relatively stable at both MF sites (MF 1 and 3; Figure 1) and at Ives 2 hyporheic (Figure 3). At Ives 1 hyporheic, TDG was more variable and changed in concert with surface water values, suggesting that Ives 1 hyporheic was in greater contact with surface water (Figure 3). At Ives 1 hyporheic, percentage saturation of TDG varied over a much larger range than it did at the other hyporheic measurement locations (Figure 3).

Mean percentage saturation of DO was lower in hyporheic locations than in the river at Ives ($P < 0.001$; Figure 3). Dissolved oxygen data responded erratically within the river at MF, were suspected to be erroneous, and were excluded from this evaluation. In contrast to TDG, DO within the hyporheic zone was frequently lower at Ives than at MF and frequently decreased below 50% saturation (Figure 3). This was the case particularly at Ives 2 hyporheic, where the mean DO percentage saturation was 43.8% (SD = 3.9%) and mean DO was lower than that at all other hyporheic locations ($P < 0.001$). At Ives 1 hyporheic, mean DO concentrations were higher ($P < 0.001$) and mean DO percentage saturation was 78.6% (SD = 22.4%). Measurements of DO were highly variable at Ives 1 hyporheic, alternating between concentrations similar to the overlying river and those measured at Ives 2 hyporheic (Figure 3). Minimum DO percentage saturation at both Ives hyporheic locations was approximately 28%, corresponding to just over 3 mg/L. Within hyporheic monitoring locations at MF, DO percentage saturation was similar to that at Ives 1 hyporheic but much more stable (Figure 3).

Ives hyporheic temperatures were relatively warm, with mean values greater than 9°C at both locations (Figure 3). The MF hyporheic locations were much colder than those at Ives ($P < 0.001$); mean temperature was 7.3°C (SD = 0.11°C) at MF 1 hyporheic and 6.0°C (SD = 0.47°C) at MF 3 hyporheic (Figure 3). River temperatures displayed a typical spring warming trend over the sampling period, gradually increasing from approximately 4°C in

February to approximately 13°C in May. Similar to other water quality results, the temperature at Ives 1 hyporheic was highly variable and exhibited a greater correlation with river values than the other hyporheic measurement locations, suggesting greater contact with surface water.

The difference in specific conductance between Ives river sensors, Ives hyporheic sensors, and the MF 1 river sensor was small, with values ranging from 137 to 157 μS/cm (Figure 3). Specific conductance was lower in the MF hyporheic zone than in the Ives hyporheic zone ($P < 0.001$) as means were less than 50 μS/cm (Figure 3). Specific conductance remained much lower in the hyporheic zone than in the overlying river at MF.

Effect of Fluctuating River Stage on Total Dissolved Gas, Dissolved Oxygen, and Temperature

Over relatively short time scales (e.g., days to weeks), water quality was highly variable at Ives 1 hyporheic and was positively correlated with river stage (Figure 4). For example, during April 12–19, 2007, TDG at Ives 1 hyporheic ranged from 102% to 112% and was positively correlated with river stage ($R = 0.82$). During that period, when river stage rose, TDG at Ives 1 hyporheic became similar to the TDG measured at Ives 1 river, suggesting that river water was flowing into the hyporheic zone. When river stage dropped, TDG levels at Ives 1 hyporheic dropped to values similar to those at Ives 2 hyporheic, where the TDG response was much more stable relative to stage fluctuations (Figure 4a). Interestingly, TDG in the river increased during periods of low river stage. This probably occurred when total river volume decreased while the volume of spilled water remained unchanged, causing an increase in the ratio of spilled water to total river volume. Similar to TDG, DO at Ives 1 hyporheic was highly variable and positively correlated with river stage ($R = 0.81$; Figure 4b). There was a similar but greatly dampened response at Ives 2 hyporheic ($R = 0.50$). The TDG at Ives 2 hyporheic remained stable during this period, suggesting that surface flow dominated, reducing dissolved nitrogen inputs through the hyporheic zone (Figure 4b). The DO at MF hyporheic locations remained stable in response to short-term river stage fluctuations (Figure 4b). During March 23–May 15, 2007, temperature was relatively stable at Ives 2 hyporheic, MF 1 hyporheic, and MF 3 hyporheic, suggesting relatively constant hyporheic discharge to the river there compared with the Ives 1 hyporheic location (Figure 4c). However, at Ives 1 hyporheic, temperatures exhibited a strong inverse correlation with river stage, especially during the early portion of our study period, when the hyporheic zone was substantially warmer than the river ($R = -0.92$

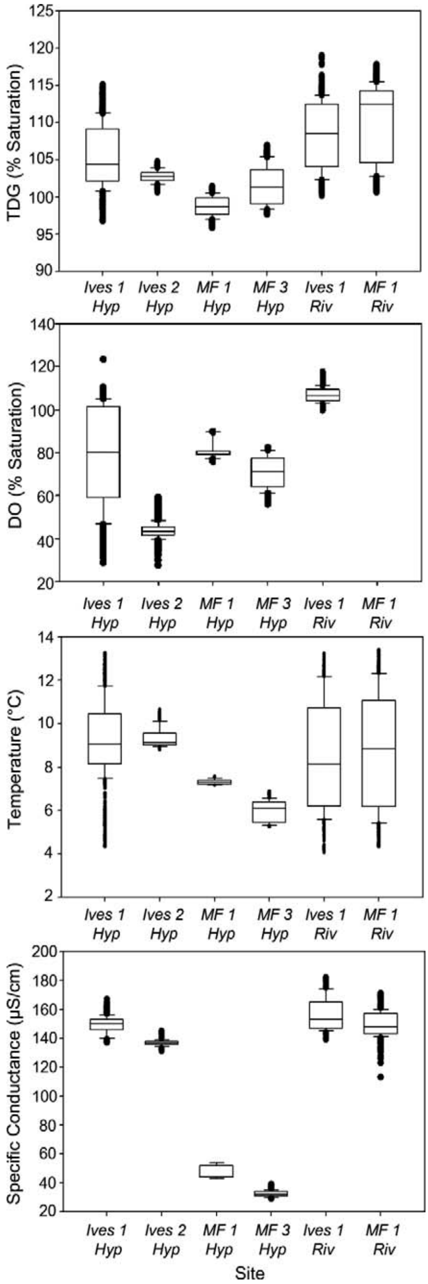

FIGURE 3.—Distribution of hourly water quality data collected during February 28– May 15, 2007, at hyporheic (hyp) and river (riv) piezometer sites on the Columbia River near Ives Island (Ives) and Multnomah Falls (MF; TDG = total dissolved gas; DO = dissolved oxygen). The lowest boundary of each box indicates the 25th percentile, the line within the box marks the median, and the highest boundary of the box indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Black circles indicate outlying values. The DO data within the river at MF were deemed erroneous and are excluded.

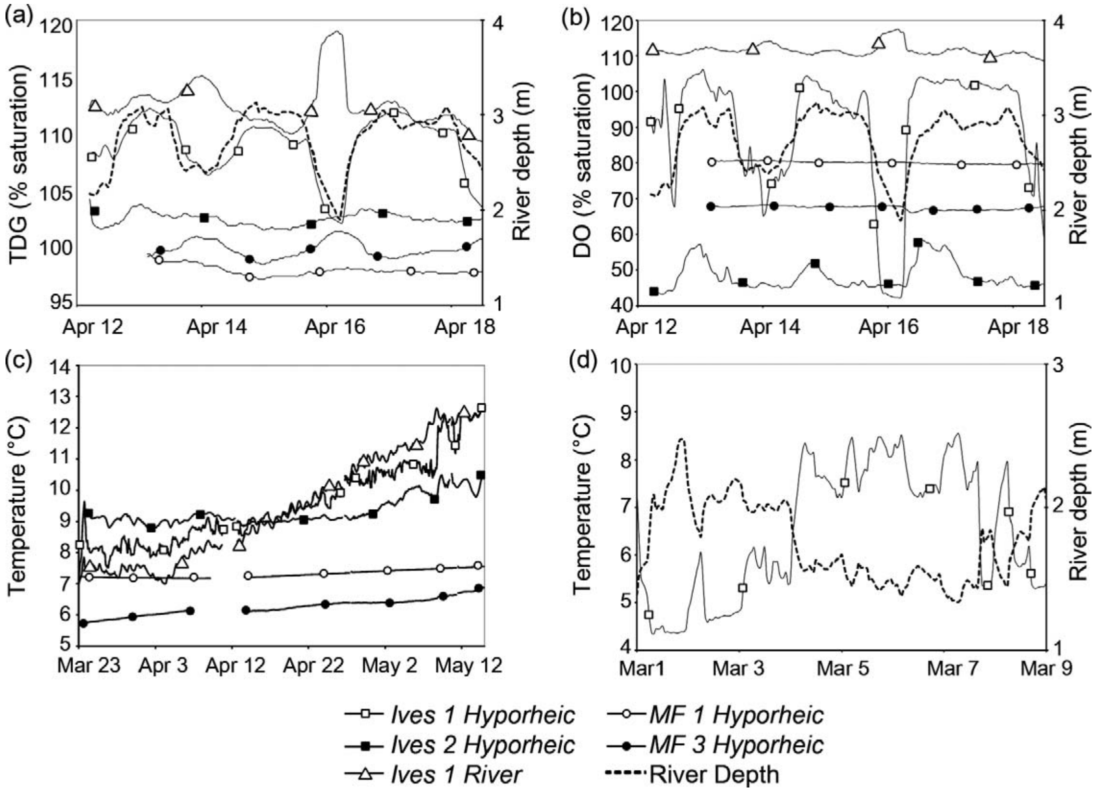

FIGURE 4.—Influence of river depth on **(a)** total dissolved gas (TDG) and **(b)** dissolved oxygen (DO) at the Ives 1 hyporheic piezometer on the Columbia River, showing increased interaction with surface water there compared with the other Ives Island and Multnomah Falls (MF) piezometer locations. **(c)** Temperature on a seasonal time scale and **(d)** temperature during short-term river depth fluctuations were the most variable at the Ives 1 hyporheic piezometer.

for March 1–8, 2007; Figure 4d). This trend continued at Ives 1 hyporheic later during our study period but was less evident as seasonal warming of the river decreased temperature differences between the river and hyporheic zone.

Estimated Exposure of Chum Salmon Redds to Total Dissolved Gas

During the 2006 spawning year, 137 chum salmon redds were distributed within our Ives assessment area at riverbed elevations ranging from 2.4 to 4.2 m (National Geodetic Vertical Datum of 1929 [NGVD 29]; Zilkoski et al. 1992). The wide range in redd elevation distribution was caused by relatively high water levels during the spawning season, which allowed chum salmon to spawn in higher-elevation habitat on the south side of the gravel bar (Figure 1). During incubation year 2007, 50% of redds were located below 3.3 m (NGVD 29) and 80% were below 3.7 m (NGVD 29). For redds located above 3.7 m (NGVD 29), exposure estimates based on surface water monitoring results were greater than those based on hyporheic monitoring results. Based on surface water monitoring, these redds were exposed to TDG greater than 103% and 105% saturation for up to 600 and 450 h, respectively. The estimated exposure to TDG greater than 103% and 105% dropped to approximately 300 and 170 h, respectively, based on monitoring results from Ives 1 hyporheic (a location in frequent contact with surface water) and dropped dramatically to 16 and 0 h, respectively, based on monitoring results at Ives 2 hyporheic (a location with minimal contact with surface water; Figure 5). For redds located at an elevation of 3.3 m (NGVD 29), surface water monitoring produced the longest estimated exposures to TDG greater than 100% (Figure 5). However, exposure time for these redds based on monitoring at Ives 1 hyporheic was greater at TDG concentrations above 103% and 105% (Figure 5). Redds located higher than 3.3 m (NGVD 29) were frequently dewatered (Figure 5). Total dissolved gas exposure estimates excluded periods during which these redds

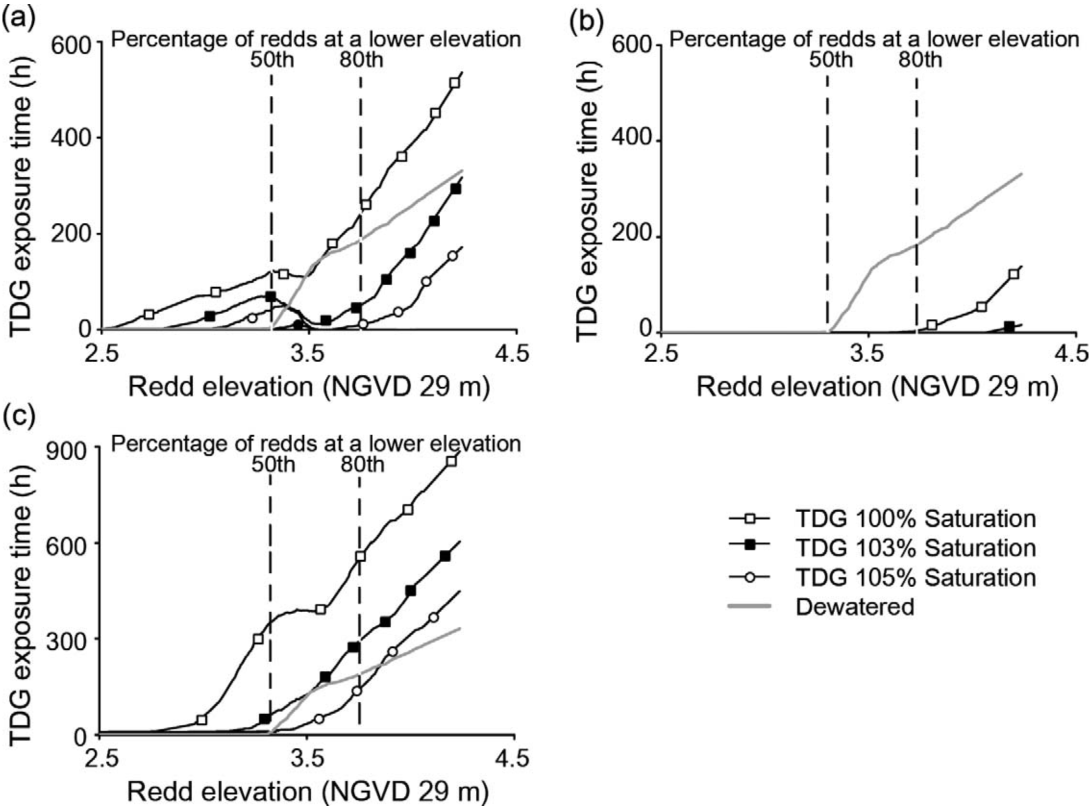

FIGURE 5.—Estimated hours of total dissolved gas (TDG) exposure and dewatering of chum salmon sac fry in redds based on (**a**) hyporheic monitoring results at the Ives 1 hyporheic piezometer in the Columbia River, (**b**) hyporheic monitoring results at the Ives 2 hyporheic piezometer, and (**c**) surface water results from the Ives 1 river piezometer. Dashed lines show the 2006 chum salmon redd elevation distribution percentiles (elevation in meters is based on the National Geodetic Vertical Datum of 1929 [NGVD 29]).

were dewatered. This is particularly evident for exposure estimates based on Ives 1 hyporheic monitoring at TDG levels of 103% and 105%. At these concentrations, exposure estimates were longer for constantly submerged redds at an elevation of 3.3 m (NGVD 29) than for frequently dewatered redds at an elevation of 3.7 m (NGVD 29; Figure 5a).

Chum salmon sac fry were exposed to supersaturated TDG on a few occasions prior to the onset of spring spill while the corner collector was operational. However, most of the exposure to supersaturated TDG occurred after the onset of spring spill (Figure 6). At the elevation of the shallowest chum salmon redd (4.2 m), there were 21 instances during which depth-compensated TDG became elevated above 103% and 14 instances in which TDG exceeded 105%. When TDG became supersaturated above these concentrations, the median exposure time was 4 h for both 103% and 105% TDG, and the maximum exposure duration was 113 and 57 h, respectively.

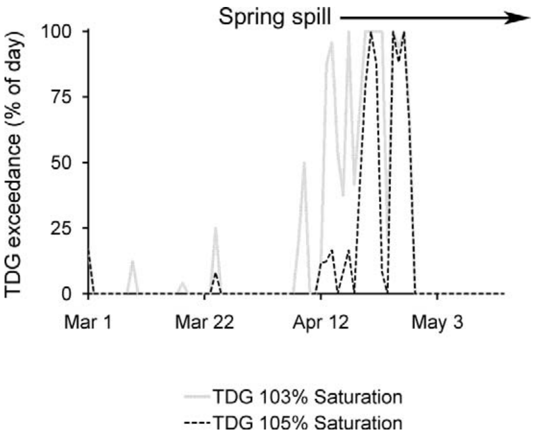

FIGURE 6.—Timing of chum salmon sac fry exposure to total dissolved gas (TDG) concentrations above 103% and 105% in the lower Columbia River. The TDG exposures were estimated using the elevation of the shallowest chum salmon redd.

Discussion

Water Quality

The response of water quality to fluctuation in river stage varied between the Ives and MF areas as well as between the monitoring sites within those areas. The relative stability of hyporheic water quality characteristics at MF 1 hyporheic suggests that river discharge fluctuations have little effect on water quality at egg pocket depth at that site, a condition indicative of a relatively constant source of subsurface water discharging through the hyporheic from groundwater or springwater (Shepherd et al. 1986; Crisp 1990). It is possible that such a water source originates from Multnomah Creek, entering the subsurface upgradient from our study site and later upwelling into the Columbia River through the hyporheic zone. This idea is supported by similarities between the water chemistry of Multnomah Creek upstream from our study site and the hyporheic zone at our study site (Arntzen et al. 2007). More variability was observed in hyporheic water quality at MF 3 hyporheic and Ives 2 hyporheic, suggesting some limited interaction with surface water at those two monitoring locations. In contrast, responses at Ives 1 hyporheic were highly variable and strongly correlated with changes in river stage (Figure 4). This response is not unprecedented; similar relationships between hyporheic water quality and surface water flow have been previously observed (Soulsby et al. 2001; Alexander and Caissie 2002; Malcolm et al. 2004; Arntzen et al. 2006). The water source causing differences between the hyporheic zone and surface water at Ives 1 hyporheic may represent bank storage water. This is consistent with the previous findings of Geist et al. (2002), who postulated that hyporheic water in the Ives area originated as river water that downwelled into the riverbed and remained there for extended time periods.

The relative instability of hyporheic water quality near Ives suggests that the direction of flux between hyporheic water and the river is reversed with river stage fluctuations. Flux reversals were evident in the response of TDG and DO to changing river stage at Ives 1 hyporheic (Figure 4a, b). When river stage was elevated, TDG and DO values measured in the hyporheic zone at Ives 1 hyporheic were similar to those of the overlying river, suggesting that river water flowed into the hyporheic zone (Figure 4a, b). When river stage decreased, TDG and DO at Ives 1 hyporheic dropped substantially, approaching the stable hyporheic values recorded at Ives 2 hyporheic (Figure 4a, b). This suggests that the direction of water flux at Ives 1 hyporheic had reversed and that water flowed from the hyporheic zone into the river. There was also a notable increase in the surface water concentration of TDG during periods of low river stage (Figure 4a). This was probably caused by increases in the ratio of water volume spilled (which remained constant during river stage fluctuations) to total tailrace water volume (USACE 2007). Given that the direction of water flux was from the hyporheic zone to the river during periods of low river stage, it is understandable that increases in river TDG during these periods had very little impact on hyporheic TDG concentrations.

Gradient reversals associated with large and frequent fluctuations in river stage have been observed previously in controlled river systems (Curry et al. 1994; Arntzen et al. 2006; Geist et al. 2008). During gradient reversals, water flow into and out of the hyporheic zone is influenced largely by advective exchange with the river. This process is generally controlled by channel morphology, the pressure head of overlying surface water, and the permeability of riverbed sediments (Landon et al. 2001; Wörman et al. 2002; Cardenas and Zlotnik 2003; Rose 2003). Variations in riverbed permeability probably affect the response of water quality to river stage changes and may reduce the residence time of groundwater within the hyporheic zone (Malcolm et al. 2003). For example, if the riverbed is highly permeable, river water easily could be forced below the riverbed surface into the hyporheic zone, especially when the river stage is higher (Vaux 1968; White 1993; Arntzen et al. 2006). Ives 1 hyporheic appeared to be influenced the most by changes in river depth. At this location, mean hyporheic temperatures were closest to those of the river, and the TDG, DO, and temperature fluctuations varied more than at the other monitoring locations (Figures 3, 4). Our study showed that redd exposure to TDG was maximized in areas where the greatest interaction with surface water occurred. Although our study focused on chum salmon, fall Chinook salmon also are known to spawn in the Ives area in locations where river water downwells into the riverbed and where the temperature and DO are similar to those of the overlying river (Geist et al. 2002). Our results thus suggest that in the Ives area, fall Chinook salmon could be at greater risk of elevated TDG exposure than chum salmon.

Dissolved oxygen variability can affect incubating salmonids by altering the ratio of DO to dissolved nitrogen (O_2:N_2). Increased mortality has been observed during periods when TDG is elevated and O_2:N_2 is low (Rucker 1975; Nebeker et al. 1976, 1979). Krise and Herman (1989) found increased symptoms of GBD in yolk sac fry of lake trout *Salvelinus namaycush* when O_2:N_2 was lowered. Hauck (1986) measured various symptoms related to GBD in young pink salmon *O. gorbuscha* when O_2:N_2 was lowered as a result of rapid elevation ascent during helicopter transport. Nebeker et al. (1976) demonstrated a significant decrease in juvenile sockeye salmon mortality when O_2:N_2 was increased while the total percentage saturation was held constant. After 71 h at 120% TDG, 50% of the fish died when O_2:N_2 was 0.966; only 7% of the fish died after 167 h when O_2:N_2 was changed to 1.593. We estimated O_2:N_2 using our water quality data with a program by Dawson (1986) and found that O_2:N_2 ratios averaged 0.698 at Ives 1 hyporheic and ranged from 0.239 to 1.107 during DO fluctuations. This indicates that there could be a significant impact to incubating sac fry during periods when TDG is sufficiently elevated.

Researchers previously recognized that diurnal surface water fluctuations in TDG and temperature can cause rapid changes in O_2:N_2 and that the rate of these changes could predispose bubble formation (Krise and Meade 1988). Beyer et al. (1976) found that 60–90 min are required for fish tissues to become saturated when TDG levels increase. The length of time required for desaturation to occur when TDG levels decrease is probably much longer than the time required for tissues to become saturated (Weitkamp and Katz 1980). This idea is supported by Hans et al. (1999), who induced internal GBD symptoms (using 130% TDG) and external GBD symptoms (using 120% TDG) in yearling spring Chinook salmon and evaluated the length of time required to reduce GBD symptoms when TDG was reduced to 104%. Under these conditions, nearly all bubbles disappeared from the gills after 2 h, from the lateral line after 5 h, and from the fins, eyes, and opercula after 96 h (Hans et al. 1999). At Ives 1 hyporheic, the TDG remained supersaturated during simultaneous water level fluctuations, potentially preventing adequate depth compensation by decreasing the hydrostatic pressure faster than dissolved gases could equilibrate within the fish tissues. The water level fluctuations also caused intermittent rather than constant exposure to elevated TDG. In general, intermittent exposure reduces total exposure time and thus decreases symptoms of GBD as compared with constant exposure (Antcliffe et al. 2002). During intermittent exposure, a cumulative effect has been observed in which fish resistance to GBD decreases with subsequent exposures (White et al. 1991). The cumulative effects of GBD during intermittent exposure cannot equate to those during a constant exposure. However, they may reduce the expected benefits of providing intermittent depth compensation.

Fluctuations in temperature within the hyporheic zone also have the potential to affect TDG levels and the embryos residing there. At higher water temperatures, the partial pressure of TDG increases, resulting in greater levels of supersaturation (Nebeker et al. 1978; Weitkamp and Katz 1980). A temperature increase of approximately 1°C will increase TDG by approximately 2.0–2.5% depending on the ambient conditions (Nebeker et al. 1978; Schneider et al. 2003). This effect could influence TDG in the hyporheic zone at Ives, especially when water level fluctuations affect the water quality there. For example, the Bonneville Dam juvenile fish bypass facility began seasonal operation on March 1, 2007, causing elevated TDG in the surface water downstream. Soon after operation began, river levels decreased substantially for approximately 4 d, during which temperature at Ives 1 hyporheic increased by more than 2°C (Figure 7a) and hyporheic TDG increased to levels approximately 5% higher than those in the adjacent river (Figure 7b).

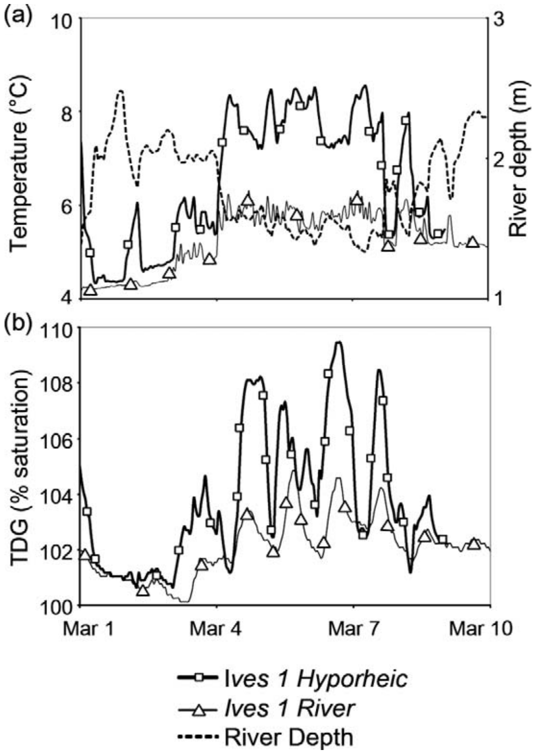

FIGURE 7.—Relationship between **(a)** temperature and **(b)** total dissolved gas (TDG) measured at the Ives 1 hyporheic and river piezometers near Ives Island on the Columbia River. When river depth decreased at Ives 1 hyporheic, temperature increased by approximately 2°C and TDG saturation increased by approximately 5%.

Total Dissolved Gas Exposure Estimates

Our hyporheic exposure estimates suggest that chum salmon sac fry were exposed to supersaturated TDG in excess of 103% for 300 h and in excess of 105% for 170 h during the 2007 incubation year. Overall, these durations represent approximately 12% and 7%, respectively, of the total incubation time. The maximum continuous period during which TDG remained above 103% or 105% was 113 and 57 h, respectively. No studies evaluating the effect of gas supersaturation on incubating chum salmon have been previously published; however, there has been some previous work evaluating TDG effects on the sac fry of other species. Some prior work suggests that GBD can occur at TDG concentrations that were frequently exceeded during our study. Krise and Herman (1989) found intracranial hemorrhaging and subcutaneous bubbles in lake trout sac fry after a 360-h exposure to 101% TDG. Wood (1979) suggested that air bubbles in the body cavity and death occur in advanced salmon sac fry and newly buttoned-up fry at TDG levels of 103–104%, with unexplained increases in mortality occurring when yolk sac fry are transferred from deep-trough trays to shallow trays. Other studies have suggested that sac fry resistance to GBD is much greater. Harvey and Cooper (1962) exposed sockeye salmon sac fry to TDG ranging from 106% to 120% for 120 h, noting yolk sacs distended by large bubbles, hemorrhagic eyes, and necrotic areas on the fins. Rucker and Kangas (1974) reported that larval coho salmon and Chinook salmon developed bubbles in the vitelline membrane after a 240-h exposure to 112% TDG. Nebeker et al. (1978) exposed steelhead sac fry to elevated TDG and suggested that levels below 105% are preferable, while higher levels (e.g., 108–110%) are probably safe if water temperatures are not elevated. Previous results are useful for qualifying the types of problems chum salmon sac fry could experience as a result of elevated TDG; however, there is a large range of sensitivity to supersaturation among different salmonid species (Weitkamp and Katz 1980). Additionally, environmental conditions during the previous studies varied substantially from the dynamic conditions that occurred during our study within the hyporheic zone, where TDG, temperature, and water level fluctuations were large and frequent. Because of these complications, studies involving larval stages of other salmonid species have only limited applicability to studies of larval chum salmon incubating within the hyporheic zone.

For management agencies to protect ESA-listed species, they must be provided with accurate information summarizing the hazards to which those species are exposed, including those associated with hydropower operation. While the risk of TDG exposure has been evaluated extensively for various species in surface water, to our knowledge this study represents the first effort to do so within the incubation environment, where groundwater–surface water interaction can play an important role in determining water quality. In the Ives area, where one of two remaining lower Columbia River ESA-listed chum salmon populations are known to spawn, accurate determination of TDG exposure during incubation is crucial. Effects of groundwater–surface water interaction may also be affecting the exposure of incubating fall Chinook salmon to TDG. Fall Chinook salmon are known to spawn in tailrace habitats downstream of several hydropower projects that participate in spring spill operations on the Snake and Columbia rivers (Dauble et al. 1999; McMichael et al. 2005). By carefully evaluating field conditions where TDG exposure occurs, estimates of TDG exposure can be improved, providing better data for chronic and acute laboratory exposure studies and allowing managers to optimize recovery strategies.

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