APPENDIX 4.4-IV

BC Hydro. 2014. Total Dissolved Gas Management Strategy. Prepared by BC Hydro Water Program, September 3, 2014

BC HYDRO TOTAL DISSOLVED GAS MANAGEMENT STRATEGY: IMPLEMENTATION PLAN

1. INTRODUCTION

It should be recognized that total dissolved gas supersaturation is very different than other water quality parameters in that it is a relative measure rather than an absolute concentration. Total dissolved gas supersaturation can produce adverse biological effects only when the dissolved amount substantially exceeds that held at equilibrium for the pressure and temperature conditions at the depth of exposure. Unlike other water quality parameters whose effects are determined by dissolved concentration, the effects of total dissolved gas are determined by the amount of dissolved gas relative to the amount the water will hold at equilibrium for the pressure and temperature conditions at the depth of exposure.

When the concentration of gas in the atmosphere is at equilibrium with that dissolved in water at surface pressure, the water is said to be fully or 100% saturated with air. There are conditions however, when the amount of dissolved air in water can exceed equilibrium with the atmosphere. In such cases, the water is said to be supersaturated with air; the higher the amount of dissolved gas in water, the greater the level of supersaturation. Because the amount of dissolved gas in water is related to its pressure[1] (P, mmHg), the level of supersaturation is often reported in terms of the difference in measured total gas pressure (the sum of partial pressures of all dissolved gases) and that expected if the total dissolved gases were at equilibrium (i.e. $P_{Measured} – P_{Equilibrium} = ᑯP$). The ᑯP measure can also be expressed as a percentage where % Saturation is calculated as

$$(ᑯP + \text{Barometric Pressure}) / \text{Barometric Pressure} \times 100 \quad (1)$$

When there is an excess of dissolved gas in in water relative to atmospheric pressure at the water's surface, there is a tendency for that gas to come out of solution at the surface pressure and eventually re-establish equilibrium. Thus air supersaturation is a transitory state; unless there is a source that continuously reintroduces excess gas lost to the atmosphere. The movement of goes out of solution can either be directly to the atmosphere at the air water interface, or when pressures are sufficiently high, in the form of bubbles. In the environment, either path to equilibrium is inconsequential to rearing fauna. In organisms that breathe the supersaturated water however, bubble formation due to elevated gas pressures in their tissues can lead to impaired survival or lead to direct mortality (Weitkamp and Katz 1981). Bubble formation in tissues can cause a variety of symptoms, both internal and external, which have collectively been termed gas bubble disease (GBD).

It is valuable to recognise the role that pressure plays in dissolved gas supersaturation. Because of the role that total pressure plays in determining the amount of air that dissolves in water, dissolved air under hydrostatic pressure is not truly supersaturated for the total atmospheric and hydrostatic pressure it is under an equilibrium depth. Thus, water at 120 % of saturation for surface pressure is actually at equilibrium (100 % of saturation) at a depth of 2 m (Figure 1) from the adverse effects of supersaturation when they are at an equilibrium or greater depth.

[1] This stems from Henry's Law which states that the pressure of a gas in solution is directly proportional to its concentration

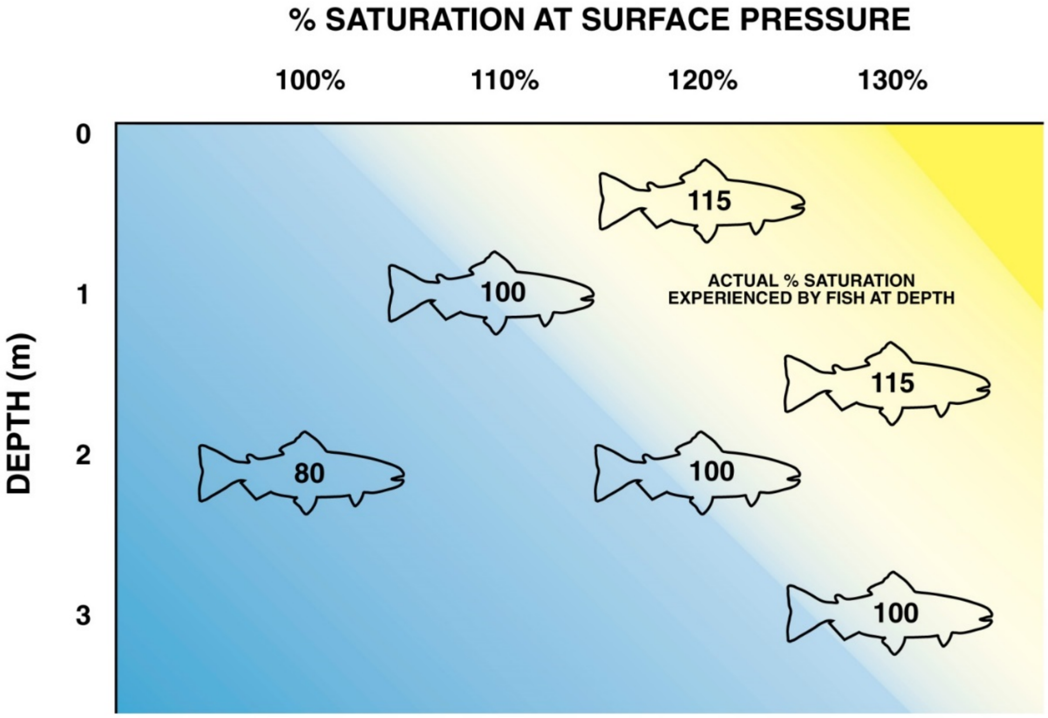

Figure 1. Reported Total Dissolved Gas Supersaturation vs Levels Actually Experience by Fish at Depth.

Because of the substantial increase of pressure with increases in depth, together with the increased solubility of air with increased pressure there is a considerable difference between most natural river situations and laboratory conditions. In laboratory conditions the fish are commonly confined to very shallow depths where there is a strong tendency for the supersaturated gases to come out of solution, while in river conditions most fish spend much or all of their time at depths with pressures that retain the gases in solution.

Laboratory studies have shown that fish and other aquatic organisms have limited capability of tolerating air supersaturated waters (Fidler and Miller 1997) when they are confined to shallow water, generally not exceeding 1 m deep. A meta-analysis of these studies found that cases of gas bubble disease only occurred when total dissolved gas (TDG) levels exceeded 110% saturation in these shallow conditions. This formed the basis for the present provincial and federal water quality guideline establishing safe limits of total dissolved gas in water. The guideline however, does not take into account water depth, duration exposure, or gas composition (i.e., air supersaturation compared to other ratios of atmospheric gases), all of which can have a profound effect of an organism's susceptibility to gas bubble disease. The guideline therefore is highly conservative.

Although most of BC Hydro's operations have little to no impact on the supersaturated state of their tail waters, there are instances where significant changes can occur. In some cases, the change can exceed the present guideline, often by a significant amount. However, not all instances have led to observable impacts. Furthermore, there is a paucity of information regarding the potential for creating high TDG events at many of BC Hydro's facilities. As a result, there is considerable uncertainty regarding TDG issues related to BC Hydro operations and the potential for harm in receiving waters. This document presents a TDG management strategy designed to systematically address these uncertainties and identify specific management actions to address the potential for harm to downstream fish.

2. Purpose of the TDG Management Strategy

BC Hydro has within its organisation several processes that can be used to address TDG issues. The first and simplest is to do nothing when studies show that no issue exists. In other instances, it may be that a change in operation, such as a preferred sequence of gate use for spills, can be used to avoid or minimize the generation of high TDG waters. Such constraints can be added to a facility's Generating Operating Order (GOO), a document that describes all of the constraints and limits associated with a given facility. A third option may be to recommend a physical works project, provided there is a strong business case to carry out the work. Finally, it is possible that neither operational changes nor cost effective physical works are possible. In such cases, a Fisheries Act Authorization can be sought that authorises a TDG-generating operation recognising that harmful effects are unavoidable.

The decision on which management action is best suited to address a high TDG issue requires the following elements of information:

a) Does air supersaturation occur at the facility?
b) If so, under what conditions does it occur?
c) How frequent do those conditions arise?
d) When it does occur, what is the magnitude and duration of the event?
e) Does the magnitude and duration of the event exceed the threshold for biological harm within the downstream conditions?
f) How frequent do potentially harmful events occur, and is there sufficient time for recovery between events?

Critical to the decision making process is how the threshold of TDG exposure is defined. The present provincial and federal water quality guidelines can be a suitable starting point. However, several *in situ* studies (Weitkamp 2007), along with anecdotal observations at BC Hydro facilities, has shown that these may be too conservative, potentially resulting in costly mitigation when none is required. A component of the strategy is to define alternative management thresholds that are less conservative than the present water quality guidelines. Meta-analysis of existing data suggests that this can be achieved by incorporating variables such as duration of exposure, water depth, and gas composition when setting these thresholds.

The purpose of the TDG management strategy is to combine the decision questions, thresholds and outcomes into a systematic approach addressing high TDG at all of BC Hydro's facilities regardless of the potential TDG source. The strategy is summarised in Figure 2, which describes how the results of a given TDG study can be used to decide an appropriate management action, which can include a continuation of monitoring.

The sections that follow provides a brief description of TDG at BC Hydro facilities and the various mechanisms by which it can arise, a description of exposure limits that are used in building the TDG management thresholds, a layout of the strategy and how it can be used, the roles and responsibilities for regulators and finally, a prioritized list of BC Hydro Facilities.

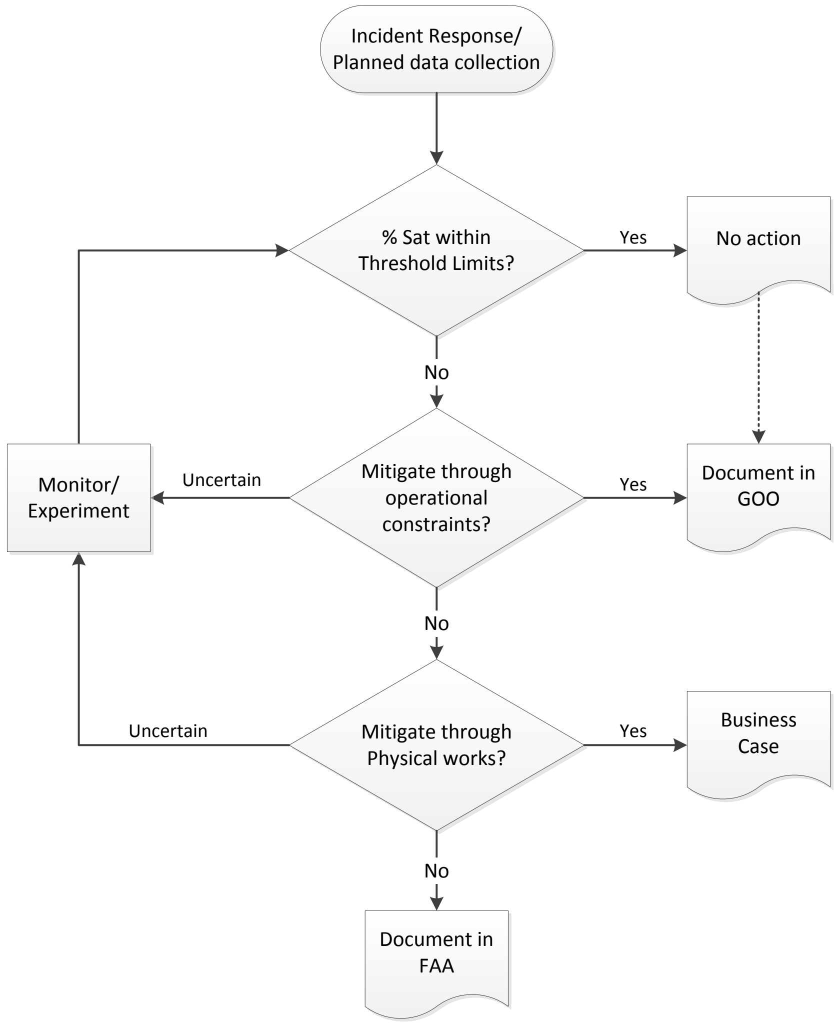

Figure 2. BC Hydro TDG strategy showing how TDG data are used to guide management decisions, including further monitoring should assessment outcomes remain uncertain.

3. Conditions for Elevated TDG Levels at BC Hydro Facilities

There are a number of factors that determine the extent of gas supersaturation when it does occur, regardless of the setting. The first of these is that there must be a pressure gradient between the gas and liquid. It is this pressure gradient that forces gas to dissolve into solution; the higher the pressure difference, the faster the rate of movement into solution and the greater the gas concentration in the liquid. The movement of gas into liquid continues until there is no longer a pressure difference, i.e. the pressure of the gas is equal to the pressure of dissolved gas in the liquid. This pressure response is independent of gas composition, but at BC Hydro facilities the gas of concern is exclusively air with a normal ratio of its constituent gases.

Pressure gradients can occur in many different ways. The most common is when air bubbles are forced deep into the water column. As these bubbles travel down the water column, the increasing hydrostatic pressure causes them to compress in size, and in turn increase in their internal pressure[2]. This pressure forces air to dissolve from each bubble into the surrounding water. It is through this mechanism that air supersaturation occurs at waterfalls and in the case of BC Hydro facilities, spillways. The extent of supersaturation depends on a number of factors. The most obvious is the depth of the plunge pool together with the hydraulic dynamics of the tailrace. Without depth and hydraulic forces that maintain bubbles at depth for some time, the bubbles do not experience sufficiently high hydrostatic pressures for long enough time to produce significant movement of gas into water. If fact, the opposite can occur where gas moves out of water and into bubbles (and ultimately to the atmosphere) if the water is already supersaturated. The height at which water falls is also a key determinant where greater heights lead to higher potential for bubbles plunging to depth. The surface area of gas to water interface also plays an important role. As the density of bubbles increase, the area over which gas exchange can occur between air and water increases. Finally, time plays a role as well. The longer that hydraulic forces keep bubbles at depth, the more time there is for this gas exchange to occur. Because so many factors are involved, it is difficult to determine the potential for supersaturated water at a given site without collecting empirical data.

In addition to spillway releases, there are three other means by which air supersaturated waters can be created at BC Hydro facilities. The first of these is by entrainment of air at penstock intake structures. This occurs when reservoir elevation at the dam forebay is below a critical level, allowing water to create a vortex at the intake entrance which in turn provides an avenue for air bubbles to enter the penstock. While in the penstock and turbine, these bubbles can experience very high hydrostatic pressures, causing the bubbles to collapse is size and air to dissolve into the surrounding water. Air entrainment can also occur at the turbine through valves located on the scroll case. These valves are used to relieve negative water pressures that can occur in the draft tube during periods of low generation, especially when the tailrace elevation is lower than the turbine wicket gates. Again, these bubbles can experience high hydrostatic pressures as they pass through the draft tube, causing air to dissolve into water. Lastly, air supersaturation can occur when compressed air is injected to the turbine scroll case to force water out of the draft tube and with the wicket gates closed, allow the turbine blades to rotate freely. This is sometimes done to allow for rapid start/stop capability, or in other cases to use the turbine as a motor and draw power to stabilise line voltages. Though the injection of air does not create bubbles as in the previous two scenarios, the pressures involved are very high. As well, water that leaks through the wicket gates can get whipped up into thin films or droplets, which creates a large surface area for gas exchange similar to the formation of bubbles. However, air injection into the scroll case produces only a brief slug of supersaturated water that is rapidly diluted as it moves downstream.

In all three cases, the level of air supersaturation created can be very high. It is important to note however that the occurrence of these conditions is relatively uncommon. Air entrainment either though vortexing at the intakes or for the purposes of relieving negative draft tube pressures typically interferes with optimal turbine performance. As a result, operational constraints, such as lower limits to reservoir drafting, are often in place to prevent this from occurring. Air injection is also rare, and is limited to a few units. Regardless, the impact to downstream fish populations can be significant when these conditions do arise [e.g., at Mica Dam 1996 and 1997 (BC Hydro, unpublished data) and Ruskin Dam, February 2007 (BC Hydro 2007)].

Air supersaturation can also occur by sudden changes in water temperature. This is typically not an issue related to BC hydro operations. However, it can occur naturally in reservoirs (and lakes) as a thermocline builds in early summer. As water temperatures rise, the solubility of dissolved gas in water decreases. Because the rate of gas diffusion in water is slow, the excess gas gets 'trapped' in the water column, creating a supersaturated state. In most instances however, the mechanism rarely causes TDG supersaturation exceed 110 %. Though not related

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[2] This is referred to as Boyles Law

to BC Hydro operations, and rarely harmful to fish, the presence of temperature induced supersaturated water can impact the potential for diluting downstream sources of more supersaturated waters.

4. Consequences of Exposure to Elevated TDG Levels

4.1. Gas Bubble Physiology

The total dissolved gas pressure in an organisms body will always tend toward equilibrium with that of the ambient environment. The direction and rate of movement of gas is determined by the pressure differential between the two areas together with the permeability of the membrane separating the two. Gas always moves from an area of high pressure to low pressure with a rate that is proportional to the pressure difference; the high the difference that faster the movement of gas. Thus gas exchange (in addition to respiration) can occur in either direction into or out of the body depending on whether total gas pressures in the body are greater on less than in the ambient environment. The primary areas of gas exchange in most aquatic organisms are the gills. Fish skin is relatively impermeable resulting in the formation of bubbles under the skin as a primary sign of gas bubble disease. In some fish, gas exchange can occur in the swim bladder as well, which may or may not be attached to the esophagus by a pneumatic duct. In more primitive animals, gas exchange can be through the skin. Regardless of the pathway, the movement of gas also ways goes from high to low pressures.

Once in the body, elevated dissolved gas levels typically do not cause harm by way of chemical toxicity, unless extreme levels are experienced or exotic (reactive) gases are introduced. For example, fish are able to tolerate oxygen supersaturation levels in excess of 150% or so, but much above that the body's ability to regulate its acid-base balance begins to break down. Excess dissolved carbon dioxide can interfere with respiration such that fish become anesthetized. The present discussion and proposed management thresholds do not address these types of exposure conditions. It is focused solely on the issue of air supersaturation where gas ratios do not depart significantly from normal atmospheric conditions.

Rather than be chemically toxic, the impact of air supersaturation is more related to the potential for air bubble formation that can in turn cause physical harm to the body by interfering with tissue function (e.g., gas gland function used to manage buoyancy) or by creating circulatory system blockages (i.e., causing tissue asphyxiation). The formation of such gas bubbles requires two key conditions, 1) the presence of bubble nucleation sites and 2) a sufficiently high internal gas pressure to overcome the sum of all ambient pressures that would prevent gas from coming out of solution.

Bubble nucleation sites can be viewed as microscopic voids into which dissolved gas can migrate and come out of solution. In the body, such nucleation sites may take on two forms. The first of these is at the tissue-fluid interface where there are surface imperfections so small that it prevents occupation by the surrounding fluid at the microscopic level. A simple example of such sites can be found when a glass of cold water is allowed to warm up to room temperature. As the water warms, the solubility of dissolved gases drops creating a slight super saturated state. The excess gas comes out of solution in the form of bubbles that line the glass-water interface. The location of each bubble marks the site of a nucleation site; a microscopic void that provides a space for gas to come out of solution. The other type of nucleation site is called a micelle, clusters of lipid molecules that have their hydrophobic tails oriented towards its center, effectively crowding out fluid and creating a void. These are believed to be common in the body and can also be created by prior exposure to high dissolved gas pressures that lead to micro-bubble formation. In the latter case, it is believed that when these micro-bubbles form, a variety of hydrophobic molecules attach to their surface, preventing collapse their when the gases are forced back into solution. The formation of nucleation sites through micelle development is believed to explain the long term residual effects of air supersaturation exposure, and hence why fish previously exposed to supersaturated air tend to be more susceptible to gas bubble disease. This susceptibility can persist for weeks after exposure, well after all excess gas has left the body. Finally, it should be noted that bubble formation in the absence of nucleation sites is also possible, but typically requires dissolved gas pressures that are several times greater than atmospheric pressure rather than the fractions (less than 150% saturation) considered here.

The other condition necessary for bubble formation is the need for dissolved gas pressure in body tissues to exceed the sum of all ambient pressures. Dissolved gas pressures within body tissues are not necessarily the same as ambient conditions. The reason for this is due to respiration. Oxygen that enters the body gets consumed, the by-product being carbon dioxide which is many times more soluble and therefore exerts a much lower partial pressure. The effect is a reduction in total gas pressure within the body compared to the ambient environment, which has been termed inherent unsaturation. Because of the oxygen dissociation dynamics of hemoglobin, the effect becomes more pronounced as the level of dissolved oxygen increases. This occurs because plasma dissolved oxygen plays a greater role in meeting metabolic needs than that carried by red blood cells, which tend to remain bound to the hemoglobin molecule. Also a factor is the presence of body fat which can absorb roughly 5 times more dissolved gas than aqueous solutions. This 'sink' for dissolved gas however, only slows the time it takes for the body to reach equilibrium with ambient gas pressures. Given enough time, fish with high body fat content will experience the same internal gas pressures as those with little body fat. Over all, inherent unsaturation provides a physiological explanation for the inherent tolerance of fish to moderate levels of air supersaturation, especially that between 115% and 120% saturation levels when access to deep waters are limited. The role of body fat is important as well, as it has implications on the duration of acceptable exposure (or in turn the time delay between repeated exposure regimes), though this factor has not yet been fully investigated in fish.

Ambient pressures that act against bubble formation are varied. The most dominant factor in aquatic organisms is hydrostatic pressure. In general, water 1 m in depth exerts roughly 0.1 atmospheres of pressure. Fish at 1 m depth that is 120% air supersaturated would experience an effective dissolved gas pressure equivalent to 110% supersaturation. Each additional meter of depth reduces effective gas pressure by a corresponding 0.1 atmospheres or 10% saturation. Continuing with the example above, the 120% air super saturated fish would be experiencing the equivalent of 100% saturation at 2 m depth. The water depth effect is often referred to as depth compensation. Other factors that may play a role in preventing bubble formation include bubble surface tension, the pressures exerted by surrounding tissues, including contracting muscle, as well as blood pressure. The latter is particular significant as atrial blood leaving the heart can be 0.05 atmospheres greater than the venous blood returning to the heart. This pressure difference is likely the reason why bubble formation and hence most symptoms of gas bubble disease typically occur in peripheral tissues. Once formed, they can travel through the circulatory system where they can eventually block capillary networks feeding critical body tissues, potentially leading to direct mortality.

4.2. Gas Bubble Disease

Gas bubble disease, as the name would suggest, refers to a condition where bubbles form in body tissues that may be fixed at a given location and lead to physical damage or mobile in the circulatory system and lead to circulatory blockages (embolisms). The former is generally associated with obvious external symptoms such a bubble formation between fin rays, along the lateral line, under the skin, in the buccal cavity or behind the eye. The presence of such symptoms are not necessarily a good predictor of mortality, though over time they could interfere with foraging success, predator avoid and in some fishes buoyance control. These indirect causes of mortality are in contrast to when bubbles form in the circulatory system, where they can be mobile until lodged at the juncture of capillary networks. In this case, blood flow can be impaired, starving the tissue of oxygen and allowing the build-up of metabolic waste. In critical tissues such at the brain, heart and respiratory system, mortality can occur quickly. It is important to note that the presence of circulatory system bubbles in not always accompanied by external symptoms of gas bubble disease. Thus external symptoms of gas bubble disease certainly indicate the potential for direct mortality, but some are able to survive for extended periods, while others succumb without the presence of any external symptoms at all.

These symptoms disappear rapidly if brought to depth. The hydrostatic pressure will collapse the bubbles and force the gas back into solution. Circulation is restored and damaged tissues can begin to heal. However, the high dissolved gas pressures will remain in the body unless ambient dissolved gas pressures are reduced. Thus fish returning to the surface will have their symptoms reappear. True recovery cannot occur until ambient conditions return to normal saturation levels, allowing the body to purge itself of excess dissolved gas, regardless of water depth.

4.3. Swim Bladder Over-inflation

Swim bladder over inflation is a condition that can arise from air super saturation of tissues, but one that does not involve bubble formation (Shrimpton et al 1990). It occurs in fish with swim bladders that may or may not be connected to the esophagus by a pneumatic duct. Swim bladders typically have gas glands that help control its internal gas pressure and hence volume. With higher dissolved gas levels, this pressure control begins to wane, and eventually is overwhelmed by the influx of dissolved gas. In fish without a pneumatic duct, bladder pressure and volume increase until it is opposed by the combined effects of surface tension, the elasticity of surrounding tissues and hydrostatic pressures. In such cases, buoyance control is lost and fish require constant movement to remain in position. If opposing forces are insufficient, the gas bladder can rupture also causing a loss of buoyance control. Fish with pneumatic ducts however, such as trout and salmon, are not as susceptible to this condition as excess gas pressures can be released through the duct and into the environment via the esophagus. The only exception is when these fish are small (typically less than 50 mm in length). The duct diameter is so small that high pressures are required for gas to pass through, pressures that the body wall cannot contain and in turn causes the swim bladder to over inflate and potentially rupture. As these fish get older, larger duct diameters and better sphincter control prevent this from occurring.

Swim bladder over inflation or rupture does not necessarily lead to immediate mortality. It is certainly indicative of high internal dissolved gas pressures which may independently lead to embolisms elsewhere in the body. However it is not necessarily an immediate cause of death. Over time however, death can occur indirectly through lower foraging success, and poorer predator avoidance capability. Exhaustion may also be an issue since these fish now must continually swim to maintain position. Though swim bladder over inflation may be recoverable when returned to normal dissolved gas pressures, ruptures may not be.

5. BC Hydro TDG Thresholds for Decision Making

A number of literature reviews have been carried out over the years summarising the effects of high total dissolved gas levels on fish. The first such review was carried out by Weitkamp and Katz (1980), which was then followed by those of Jensen et al. 1986, Fidler and Miller (1997a) and finally Weitkamp (2008). More recently, Weitkamp (2013) compiled a brief summary of literature addressing TDG supersaturation topics relevant to TDG regulation. The general theme found within of all reviews was that the GBD generally increased with total gas pressure, but that the response tended to be highly variable. Water depth was found to be a major mitigating factor. Gas composition, duration of exposure, between species differences and life stage differences were also identified as potential factors. Also, there was a tendency for fish in the field to be more resilient to high TDG exposure than fish of similar species in the laboratory, which was believed to be the result of having greater available depths.

Combining these varied outcomes into a comprehensive water quality guideline proved problematic. In the end, the solution developed for Canadian waters was to use the lowest levels of gas supersaturation that lead to at least some mortality as a conservative guideline that could be applied regardless of the circumstance (Fidler and Miller 1997a). The guideline based on this definition was found to be 110% gas supersaturation, a level of exposure that resulted in little to no mortality regardless of water depth, gas composition, duration of exposure, fish species, and life stage. At BC hydro facilities however, many of these mitigating factors are known and can be incorporated to better resolve threshold levels of gas supersaturation that are less restrictive to facility operations, yet still create little to no harm to downstream fish populations. The purpose of the BC Hydro TDG strategy is to incorporate this knowledge in developing realistic TGD thresholds that reflect prevailing environmental and operations conditions and implementing meaningful and cost-effective corrective management actions when necessary.

5.1. Mitigating Factors

Gas Composition

All incidents of gas supersaturation at BC Hydro and other hydroelectric facilities exclusively involve air at atmospheric ratios. At present, there are no known processes or mechanisms used at BC hydro facilities that would create gas supersaturation conditions involving or favouring a single gas over others (e.g., oxygen, nitrogen or carbon dioxide/monoxide supersaturation). As a result, all meta-analysis used to derive management thresholds exclude studies that involve gas ration that differ significantly from normal atmospheric conditions.

Water Depth (Hydrostatic Pressure)

The concept of depth compensation has been well established: every 1 m of water depth creates a hydrostatic pressure of roughly 0.1 atmospheres that acts to hinder bubble formation in tissues. Thus fish in 120% supersaturated waters, but at 2 m of water depth, would never experience bubble formation in their tissues, even though these tissues become supersaturated over time. It would be equivalent to being in 100% saturated waters. If fish rise to the surface however, the effect of hydrostatic pressure is lost and bubbles will begin to form and create gas bubble disease. A number of investigations (Weitkamp 1976, Dawley 1986. Antcliffe et al. 2002, Beemean et al. 2003) have shown that access to water depth is sufficient to slow or minimize bubble formation as normal swimming behaviours associated with predator avoidance or foraging would bring fish periodically to depth; the longer the time at depth, the less the likelihood of gas bubble disease. Thus a key factor is whether water depth is constrained downstream of the source of supersaturated waters.

In situ studies (Weitkamp 2008, 2013), have shown that mortalities are rare in riverine conditions where depths of several meters or more are available. As well, the hydrostatic pressure on fry in waters deeper than 0.5 m have been found to be sufficient to prevent over expansion of the swim bladder. (Shrimpton et al. 1990)

Exposure Duration

The movement of dissolved gas from the ambient environment to fish tissues is largely a function of the pressure difference between the two bodies. Thus time to a given level of tissue supersaturation, say 115%, will take longer at 120% compared to 130% ambient supersaturation. Time to mortality therefore follows the same principle and has been shown to approximate an exponential relationship. There are key modifying factors however. One of these is fat content. Dissolved gases tend to be roughly 5 times more soluble in fatty tissues than non-fatty tissues. Fish with more fatty tissue will require more time to fully saturate than lean fish. Factors that impact metabolic rate, and hence the inherent unsaturation effect, may also be at play, but these have not been well investigated (e.g., active vs. sedentary fish or the effect of swim bladder regulation).

Life Stage

Embryos have been shown to be largely resistant to TDG levels exceeding 120 % (Weitkamp 1976, Weitkamp 2008, Alderdice and Jensen 1985). However, hatched alevins are less resistant to gas bubble disease (Weitkamp and Katz 1980, Weitkamp 2008), and that resistance continues to wane as they approach the button up stage (Bruce and Greenbank, unpublished data, Bruce 2012). As well, salmonid fry less than 50 mm in size tend to be prone to swim bladder over inflation if in shallow waters. Once fish are greater than 50 mm in length, the signs of gas bubble disease and the likelihood of mortality are no longer size dependent, though there can be between species differences (Fidler and Miller 1997).

5.2. Threshold Levels

The threshold levels presented below come from a meta-analysis of data collated from published studies prepared by Fidler and Miller (1997b). The meta-analysis only considered those studies that involved air supersaturation; where the ratio of gases did not depart significantly from normal atmospheric conditions. Excluded from the analysis were studies on fish eggs, as well as those on alevins, since both life stages showed considerable tolerance to high dissolve gas pressures. It is important to note that these thresholds are based primarily on studies of fish constrained to shallow water in a laboratory setting, though a few deep tank and open water studies were included as well. A more detailed description of this meta-analysis can be found in Bruce (2012). Results of this meta-analysis identified three supersaturation thresholds useful for decision making:

Up to 110% - This is the present Provincial and Federal water quality guideline and is to be used when gas composition is unknown (i.e., air supersaturation can be ruled out), regardless of exposure conditions (e.g., access to water depth or exposure duration). Below this threshold, no mortality is expected regardless of gas composition or exposure conditions. This will be referred to as the "**uncertainty threshold**"

Up to 115% - This threshold is to be used when elevated TDG is the result of air supersaturation and exposure duration is long term. Studies show that fish with access to waters deeper than 0.5 m in depth can survive levels of air supersaturation up to this limit indefinitely. In waters shallower than 0.5 m however, exposure duration is limited 20 days, after which mortality can occur. The mechanism for this extended tolerance in shallow water fish is uncertain. It may be linked to sub-lethal effects, including swim bladder over inflation, which leads may contribute to lower tolerance to other factors such as poor feeding success or exhaustion. Fish with access to deeper waters are likely able to take advantage of periodic exposure to higher hydrostatic pressures that minimise/prevent bubble formation or swim bladder over-inflation. Several studies show that fish with sub-lethal gas bubble disease can quickly recover when exposed to normal air saturation levels (Weitkamp 2008). This will be referred to as the "**chronic air supersaturation threshold**". Because sub-lethal effects are likely to lead to indirect mortality sooner in the field than a laboratory setting, the duration threshold for impact was reduced to 10 days. Validity of this threshold for shallow water habitats will be assessed through monitoring and will be shortened or lengthened accordingly.

Up to 120% - This threshold is to be used when elevated TDG is the result of air supersaturation and exposure duration is short term. Studies show that fish with access to waters deeper than 1 m in depth can survive levels of air supersaturation up to this limit for at least 2 days. Beyond this duration, or for fish that are in waters less than 1 m in depth, mortality can occur at these levels. Because mortality can occur quickly, this threshold will be referred to as the "**acute air supersaturation threshold**".

Total dissolved gas pressures that exceed these thresholds can potentially lead to mortality, but not necessarily so. Real world conditions generally result in TDG supersaturation occurring where substantial depths are available (>3 m). Most fish in these natural conditions maintain a depth distribution that avoids or minimizes the biological effects of TDG supersaturation. Numerous investigations and monitoring of fish where TDG levels exceed 120 % have repeatedly demonstrated low incidence and minor severity of GBD in migrating and resident fish populations. Fish in 3 m or more of water are not actually exposed to supersaturation and can tolerate these conditions indefinitely without developing GBD. Another example is the case where fish are repeatedly exposed to high total gas pressures, but for only short durations at a time. As a result, the thresholds given here should be considered a starting point with respect to carrying out risk assessments. With the strategy, it is possible that these thresholds can be shifted to encompass higher TDG levels, but this must be supported by empirical evidence gathered through monitoring/research activity.

5.3. Monitoring Effort

Anytime either the chronic or acute guidelines are exceeded, a monitoring program should be carried out to determine the level of risk this exceedence has created. Three levels of monitoring/sampling intensity have been identified, each building on the other.

Low Effort Monitoring

This level of monitoring consists largely of visual habitat assessments with a focus on locating/identifying dead or floating fish in shallow water habitats. It is generally associated with exceedence of the chronic air supersaturation threshold and should be directed towards shallow water habitats where impacts are most likely to occur. It should be carried out during the dissolved gas event at the time of threshold exceedence, or soon after. Gas bubble disease symptoms can disappear quickly, so a delay in implementing the monitor could lead to misleading conclusions (i.e., conclude no effect when in fact there were effects).

Visual assessments should also be accompanied with total gas pressure measurements taken at various locations, including spot measurements within the hyporheic zone where incubating alevins and overwintering fry may be residing. These hyporheic measurements can be taken by a probe driven into gravel/cobble substrate and should accompanied by surface water measurements immediately above to act as a reference. This data will help determine whether hyporheic rearing conditions differ significantly from surface waters.

Some fish sampling by seine net or minnow trap is also recommended, but not essential. This will help determine if fish are experiencing gas bubble disease symptoms that are potentially lethal. Should fish with symptoms of gas bubble disease be encountered, whether dead or alive, sampling effort should be increased to that required of an impact assessment.

Intensive Effort Monitoring/Study

Intensive effort monitoring will include the same data requirements as the low effort sampling described above, but with mandatory fish sampling in shallow habitats less than 1.0 m in depth. In deeper open waters, sampling should include data that can be used to determine the depth distribution, including diel vertical or inshore/offshore movements. This will inform the survey on whether fish in open waters spend sufficient time in the shallows to create a concern for gas bubble disease. It should be noted that collection of such fish depth distribution information is a key recommendation developed by Fidler (2003) for assessing the potential risk of an air supersaturation event above guideline values.

As above, should fish with symptoms of gas bubble disease be encountered, whether dead or alive, sampling effort should be increased to that required of an impact assessment.

Impact Assessment

Impact assessments are to be carried out whenever fish with symptoms of gas bubble disease, whether dead or alive, are encountered. Such impact assessments should include the type of information gathered in the low and intensive effort monitors, along with other data needed to be able to quantify the impact. This can include laboratory or in situ studies designed to determine time to mortality data for a given exposure regime or species, along with studies that attempt to quantify fish densities and relative vulnerabilities to air supersaturation exposure. The methodology used will vary depending on the circumstance and availability of existing data. Thus impact assessments will always begin with a collation of existing information followed by a detailed experimental design. It should be noted that cases where a high TDG event is associated with fish mortality, the Compliance Protocol will be used to coordinate the development of TDG corrective action plan, which can include funding for studies that would help expedite strategy implementation and completion at the impacted facility.

5.4. Agency Notification

Both Provincial and Federal agencies will be notified when the proposed management thresholds have been exceeded, which will include local/area fish/habitat biologists. Reporting will include information on prevailing air supersaturation levels, the duration of exposure, and the level of monitoring effort being carried out. This notification will initiate a dialog between agencies and BC Hydro. Additional notifications such a regular reporting of supersaturation levels, study results or consultation on possible corrective actions will be at the request of the agency.

5.5. TDG Threshold Summary

The TDG management thresholds and associated actions are summarized in Table 1. With the collection of appropriate data, the table can be used to quickly determine whether management thresholds have been exceeded which include the modifying effects of water depth and exposure duration. It allows one to quickly assess the need for additional monitoring/study and helps determine the need for agency notification.

Table 1. Summary of TDG management thresholds, modifying factors, corresponding mitigation response, and need for agency notification.

TDG Measurement	Downstream Water Depth	Exposure Duration	Response	Agency Notification
TDG < 110% [1]	Any	Any	None	
110%< TDG <115%	> 0.5 m	Any	None	
	≤ 0.5 m	≤ 10 days	None	
	≤ 0.5 m	> 10 days	Low Effort Monitoring	Yes
115%< TDG <120%	> 1.0 m	≤ 2 days	None	
	> 1.0 m	> 2 days	Low Effort Monitoring	Yes
	≤ 1.0 m	Any	High Effort Monitoring	Yes
TDG > 120%	> 1.0 m	Any	High Effort Monitoring	Yes
	≤ 1.0m	Any	Impact Assessment	Yes

[1] threshold when gas ratios are significantly different from normal atmosheric conditions or are unknown

6. Management Decisions

As introduced in Figure 1 above, there are five possible outcomes from implementing TDG management strategy. These are 1) uncertainty still exists and more study is required, 2) no further action is required, 3) document operations changes to mitigate TDG occurrence, 4) document the need to develop a business case for a physical works structure, or 5) identify that cost effect mitigation is not possible and that a Fisheries Act Authorization is to be sought. Central in determining which action to take is an evaluation of whether TDG measurements exceed the thresholds described in Table 1 and whether the data at hand is sufficient to make a decision with certainty. This includes the results of any monitoring that is associated with the threshold exceedences.

The simplest case is where all TDG measurements are below threshold values and sufficient data exist that one can conclude this applies to the full range of facilities operations. In this case, no further action is required except to note in the Generating Operating Order at the facility in question that this is the case. This would provide a permanent record of the outcome and identify that further TDG studies are unnecessary. If the data are insufficient or apply to a limited range of facility operations, the critical data gaps can be identified in the GOO so that pertinent data can be collected in the future.

When TDG measurements exceed the thresholds in Table 1, several outcomes are possible. These depend on whether feasible operational changes or cost-effective physical works can be implemented to help mitigate the frequency, duration or magnitude of potential high TDG events. Both mitigation options require robust data that demonstrate feasibility. This will include the results of all past monitoring, but may also require additional study that is not necessarily captured in the monitoring work (e.g., trial spills, TDG fate modelling, or specific dose response experiments). The need for such additional work will be determined on a case by case basis by BC Hydro, but can include input from Provincial and Federal regulators. The need for additional monitoring or additional study is captured in the strategy as a feedback loop to TDG management threshold exceedence assessment. When feasible operational prescriptions are developed, these will be documented in the GOO for future reference. Potential physical works deemed feasible will be considered on a business case basis, requiring a formal triple bottom line proposal for consideration.

In some instances, it is likely that neither operational change nor physical works would be practical in mitigating TDG events. In such cases, a FAA with be sought recognising this limitation, and thus authorizes BC Hydro to operate despite the risk of downstream harm.

7. Provincial and Federal Regulator Roles

Provincial and Federal regulators have several roles to play in the implementation of BC Hydro's TDG management strategy. The first of these is a general oversight function where strategy implementation is reviewed on a regular basis to determine its overall success in helping direct management decisions and actions that adequately reduces the impact of elevated TDG to the environment. This includes a review of thresholds, mitigating factors and levels of monitoring effort, as well as procedures for agency notification and the outcomes of management decisions that were taken. The goal of this review is to ensure agency awareness of decisions being made as well as provide opportunities to refine or streamline the strategy as required. This oversight process can occur at agency discretion, but for planning purposes is assumed occur twice per year.

The second area of involvement is in the review, revision and acceptance of any Fisheries Act Authorization amendments that may arise from strategy implementation. This will include a technical review of the empirical data/studies that may have led to proposals involving TDG levels greater than those presented in the strategy.

8. PRIORITY LISTING OF BC HYDRO FACILITIES

Strategy implementation is to be done largely on an opportunistic basis or in direct response to known air supersaturation concerns. Presently, there are 13 assessments underway that are in different stages of completion (Table 2). These are all driven as a result of Water Use Plan monitoring, capital project implementation, or Generation initiatives linked to spill. Completion of these assessments will be the first priority of strategy implantation moving forward. There are another 9 facilities where the potential for air supersaturation issues has been identified in the past, but data collection work has not yet been formally initialed (Table 2). These form a second priority group where opportunities for data collection will be actively sought. The remaining facilities are considered third priority, where the potential for high air supersaturation is believed to be low, but requires confirmation through empirical assessment. These assessments will be initiated as opportunities arise.

An assessment will be considered complete when all relevant data have been collated into a data base, an analysis has been carried out to assess downstream risk, a technical memo or report has been completed to document these results, and a TDG management decision has been taken.

Table 2. Priority listing of BC Hydro facilities as it pertains to TDG strategy implementation, recognising the opportunistic nature of the delivery plan.

Facility	Presently identified as having a TDG Issue[1]	WUP, Capital Project or Generation related studies underway	Priority	Comment
Duncan	✓	✓	1	Complete assessments currently underway
GM Shrum	✓	✓	1	
Hugh Keenleyside	✓	✓	1	
Kootenay Canal	✓	✓	1	
Ladore	✓	✓	1	
John Hart	✓	✓	1	
Mica	✓	✓	1	
Peace Canyon	✓	✓	1	
Revelstoke	✓	✓	1	
Ruskin	✓	✓	1	
Seven Mile	✓	✓	1	
Stave Falls	✓	✓	1	
Waneta	✓	✓	1	
Bridge No.1	✓		2	Actively seek opportunities to initiate assessments
Bridge No.2	✓		2	
Elko	✓		2	
Lajoie	✓		2	
Quinsam Diversion	✓		2	
Seton Diversion	✓		2	
Spillamachine	✓		2	
Strathcona	✓		2	
Terzaghi	✓		2	
Aberfeldie			3	Initiate assessments as opportunities arise
Alouette			3	
Ash			3	
Burrard			3	
Cheakamus			3	
Clowhom			3	
Coquitlam			3	
Falls River			3	
Jordan			3	
Puntledge			3	
Shuswap			3	
Walter Hardman			3	
Whaleach			3	
Whatshan			3	

[1] As identified by Schmidt et al. (2001)

9. References

Alderdice, D.F. and J.O.T. Jensen. 1985. An explanation for the high resistance of incubating salmonid eggs to atmospheric gas supersaturation of water. Aquaculture 49: 85-88.

Antcliffe, B.L., L.E. Fidler, and I.K. Birtwell. 2002. Effect of dissolved gas super saturation on the survival and condition of juvenile rainbow trout (*Oncorhynchus mykiss*) under static and dynamic exposure scenarios. Canadian Technical Report of Fisheries and Aquatuc Sciences 2370. 70 p.

BC Hydro. 2007. Assessment of high TGP impacts below Ruskin Dam: February 2007. Report No. E568. 31 p. + App.

Beeman, J. W., D. A. Venditti, R. G. Morris, B. J. Adams, and A. G. Maule. 2003 a. Chapter I: Depths and hydrostatic compensation of farmed fish and wild fish in Rufus Woods Lake. Pages 2-47 in, Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T.C. Robinson, and A. G. Maule. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington. http://wfrc.usgs.gov/pubs/reportpdf/usgsfrgbdgrandcouleedam.pdf#page=8

Bruce, JA. 2012. Site-Specific Total Dissolved Gas (TDG) Management Plan: Stave Falls and Ruskin Facilities. Prepared by BC Hydro Environmental Risk Management, May 2012. Burnaby BC. 63 p.

Dawley, E.M. 1986. Effect of 1985-86 levels of dissolved gas on salmonids in the Columbia River. Report DACW57-85-F-0623 by National Marine Fisheries Service, Seattle, Washington. 31 p. http://www.nwfsc.noaa.gov/assets/26/7246_07162010_082840_Dawley.1986-rev.pdf

Fidler, L.E. and Miller, S.B. 1997a. British Columbia water quality criteria for dissolved gas saturation – technical report. Contract report to the BC Ministry of Environment, Department of Fisheries and Oceans, and Environment Canada. Aspen Applied Sciences Ltd., Cranbrook, B.C. Canada.

Fidler, L.E. and Miller, S.B. 1997b. User's Manual for the Department of Fisheries and Oceans British Columbia TGP Database. Contract report to the BC Ministry of Environment, Department of Fisheries and Oceans, and Environment Canada. Aspen Applied Sciences Ltd., Cranbrook, B.C. Canada.

Jensen, J.O.T., Schnute, J. and D.F. Alderdice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose-response model. Can. J. Fish. Aquat. Sci. 43: 1694-1709.

Shrimpton, J.M., Randall, D.J. and L.E. Fidler. 1990. Factors affecting swim bladder volume in rainbow trout (Oncorhynchus mykiss) held in gas supersaturated water. Can. J. Zool. 68:962-968.

Weitkamp, D.E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society. 109:659-702.

Weitkamp, D.E. 1976. Dissolved gas supersaturation: live cage bioassays at Rock Island Dam, Washington. Pages 24-36 in Fickeisen and Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Weitkamp, D.E. 2008. Total dissolved gas supersaturation summery of biological effects from literature 1980-2007.

Weitkamp, D.E. 2013. Literature relevant to total dissolved gas regulation. Report to BC Hydro, Vancouver, British Columbia. 16 p.