Report of the Independent Scientific Advisory Board

Review of the U.S. Army Corps of Engineers' Capital Construction Program

Part II.

B. Dissolved Gas Abatement Program

Independent Scientific Advisory Board
for the Northwest Power Planning Council
and the National Marine Fisheries Service

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Issue

The Northwest Power Planning Council has been directed by the Congress, in the Conference Report accompanying the Energy and Water Development Appropriations Act for the Fiscal Year 1998, to review "the major fish mitigation capital construction activities proposed for implementation at the Federal dams in the Columbia River Basin." The Council was directed to conduct this review with the assistance of the Independent Scientific Advisory Board (ISAB).

The Council identified the Corps' Dissolved Gas Abatement Program as one of five specific projects for which it requested assistance from the ISAB (Ruff 1998). Other specific projects included installation of extended-length screens at John Day Dam and at other dams, further development and testing of the surface bypass prototype at Lower Granite Dam and at other dams, Bonneville Dam juvenile fish passage improvements including the relocation of a bypass outfall, and adult fish passage improvements. Reports summarizing the ISAB evaluations of (1) extended-length screens and the Bonneville Dam juvenile bypass outfall (ISAB Report 98-4) and (2) surface bypass development (ISAB Report 98-7) have already been provided (ISAB 1998a,b).

The ISAB, as generally directed by the Council (Ruff 1998), has attempted to:

1. evaluate how the Gas Abatement Program at mainstem dams fits in the context of the Columbia River ecosystem;
2. evaluate the effectiveness of the Program to mitigate for the effects of mainstem hydroelectric dams (including both positive and negative aspects);
3. identify major, relevant uncertainties or research questions; and
4. evaluate how the scientific uncertainties affect the use and management of gas abatement measures under several scenarios of hydrosystem reconfiguration and over several time frames.

This memorandum presents the outcomes of those evaluations. We were aided in our review by a briefing by the Corps and concerned agencies on July 15, 1998, responses by the Corps to our specific written questions, and numerous reports and reprints of published literature.

ISAB Recommendations:

• *The Corps should continue its Gas Abatement Program to reduce dissolved gas supersaturation levels in the mainstem Columbia and Snake rivers to as low as practicable, with a modified set of objectives for the short and long terms.*

• *The objective of reducing the total dissolved gas saturation of the Columbia/Snake mainstem to the Clean Water Act standard of 110% during times when water is spilled at dams involuntarily is unattainable even with major (and apparently impractical or prohibitively expensive) reconfiguration of the hydropower system short of dam breaching or major drawdowns. Attainment of the standard should be considered a policy issue and separated from technical considerations. Technical work should focus on what is technically attainable and biologically acceptable, balancing all relevant risks.*

- *A few critical studies would be useful to refine estimates of the biologically acceptable percentage of atmospheric gas saturation in the context of the salmonid migration corridor, now believed to be about 120%, as a goal for near-term (<10 years) abatement efforts. These studies are considered valuable additions to understanding acceptable levels for migrating salmonids and the mainstem ecosystem* ***, but not necessary for the Corps' Gas Abatement Program to proceed.***

These studies are (1) depth distribution of juvenile and adult salmonid migrations and resident aquatic life in relation to gas compensation depth, (2) gas bubble trauma and its critical physiological, behavioral, and reproductive effects in migrating adult salmonids, and (3) effects of supersaturation near 120% (believed safe for migrating salmonids) on other components of the mainstem ecosystem.

- *Physical injury induced by alternative gas abatement devices should be evaluated (and relative risk compared to gas supersaturation in the river-reservoir system and other fish passage approaches) before novel devices are installed.*
- *The Corps should continue its efforts to monitor and model the production and equilibration of dissolved gas in the hydrosystem (including contributions from Canada) and model the generation of biological effects, and relate its findings to the gas bubble trauma monitoring programs conducted by others.*
- *Installation of proven technologies, such as flow deflectors ("flip lips") on spillways, which provide significant reduction in gas saturation with small amounts of physical injury to fish, should proceed at all possible speed as an interim measure, regardless of decisions about future hydrosystem configuration (which likely will take >10 years to implement).*
- *The Corps should explore and evaluate all reasonable concepts for long-term gas-abatement solutions, but at a low level and subject to peer review as the evaluations progress and before prototype testing.*

Background

Spilling water and downstream-migrating juvenile salmonids over mainstem dams has been demonstrated to yield higher survival than passage through turbines. Smolt survival of several species has been studied at several dams [Schoeneman et al. 1961 (chinook salmon at McNary Dam); Johnson and Dawley 1974 (chinook salmon at Bonneville Dam); Long et al. 1975 (steelhead at Lower Monumental Dam); Raymond and Sims 1980 (chinook salmon at John Day Dam); Weitkamp et al. 1980 (steelhead at Wells Dam); Heinle and Olson 1981 (coho salmon at Rocky Reach Dam); Ledgerwood et al. 1990 (chinook salmon at Bonneville Dam); Iwamoto et al. 1994 (chinook salmon at Little Goose Dam); Muir et al. 1995 (chinook salmon at Lower Monumental Dam). Spill mortalities are generally 0-2%, whereas turbine-induced mortality is 10-20% (Whitney et al. 1997).

Spill also appears to pose less risk for fish at dams than some engineered fish bypasses that involve screening of fish from turbine intakes, passage through gatewells and piping, and release into the tailwater (Whitney et al. 1997). Turbine intake screens have not been effective enough to achieve fish passage goals for all species and stocks without the addition of spill (see ISAB 89-7 for discussion of this point in relation to surface bypass development).

However, spill contributes to an increase in total dissolved gas saturation (TDGS) in the river downstream of dams such that conditions well above the generally accepted water quality standard of 110% (NAS/NAE 1973) can be created. Monitored levels have exceeded those demonstrated to be lethal to juvenile salmonids in laboratory studies because of gas bubble disease (GBD) (Ebel 1969; Bouck 1980; Weitkamp and Katz 1980; USACE 1994).

Despite potential detrimental effects of elevated TDGS, the NMFS' Endangered Species Act Section 7 Biological Opinion (NMFS 1995) includes as a "reasonable and prudent alternative", the spillage of water at dams during the migration season for the protection of juvenile spring/summer chinook salmon. Under the Biological Opinion, the NMFS directed the U.S. Army Corps of Engineers to achieve 80% fish passage efficiency (FPE) using spill. Because the prescribed spill program is likely to cause TDGS to exceed 110%, the NMFS seeks annual waivers of these standards by state water quality control agencies in order to implement the spill program.

Spill may occur for reasons other than the managed spill program under the Biological Opinion. Spill occurs when the volume of water flowing in the river exceeds the physical capacities of fully operating turbines within the powerhouse to pass it. Some turbines at a dam may not be operable (such as requiring maintenance), thus lessening the physical capacity of the powerhouse to pass water. Turbines also may not be used because there is no market for the electricity they would produce, thus the turbines are stilled and the water shunted over spillways. Spill forced upon dam operators by the limitations of hydraulic capacity of their powerhouses is generally called "involuntary spill". Spill under the Biological Opinion (or other requests by fishery managers) is generally termed "voluntary spill" or "managed spill." In many high-water years such as 1996, spill is a mixture of voluntary and involuntary types; in 1997, runoff was so high that most spill was involuntary.

From a theoretical, technical standpoint, there is probably an optimum mix of spill, bypass, and turbine passage (with present technologies) for maximizing survival of downstream-migrating smolts. Spill, up to a point, is better than turbine passage or bypasses; beyond that it induces levels of total dissolved gas saturation that cause debilitating gas bubble disease in fish that is worse than effects of bypass systems as well as worse than damages from turbines. What is simple in concept has not been simple to discover in real life.

The region has been investing in three parallel tracks of effort to directly determine that optimum and to make spill even more acceptable (lower the amount of induced TDGS by changing the technology of spill). The first track has been biological and TDGS monitoring to record actual damage to fish from TDGS in the river system in real time and to manage spill levels accordingly. The Fish Passage Center coordinates examinations of migrants collected in bypasses for signs of gas bubble disease (bubbles in selected tissues) and the NMFS has monitored resident fishes. The second track has been biological research that has attempted to describe realistic exposures of fish to TDGS in the river system, document the TDGS levels that cause biological effects, and test the assumptions behind the biological monitoring program. The third track has been a program to minimize the amount of TDGS induced by the hydropower facilities (the "Gas Abatement Program" of the Corps of Engineers).

The purpose of this ISAB evaluation is to focus on the direction for the Corps' Gas Abatement Program. However, this must be done from the perspective of a parallel, comparative evaluation of the demonstrated and expected results from the other two tracks. We provide a description of each track and our assessment of the Gas Abatement Program (including any critical biological studies) below.

Physical and Biological Monitoring

Physical monitoring of total dissolved gas saturation in relation to river flows and dam operations, particularly in 1996 and 1997, showed conclusively the need for gas abatement measures at basin dams in wet years regardless of any spill management under the Endangered Species Act (Figures 1-4). Although there is some lowering of supersaturation toward air equilibrium (100%) as water passes through reservoirs, levels were higher than 110% in dam forebays through much of the high-water season. Spill was largely involuntary (despite artificial bookkeeping attempts to attribute some spill to fish management). Flows were too great for the turbines, and hydroelectricity was so regionally plentiful in the wet years that turbines were not operated for lack of a power market. Thus, the decision about whether to continue the Corps' gas abatement program does not hinge on arguments, technical or policy, about the usefulness of spill as a management strategy for passing downstream migrants. Spill will occur in wet years, and it will cause very high dissolved gas saturation (in the vicinity of 130% to 140% air saturation, enough to cause certain biological damage) with conventional spill technology in place at most dams. The work through 1998 also shows the efficacy of conceptually straightforward dam modifications such as flow deflectors or "flip lips" to reduce gas supersaturation levels to the vicinity of 120%.

One clear deficiency in the record of dissolved gas saturation values and the generation and dissipation of supersaturation is any clear idea of what the natural condition might have been. What is the "natural background?" At some locations and at some seasons, considerable gas supersaturation undoubtedly developed naturally without help from dams. What we could say about the frequency, duration, timing, and prevalence of these natural exceedences would help contrast them with the exceedences we are trying to manage and the biological stressors the native populations might have endured. Regrettably, these data are not available.

Efforts by the Corps to synthesize its physical monitoring information in the form of gas generation and equilibration models of the hydrosystem are valuable for developing an assessment tool for alternative abatement technologies (Battelle 1998 draft). The geographic scope of the problem becomes clear when one realizes that supersaturation begins at Canadian treaty storage dams in British Columbia and continues into the estuary. However, the gas production model is only accurate to about 5% total gas saturation (DGAS Phase II Study Overview, 1997). This ensures a limited ability to predict effects or make biological correlations at a scale finer than +/- 5%.

Biological and physical monitoring within the reservoirs has not yet progressed to the point where definitive patterns of exposure of fish to supersaturated water in the reservoirs can be described. Few physical measurements are made beyond dam forebays and tailwaters. The major uncertainty is the actual location of the fish in relation to the gas compensation depth (the depth at which water pressure equals the added gas pressure from supersaturation) in reservoirs. If such a description is needed, additional research and monitoring will be necessary before the validity of models of fish location in relation to supersaturated water can be established (Fish Individual-based Numerical Simulator, FINS; Battelle 1998 draft). We do not believe it is essential to have this information to proceed with gas abatement, however, because TDGS values are highest in shallow dam tailwaters where depth compensation is least possible.

Biological monitoring at the dams has shown fairly consistent results for several years (Figure 5), and could be discontinued without great loss to understanding (although this monitoring is outside the current ISAB evaluation). Carried out since the early 1990s, the examinations of fish in bypasses have shown a clear pattern. There is a low percentage of fish with bubbles in tissues when TDGS values slightly exceed the water quality standard. This percentage increases markedly when high-spill levels of >120% are reached, but a large percentage of fish sampled in dam bypasses still do not show signs of gas-bubble trauma. A clear action level for cessation of spill, sought from the beginning of this monitoring, has not been defined. A level of about 120% is where symptoms in downstream migrants appear to increase substantially.

Biological monitoring of overall smolt survival is germane to the gas supersaturation question. Given the large number of fish tagged with PIT tags each year in the system, it would seem reasonable that a very targeted set of monitoring experiments could be conducted to answer many of the questions about survival under supersaturated conditions. Indeed, both the NMFS and others have used the NMFS migrant survival study data (e.g., Iwamoto et al. 1994; Smith et al. 1998) to attempt to bring clarity to the picture. The result so far has been largely one of conflicting conclusions. We believe these conflicts in interpretation will continue until adequate PIT-tag survival data are obtained from dams in the lower Columbia River.

Gas bubble disease symptoms have been found in resident fish held near the surface in net pens and monitored when TDGS levels were above about 115-120%. Natural behavior of resident fish in the wild, such as occupancy of deeper layers, could mitigate the negative effects of supersaturated waters. However many resident fish are obliged to use shallow waters to carry out their life cycles. Early life stages of resident species have been shown to be especially susceptible to gas bubble disease above about 110-115%. Food organisms such as cladocerans have also shown to develop bubbles in supersaturated water and lose the ability to swim normally. Few invertebrates in the food chain have been monitored adequately, although levels of gas saturation acceptable to fish have been assumed adequate for invertebrates. The monitoring of ecosystem components conducted so far has been inadequate to confidently relate TDGS levels believed safe for selected species and ages of migrating salmonids to safety for the mainstem ecosystem as a whole. This concerns the ISAB because of its (and its predecessor advisory groups') stated perspective of viewing salmonids in their ecosystem.

Figure 1. Total dissolved gas levels at mainstem Snake and Columbia river dams, 1995, showing annual minimum, average, and maximum at selected forebays (immediately upstream of a dam) and tailwaters (immediately downstream of a dam), and a polynomial regression line showing general longitudinal trends.

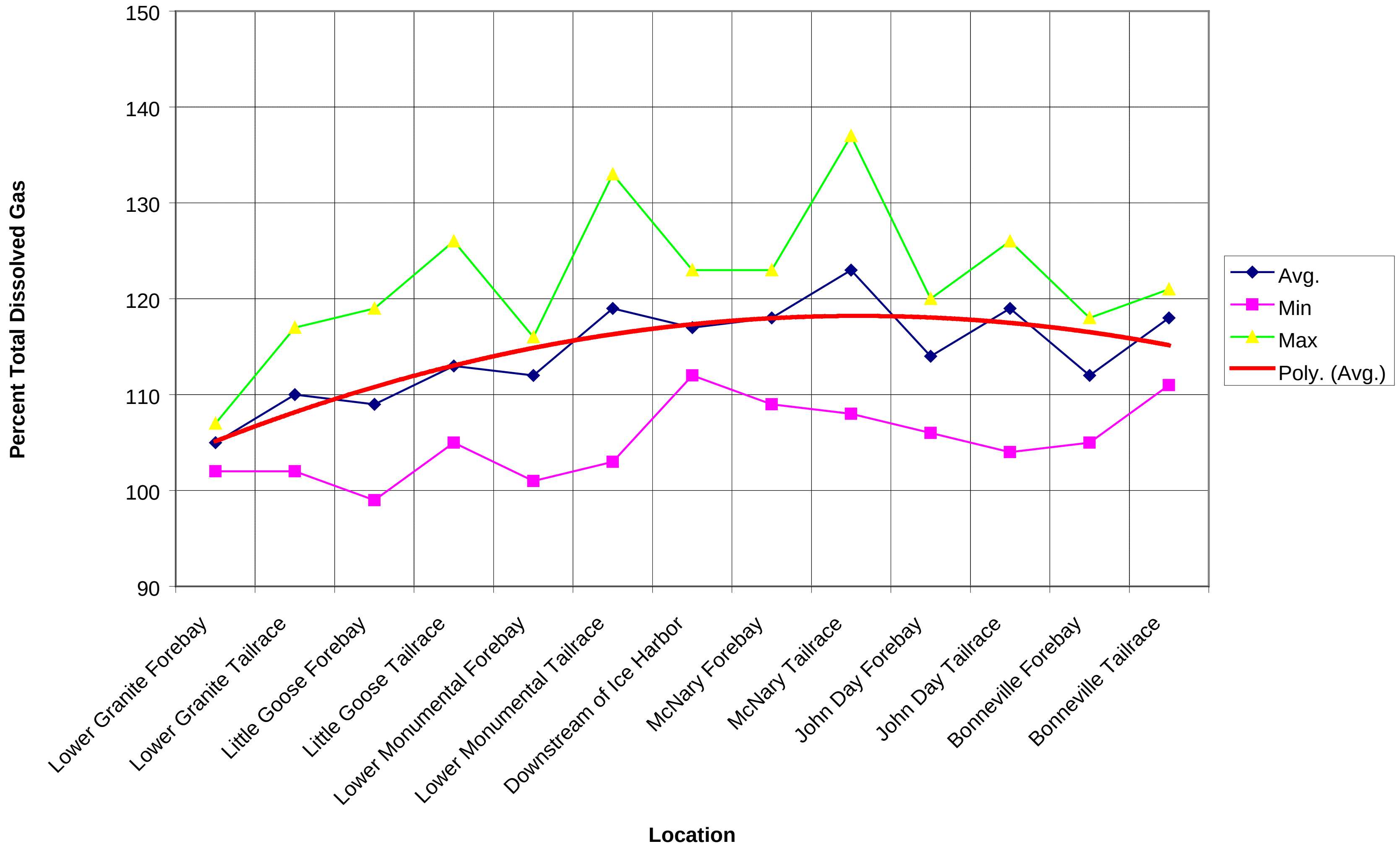


Figure 2. Total dissolved gas levels at mainstem Snake and Columbia river dams, 1996, showing annual minimum, average, and maximum at selected forebays (immediately upstream of a dam) and tailwaters (immediately downstream of a dam), and a polynomial regression line showing general longitudinal trends.

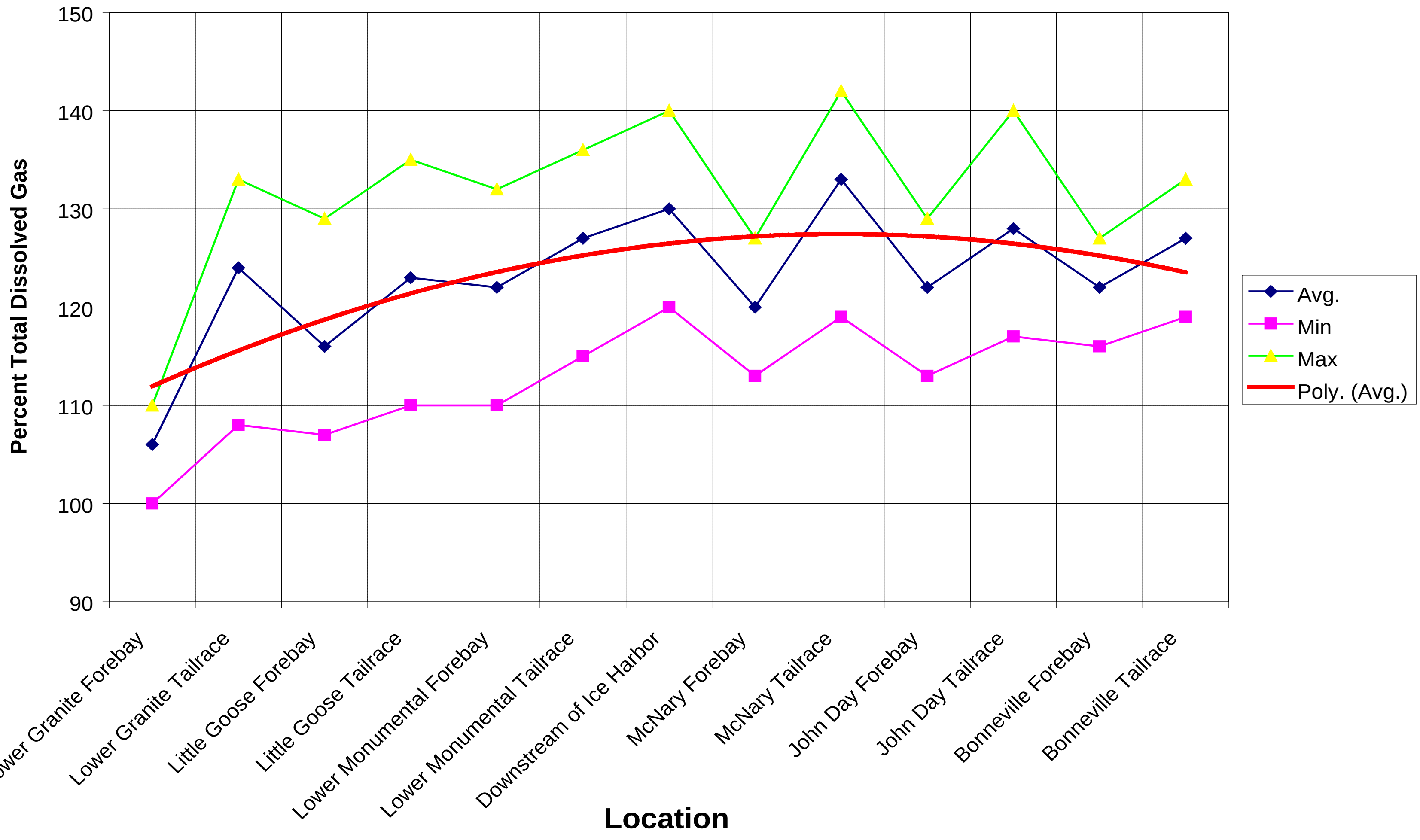


Figure 3. Total dissolved gas levels at mainstem Columbia river dams and tidal freshwater, 1997, showing the longitudinal pattern at roughly two-week intervals, April-August, at selected forebays (immediately upstream of a dam) and tailwaters (immediately downstream of a dam).

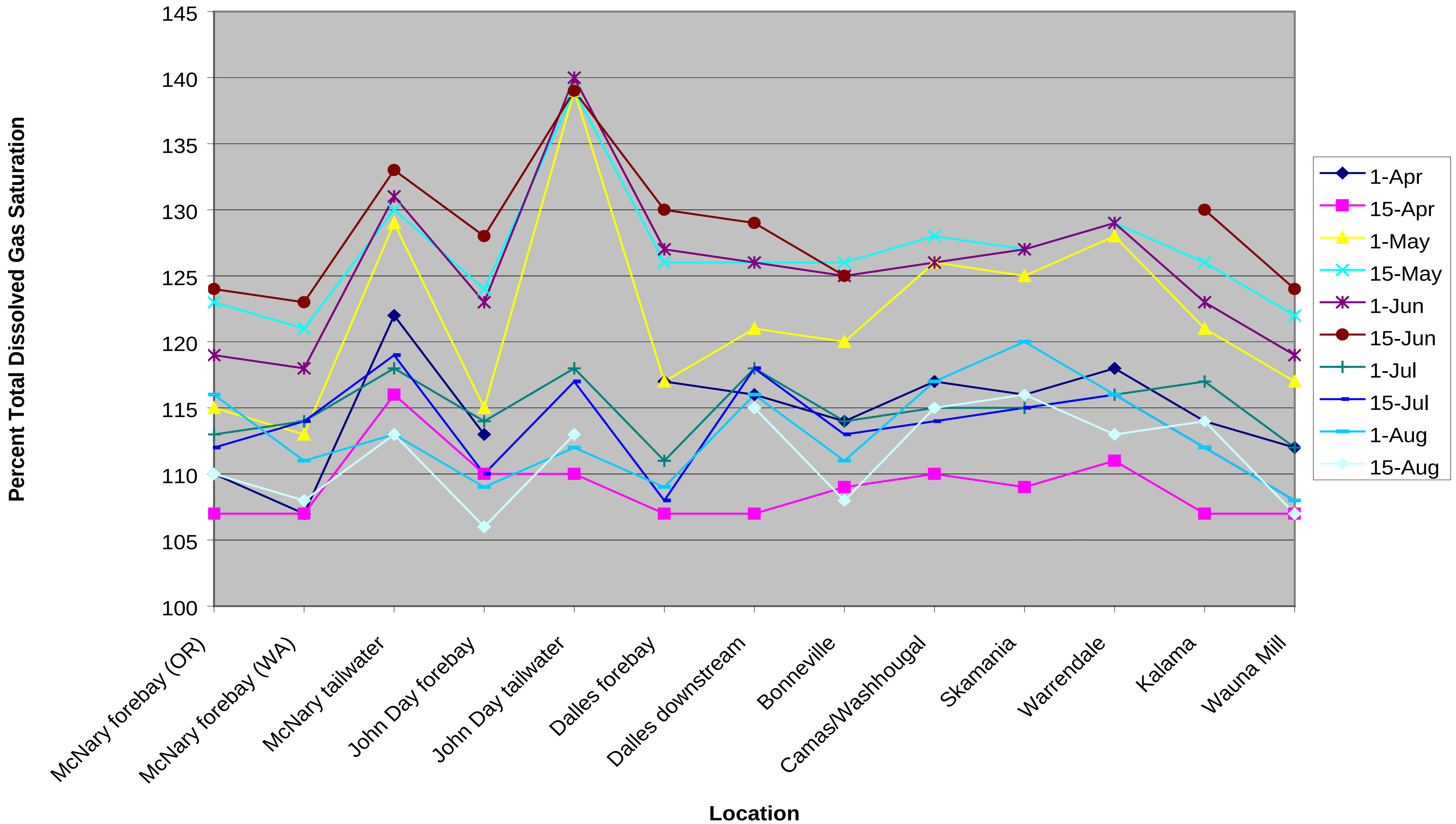


Figure 4. Seasonality of total dissolved gas saturation April-August 1997 at several stations from McNary forebay to tidal fresh water.

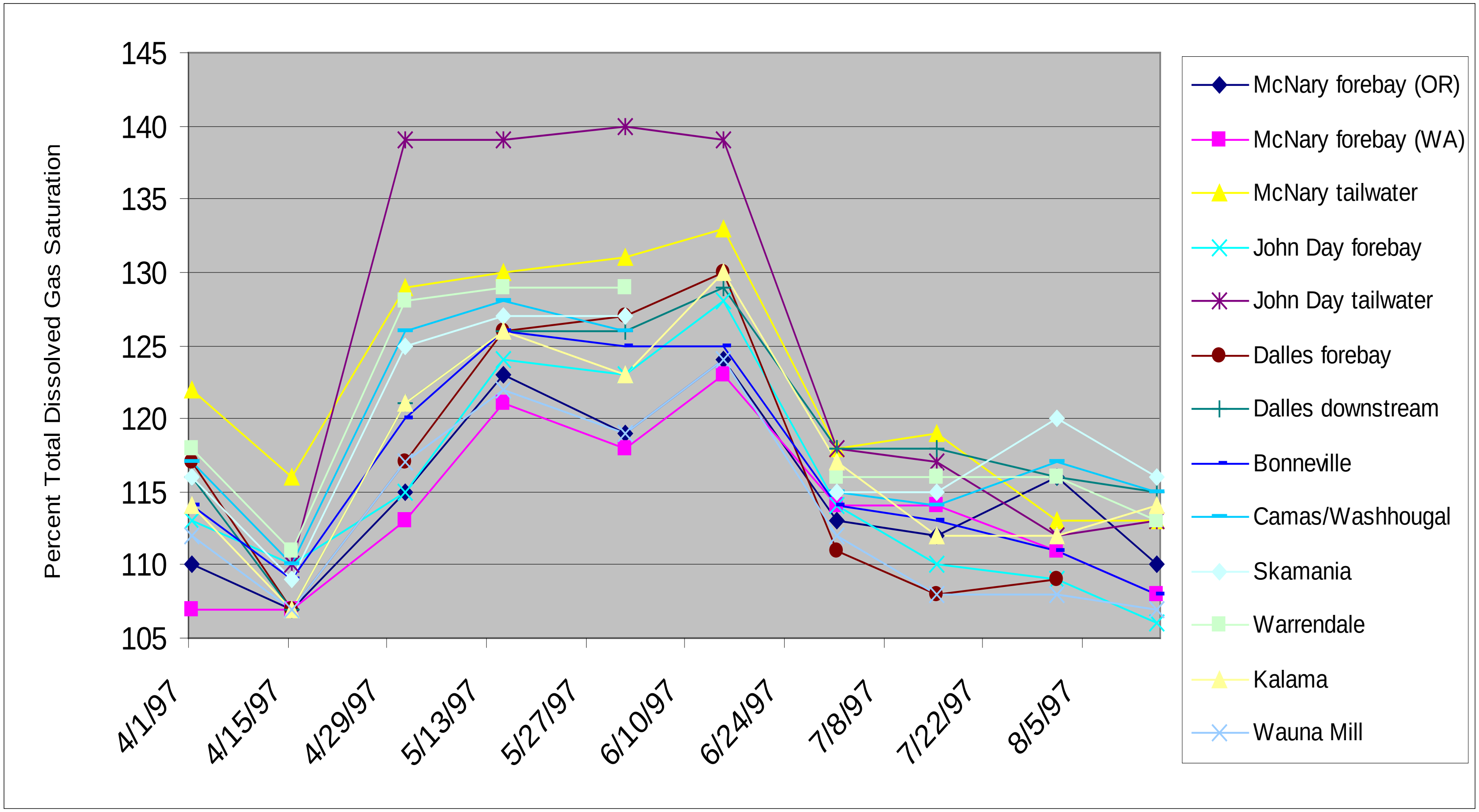
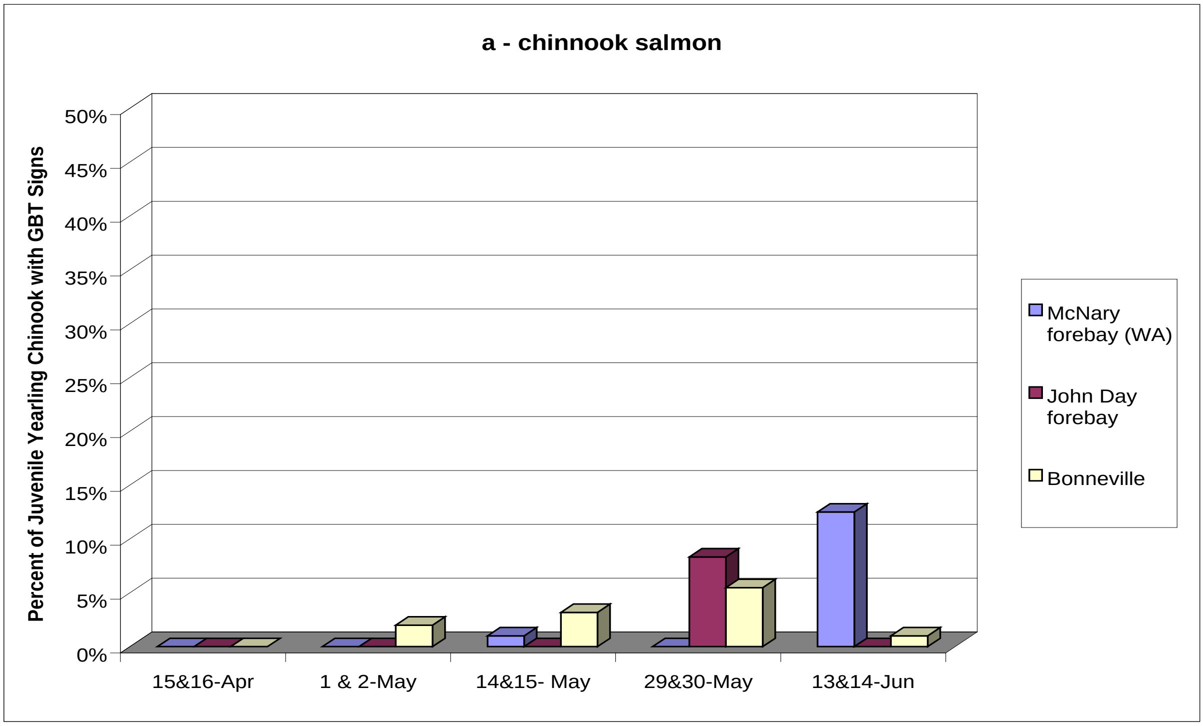
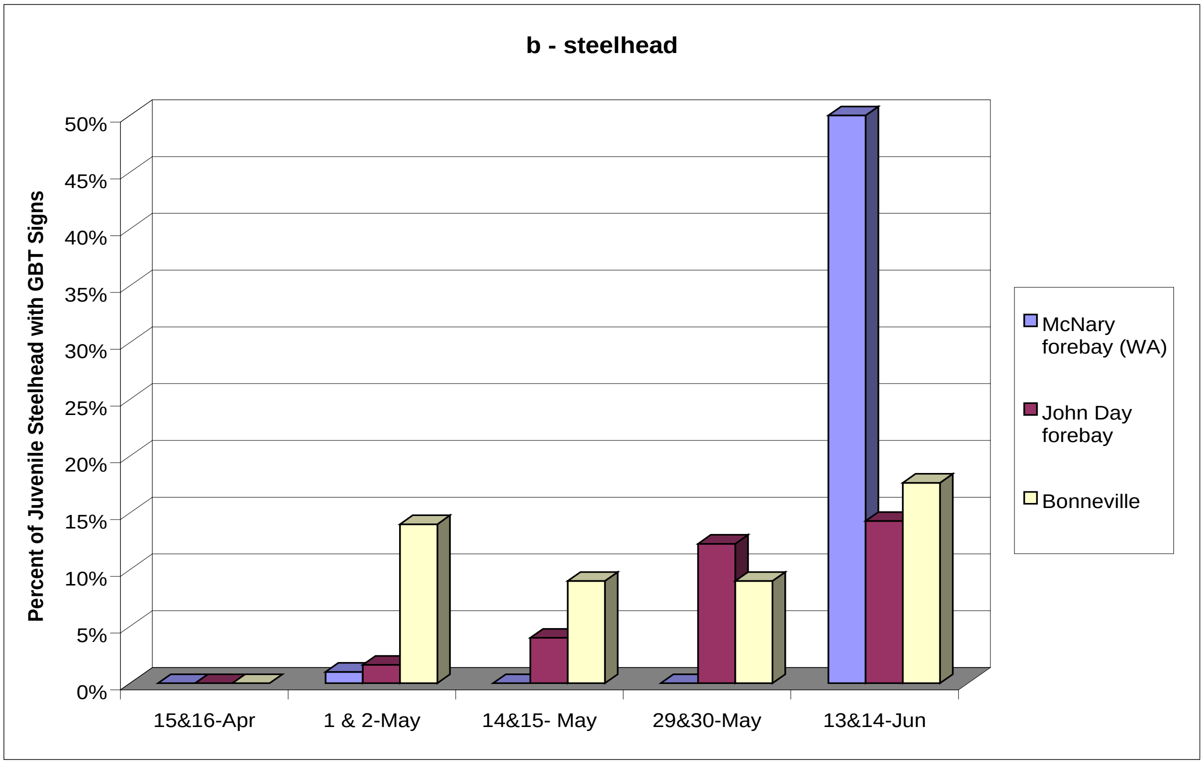


Figure 5. Seasonal progression of signs of gas bubble disease in juvenile salmonids sampled by the Fish Passage Program at McNary forebay, John Day forebay, and Bonneville Dam (a- chinook salmon; b- steelhead).





Biological Research

Biological research has uncovered the vast complexity of exposure to high total dissolved gas saturation and the consequent damages that may lead to decrease in survival. It seems to us that the endless biological complexities and uncertainties shown by recent experiences in biological research on the effects of gas supersaturation make a quick definition of acceptable gas levels in the river for biota unlikely. Despite a high desire to more fully understand the action of high gas supersaturation on the physiology, behavior, and survivorship of salmonids and other ecosystem components, the amount of potentially interesting research is nearly endless (and clearly beyond either real need for gas-abatement decision-making or the ability of the region to fund). However, we sought out any critical few studies that we believe could be particularly useful or perhaps essential to the Corps' Gas Abatement Program.

As an example of the complexity of TDGS exposures, we observed that simple statistical comparisons between gas bubble disease signs in migrating salmonids at dams and gas supersaturation levels found there have been misleading. Likewise, mortalities attributed to specific river reaches through reach survival studies (Smith et al. 1998) can be misused. While both the biological monitoring for signs of gas bubble disease and the NMFS research on reach-specific survival provide important data, a strictly statistical evaluation of signs and survival with local TDGS neglects to recognize that the migrants are accumulating exposure over time as they move downstream (in a sense, a downstream-moving bioassay). A dose-accumulation model for dissolved gas effects on migrating fish is more appropriate. This may be a useful outcome of the Corps' physical-biological modeling (see Battelle 1998 draft). In a dose-accumulation model, the time it takes for a toxicant (in this case, gas supersaturation) to take effect is considered. Because of the time it takes juvenile salmonids to pass through Snake River reservoirs, the effects of upriver exposures may not be manifested until fish have reached the lower river reaches. Information on durations of exposure required for different levels of TDGS to cause biological effects (e.g., Blahm et al. 1975; Dawley and Ebel 1975; Fickeisen and Montgomery 1978; Bouck 1980; Colt et al. 1986; Jensen et al. 1986; Backman et al. 1991; Aspen Applied Sciences, Inc. 1998; and as reviewed by Fidler and Miller 1993) needs to be coupled with downstream migration rates.

Constant high survival between Lower Granite Dam and Lower Monumental Dam, for example, may not indicate biologically acceptable dissolved gas conditions there. Effects of gas supersaturation may be accumulating without an immediate effect on survival. NMFS survival data indicates that the poorest survival in the Snake River occurs at the lower reaches from Lower Monumental Dam (LMO) to McNary Dam (MCN). One interpretation is that dissolved gas conditions in the lower Snake are worse than upstream (and the effects are shown there). However, a more likely interpretation is that doses of high gas accumulate in the fish as they migrate downstream and reduction in survival is exhibited primarily when fish have reached the lower river reach. Lower survival probabilities on later dates may indicate that the accumulation of damaging doses occurs more rapidly at warmer temperatures, as has been demonstrated in previous studies (Nebeker et al. 1979) and is manifested sooner (i.e., farther upstream) than at cooler temperatures. Because predation may be the actual mechanism for death, one might look for high predation rates at locations where fish have been exposed to potentially lethal saturation levels for a sufficient duration in their migration to affect equilibrium or other behavioral characteristics. In fact, especially high predation on downstream migrants has been documented in John Day Reservoir, which migrants reach after passage through high-saturation waters of the lower Snake and McNary Reservoir (Poe et al 1991).

Depth of fish migration is a critical uncertainty that complicates TDGS exposure information. It has been known for a long time that fish below a “compensation depth” reside in water pressures that compensate for high dissolved gas levels and where the formation of damaging bubbles does not occur. Yet definition of migration depth for purposes of estimating gas bubble disease exposure and incidence has been elusive. Recent telemetry studies by the USGS Biological Resources Division in McNary Pool suggest complex vertical positioning behavior that makes a simple expression of exposure difficult. Fish apparently migrate at depths that intermittently compensate for nominal supersaturation (at the water surface) and either prevent bubbles from forming in fish tissues or intermittently force bubbles back into solution. For adults that must surface to use fish ladders, this option does not apply, however, and questions remain about their susceptibility.

These results relate in some uncertain way to observations in 1997 that in-river smolts showed fewer GBD signs than fish sampled in the smolt bypass at the next downstream dam. Fish do not seem to lose signs in passage through turbine entrance/gatewell/bypass piping, as some observers had suspected, but they may gain bubbles in this passage. Much research would be necessary to sort this out.

If the gas abatement program is intended to be guided by actual biological suitability of the environment during passage of downstream migrants, then refinement of our understanding of the realistic, depth-compensated exposures to bubble-forming gas pressures by juvenile salmonids seems to be an essential part. We believe, however, that it is more technically justified to reduce TDGS levels to the extent practicable than to expect that these complexities will be resolved in the near future.

A clear deficiency in understanding the biological effects of high dissolved gas saturations in the Columbia-Snake mainstem is information on adult salmonids. Cautious use of adults in experiments, for protecting reproductive stocks, has limited research on adults. Yet the same protectiveness of the broodstock should dictate that we protect this critical (and potentially sensitive) life stage.

If additional research is conducted, investigators should give more attention to species or life stages that are more sensitive to gas bubble trauma or more likely to be injured by mitigation measures than are juvenile salmon. Most studies have investigated chinook and steelhead yearlings. Studies might give more attention to underyearlings or other species. Similarly, mitigation measures may injure some species and life stages more than others. For example, some information indicates lower survival rates for sub-yearlings (than yearlings) passing through flip-lip flow deflectors. Sockeye salmon smolts show a propensity for greater injury and descaling rates in many bypass and transportation systems and may be more susceptible to physical injury than other species by gas abatement devices. The ISAB has been concerned overall with maintaining diversity among species and stocks, and would not like to see either gas saturation levels or abatement devices that markedly alter diversity.

There are many other uncertainties in biological understanding. Without detailing all of these uncertainties, or impugning the work of researchers who are interested in the details of gas bubble trauma at physiological, organismal, and ecological levels, we conclude that much interesting, scientifically valid, but topically diffuse biological research will not any time soon establish the optimal mix of spill and other passage routes for best salmon survival.

If additional biological research is required to justify gas abatement measures (but we do not believe it is), three areas of research stand out to us as particularly important in the near term to attain the goals of gas abatement to levels that are biologically acceptable. These are: (1) depth distribution of juvenile and adult salmonid migrations in the mainstem migration corridor in relation to gas compensation depth (this research could clearly establish that surface gas saturation data are inappropriate as a biologically relevant standard for salmonid migrants, although risks to shallow-water resident species will remain), (2) identification of critical exposures for physiological, behavioral, and reproductive effects of gas bubble trauma in migrating adult salmonids for which few data are available (key experiments/observations could verify the similarity of responses of juveniles and adults), and (3) clarification of the effects of high dissolved gas saturations on resident ecosystem components of the mainstem. We believe, however, that sufficient biological justification already exists to install gas abatement devices to reduce gas supersaturation to as low as practicable, providing the devices themselves do not reduce survival by more than 2-3%.

Regardless of whether such research is conducted, physical injury induced by alternative gas abatement devices should be evaluated. Such evaluation may require more biological research. There is evidence that even relatively proven technologies such as spill deflectors induce a definable increment of mortality that may be comparable to that from alternative fish passage routes. The relative risks from spill with gas-abatement devices should be compared to those of unabated gas supersaturation in the river-reservoir system and fish passage approaches other than spill (as a reality check for otherwise promising abatement devices for gas reduction).

Gas Abatement Program

The Corps has a program for reducing total dissolved gas supersaturation at its mainstem dams. The objective of the program is to respond to the recommendations of the expert panel on gas bubble disease to the National Marine Fisheries Service that structural and operational changes would be needed to reduce total dissolved gas supersaturation in the river system based on the managed spill program (Panel on Gas Bubble Disease 1994, 1996). Subsequently, the National Marine Fisheries Service's Biological Opinion (1995) for Operation of the Columbia River Hydro System detailed that the Corps of Engineers should develop and implement a gas abatement program at all projects. The original goal of the program was to determine how the projects could be modified to comply with the federal and state water quality standard for total dissolved gas saturation (110% up to the ten-year, seven-day peak flood event; USACE 1996).

The Corps' program has involved conceptual evaluation of technical alternatives for reducing dissolved gas in spilled water (Phase I; USACE 1996), work plans for detailed engineering evaluations and biological studies (Phase II; USACE 1998) and eventual actual construction of devices at dams. A wide range of gas abatement devices has been explored, which range from established technologies such as flow deflectors ("flip lips") on dam spillways that prevent deep plunging of spilled water to exotic spillway designs that incorporate elaborate baffles to facilitate air equilibration. The program has conducted systematic evaluations of engineering feasibility, efficacy, and cost for the suite of alternatives. Field studies of gas entrainment at existing spillways have shown that reducing the depth of the plunge basins at dams would be effective in reducing gas supersaturation, but at high monetary cost with potential loss of juvenile salmon through physical injury (Dawley et al. 1998).

Early evaluations identified physical damages to spilled organisms as a significant corollary risk for spillway modifications (R2 Resource Consultants, Inc. 1998). For example, baffles installed to break the flow of water over, or at the base of, spillways can impinge and mechanically damage fish. As a general rule, the devices most effective in preventing spill plunging into deep pools seemed to be the most physically damaging to the fish. Gas abatement at a project thus becomes a balance between induction of gas supersaturation (with effects in the river and reservoir downstream) and the physically damaging side effects of spill at the site. Although practice has usually demonstrated a net benefit for devices such as simple flow deflectors (Muir et al. 1998), the balance for other devices is uncertain.

A major conclusion from these engineering studies is that the Clean Water Act criterion (and state standard) of 110% saturation at the water surface in the spillway tailwater is unattainable at any reasonable cost in dollars or at acceptable levels of physical damages to migrating salmonids when spill is used, whether voluntary (for fish passage management) or involuntary (due to too much water for the turbines to handle). This presumes that the dams remain in place, without breaching or major drawdown. For example, it appears technically impossible with any device now known to maintain gas saturation values at 110% or below at the levels of involuntary spill experienced in 1996 and 1997. Maintenance of about 120% and below is feasible with devices currently available (deflectors) under most circumstances of controlled spill.

Breaching of the four lower Snake River dams (which would be a major system reconfiguration) would eliminate spill in the lower Snake River and likely make the 110% dissolved gas standard attainable in that reach. This projection should be tempered, however, by our lack of understanding of the natural saturation levels prior to damming. Recent monitoring of the unimpounded reaches upstream of Lower Granite Dam, however, suggest values in an unimpounded lower Snake River would be near air equilibrium. Similarly, a major drawdown of one or more reservoirs during the high-flow season (whether permanent or temporary, partial or full) would eliminate or reduce the factors causing supersaturation at those facilities (high elevation spill into deep plunge basins).

We conclude from this feasibility analysis that attainment of the 110% criterion/standard, *per se*, is thus a *policy* question, not a technical one. The technical questions appropriate for the ISAB relate to possibly defining biologically acceptable conditions in the ecological context of the river-reservoir system and finding engineering designs or system operations to achieve levels of TDGS as low as practicable without inducing more injury to migrating salmonids than would the TDGS. Questions of whether to meet water quality standards through major system reconfiguration must be taken up in another forum.

The ISAB believes the Corps' Gas Abatement Program should continue, although with modified objectives and time scales consistent with attaining gas supersaturation levels as low as practicable below all projects as expeditiously as possible. We do not yet know what a "safe" level is for the mainstem ecosystem, including both anadromous salmonids and other ecosystem components, and we are unlikely to find it out any time soon and without large expenditures for research. But we do know (with a high level of confidence) that the safe level is below 130-140% observed in recent years. We recommend continuation of the Corps' program for three main reasons: (1) reduction in total dissolved gas saturation is needed in high-flow years such as 1996 and 1997 regardless of Endangered Species Act considerations for spill management at other times; (2) some engineering devices have demonstrated effectiveness or high promise for reducing gas saturation to levels that appear biologically acceptable for migrating salmonids in their ecosystem context, and (3) an "as low as practicable" approach is consistent with a philosophy of taking actions that will progressively return the river system toward the "normative" condition, even if not all the way to the desired goal (as recommended by the Independent Scientific Group (ISG) 1996). If additional biological studies are mandated to justify abatement expenditures, they should be limited to a critical few. They may be useful to narrow the large uncertainties in establishing biologically acceptable gas saturation levels above the current water quality standards. Special studies will be needed to define the potentially overarching side effects of physical damages from some gas-abatement devices.

In consideration of potential modifications of the hydropower system, we concur with recommendations by NMFS that abatement be considered in two time frames. First, the near term time frame (<10 years) can include installation of proven technologies such as flow deflectors on spillways that do not now have them. Some other modifications that are relatively inexpensive and effective could also be considered and used. Even if the dams are to be breached or drawn down, breaching or a drawdown schedule will not happen quickly and the benefits of installing gas-abatement measures can be gained rapidly in the interim. If the dams remain, even if operated quite differently than at present, the spillway modifications will be useful for the long term as well. The Corps can, at a slower pace, consider all feasible options for gas abatement in the long term (>10 years). A measured pace of engineering evaluations, possible prototype testing, regulatory approvals for new devices, and system-wide gas reduction efforts using these technologies and judicious system operation can be conducted over the next several years and be aided by periodic peer review.

If taken in two time frames, the Corps' Gas Abatement Program will be applicable and useful for each of the four alternative scenarios for operation of the hydropower system identified by the Council staff for ISAB evaluation (Ruff 1998). These scenarios (and suggested applicability of gas abatement measures) are:

1. *All existing mainstem dams, including dam modifications, remain in place and operational for the foreseeable future*. In this scenario, gas abatement modifications made both in the short term and long term would potentially have a long lifetime at all projects, unless displaced by a better technology. The full gas-generation potential of the hydropower system would be used for planning modifications.

2. *All dams remain in place except that the four lower Snake River projects are breached to provide a natural river condition in the Snake River within the next 5-10 years*. In this scenario, short-term gas-abatement modifications would be applied to all projects on both the Snake and Columbia rivers, with possible exception of the first Snake River dams to be breached. Long-term modifications would not be considered for the Snake River projects but would be tailored to the Columbia River projects. These long-term modifications would take into account the lack of gas generation in the lower Snake River (therefore, the long-term solutions may differ from those in scenario 1).

3. *All dams remain in place except that a lower Columbia River project, such as John Day Dam, is breached or lowered within the next 10 years*. In this scenario, only short-term modifications would be applied to the Columbia River dam. Both short-term and long-term modifications would be applied to all other projects, as warranted. Potential gas re-equilibration in the reach of the current Columbia River dam's reservoir would be considered when long-term gas-abatement modifications are considered for the remaining lower Columbia River dams.

4. *Dams remain in place except that the four lower Snake River projects are breached to provide a natural river condition in the Snake River and John Day Dam is breached or lowered in the Columbia River within the next 5-10 years.* In this scenario, only short-term modifications are applied to the lower Snake River dams and John Day Dam. The earliest Snake River dams to be breached may not warrant any further modification, however. Long-term modifications to the remaining lower Columbia River dams would take into consideration the loss of gas generation in both the lower Snake River and at John Day Dam with potential re-equilibration in the John Day reach.

Conclusion

The Corps' Gas Abatement Program is important for rectifying supersaturation of waters of the Snake and Columbia rivers with dissolved gases by the hydropower system. It should continue, with high-priority. Gas supersaturation is a problem in high-flow years with involuntary spill whether or not spill is used as a management approach for aiding salmon passage in other years. Although attainment of the standard of 110% throughout the hydropower system is unlikely in high flow years with the majority of dams in place, a program of modifications of dams to reduce gas supersaturation to the lowest levels practicable should have benefits to salmon and other components of the ecosystem. The modifications will be useful whether or not selected dams are breached or drawn down if they are viewed in two time frames, short term (<10 years) and long term, and applied in a manner consistent with the system configuration options chosen.

Additional biological studies are not immediately necessary for continuation of the gas abatement program, except for evaluation of potential damages from abatement devices themselves. Studies of depth distribution of biota, of adult responses to dissolved gas supersaturation, and of ecosystem responses would be of especially high priority if attainment of a specific safe level of gas supersaturation in the river (above 110%) is to be justified on biological grounds. However, the ISAB believes that full justification of a specific “safe” saturation value other than 110% on the basis of biological research is not attainable in a reasonable length of time to conserve the dwindling resources and at reasonable cost. The alternative of proceeding with gas abatement to the lowest level practicable at reasonable cost is preferable on biological grounds, although cost considerations inherent in “practicable” are not entirely a technical judgment appropriate for the ISAB.

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