Washington State Dissolved Oxygen Standard

A Review and Discussion of Freshwater Intragravel Criteria Development

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Cover photo: Napeequa River below falls (photo by James Garner).

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A Review and Discussion of Freshwater Intragravel Criteria Development

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Abstract

In 2006, the U.S. Environmental Protection Agency issued a Clean Water Act (CWA) approval of Washington's 2006 revision to the surface water quality standards. The approval required an Endangered Species Act condition. This condition was to review the freshwater dissolved oxygen (DO) criteria contained in the standards. This document partially fulfills that condition.

In addition to the direct CWA approval-based requirement to review the DO criteria, the Washington State Department of Ecology (Ecology) received recommendations from state and tribal agencies to re-evaluate Washington State's freshwater DO criteria. These recommendations contend that the current criteria are not protective of salmon spawning and rearing. Specifically, the intragravel DO requirements for salmon embryo and larval development are of foremost concern.

This document provides Ecology's Water Quality Program with a review of issues relating to freshwater DO criteria. The report was prepared by Ecology's Environmental Assessment Program.

This document provides scientific information about the characteristics of DO in Washington streams, including:

- A discussion of the relationship between the DO concentration and DO saturation.
- An analysis of Ecology's ambient monitoring data in relation to criteria recommended by other Pacific Northwest agencies and tribes.
- A discussion of current scientific knowledge about environmental factors that contribute to intragravel DO conditions.

Additionally, this document provides a review of freshwater DO criteria developed by other Pacific Northwest states and tribes for the protection of salmon spawning and rearing.

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Background

Water Quality Standards

The Washington State Department of Ecology (Ecology) administers the state's surface water quality standards (Chapter 173-201A WAC). These regulations establish minimum requirements for the quality of water that must be maintained in lakes, rivers, streams, and marine (salt) waters. This is done to ensure that all the designated uses associated with these waterbodies are protected. Examples of designated uses include aquatic life and wildlife habitat, fishing, shellfish collection, swimming, boating, aesthetic enjoyment, and domestic and industrial water supplies.

Numeric criteria associated with the designated uses are set in regulation. Washington State's water quality standards contain numeric criteria for toxic pollutants and the following conventional parameters: temperature, dissolved oxygen (DO), pH, total dissolved gas, turbidity, bacteria, and phosphorus.

In 2006 Ecology made revisions to the state's surface water quality standards. The freshwater DO criteria were not revised, although much review of the criteria was done prior to finalizing the rule.

EPA's final Clean Water Act approval of the revised standards included a consultation with the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fishery Service under Section 7(a)(2) of the Endangered Species Act (ESA). That consultation concluded that EPA's approval action was largely beneficial and would not jeopardize the continued existence of any endangered or threatened species. As part of that consultation, conditions were set forth to minimize any adverse effects to ESA-listed species, including a review of the DO criteria. This document partially satisfies that condition.

The factors concerning the development and review of freshwater DO numeric criteria are the focus of this document.

Dissolved Oxygen Criteria

Aquatic organisms are very sensitive to reductions in the level of DO in the water. The health of fish and other aquatic species depends on maintaining an adequate supply of oxygen dissolved in the water. Oxygen levels affect growth rates, swimming ability, susceptibility to disease, and the relative ability to endure other environmental stressors and pollutants. Hicks (2002) provides a technical review of DO requirements to maintain healthy and productive populations of aquatic species in Washington State.

The Washington State surface water quality standards are designed to maintain conditions that support healthy populations of fish and other aquatic life. Freshwater aquatic life use categories are described using key species (salmonids versus warm-water) and life-stage conditions (spawning versus rearing). Minimum acceptable DO concentrations are used as criteria to fully protect different categories of aquatic communities at very high levels of function [WAC 173-201A-200]. (Ecology, 2006.)

Oxygen levels can fluctuate over the day and night in response to changes in climatic conditions as well as the respiratory requirements of aquatic plants and algae. Since the health of aquatic species is tied predominantly to the pattern of daily minimum oxygen concentrations, the Washington State criteria refer to the lowest 1-day minimum (or available instantaneous measurement) oxygen concentrations that occur in a waterbody.

History of Washington's Dissolved Oxygen Criteria

In January 2003, Ecology developed a discussion document and literature summary entitled *Evaluating Criteria for the Protection of Aquatic Life in Washington's Surface Water Quality Standards for Fresh Water – Dissolved Oxygen* (Hicks, 2002). This document proposed changes to the DO criteria as part of the 2003 standards revisions. Public comments questioned these proposed revisions and Ecology postponed changes to the DO criteria until further information could be gathered.

EPA, USFWS, NOAA Fisheries, and Ecology met in January 2006 to discuss federal agency concerns about the DO criteria in the standard for protection of incubating salmonids. Ecology agreed to further study the relationship between surface water DO concentrations and intragravel dissolved (IGDO) concentrations. Ecology then established a work group to develop an IGDO study. The goal of the study was to investigate uncertainties that the current 9.5 mg/L water column criterion was sufficiently protective to meet IGDO salmonid requirements. The work group representatives included staff from EPA, USFWS, NOAA Fisheries, Tribes, and other parties interested in Washington's DO criteria development.

To assist in this research, EPA contracted with Aqua Terra Consultants to perform a literature review. The goal of this review was to document the current scientific knowledge of IGDO and surface water DO interaction. The objectives of the review were to provide (1) a description of DO depression effects between surface water DO and IGDO, (2) common sources of such depression gradients, and (3) justifications for and against the use of concentration-based versus percent-saturation-based water quality numeric criteria. This research resulted in a draft summary of findings (Appendix A). Ecology also performed a literature search on IGDO-related studies and provided this information to EPA and the work group.

Why Are We Writing this Document?

In February 2008, Ecology received EPA's final approval of the revised 2006 water quality standards. The approval required an Endangered Species Act (ESA) condition to review the freshwater DO criteria contained in the standards. This document partially fulfills that condition. This document also discusses key scientific and policy elements that need to be considered to improve DO criteria.

Discussion of Pacific Northwest Dissolved Oxygen Criteria

EPA Recommendations for Dissolved Oxygen Criteria in Freshwater

The U.S. Environmental Protection Agency (EPA) 1986 criteria document provides recommended DO criteria for the protection of freshwater aquatic life (EPA, 1986b). Current Washington State numeric DO criteria are based on EPA recommendations for the protection of cold-water species (e.g., salmon). EPA-recommended water column DO concentrations were established to protect early life stage conditions in intragravel habitat. Specifically the criteria were set to meet a 6.5 mg/L intragravel concentration with an assumed 3.0 mg/L average DO depression from the water column DO concentration. Therefore, many states and tribes in the Pacific Northwest adopted a 9.5 mg/L minimum water column criterion.

The EPA-recommended criteria were based on production impairment estimates that were based on growth data affected by temperature, disease, and pollutant stresses. The average DO concentrations discussed above were values 0.5 mg/L above the slight production impairment values (EPA, 1986b). Some states and tribes have since adopted more restrictive DO criteria to ensure increased protection of embryo and larvae stages of cold-water species.

In contrast with the EPA decision to set criteria calculated from *slight production impairment* DO concentrations, some agencies have set criteria based on *no production impairment*. This most-stringent DO concentration recommended by EPA sets a minimum average concentration of 11.0 mg/L based on assumptions in the 1986 EPA criteria document (EPA, 1986a). (See Table 1.)

Table 1. Recommended cold-water species dissolved oxygen criteria for salmonid waters (EPA, 1986b).

Level of impairment to embryo and larvae stages	Water column minimum average concentration	Intragravel minimum average concentration
No production impairment	11.0 mg/L	8.0 mg/L
Slight production impairment	9.0 mg/L	6.0 mg/L
Moderate production impairment	8.0 mg/L	5.0 mg/L
Severe production impairment	7.0 mg/L	4.0 mg/L
Limit to avoid acute mortality	6.0 mg/L	3.0 mg/L

Comparison of Pacific Northwest Dissolved Oxygen Criteria

For this document, Ecology reviewed DO water quality standards of Pacific Northwest (PNW) government agencies. The review included western states, tribes, and the Canadian province of British Columbia. The objective of this review was to identify and compare those agencies that include protection of IGDO conditions beyond the 9.5 mg/L minimum water column concentration discussed earlier. To be included in this comparison, an agency's water quality standard must have included specific numeric criteria for IGDO values to protect early life stages of salmonids. When a specific IGDO criterion was not identified, we further reviewed the water column criteria. If more stringent criteria than the EPA-recommended 9.5 mg/L concentration were adopted, then the information was also included in this comparison. Additionally, the Washington State DO criteria were included for comparison purposes.

This review considered surface water quality standards from four states, British Columbia and ten PNW tribes. The Oregon, Idaho, Alaska, and British Columbia water quality standards all include specific intragravel DO criteria in addition to water column DO criteria. Six of the ten tribal water quality standards also include more stringent DO criteria than the EPA 9.5 mg/L water column recommended criterion. Four other tribal surface water standards did not include specific intragravel DO criteria. Similar to Washington's standards, these tribal standards only included DO water column criteria and therefore were not included in this review.

Table 2 provides a comparison of the numeric DO criteria of applicable Pacific Northwest agencies. The table is separated by two types of criteria: water column minimum DO requirements and intragravel minimum DO requirements. There are two averaging methods and an instantaneous method for both water column and intragravel criteria. Additionally, some agencies include percent saturation criteria to augment the minimum DO concentration requirements.

Criteria based on minimum DO concentrations

A 1-day minimum is often described as an instantaneous minimum. This type of criterion requires that a waterbody meet a particular minimum DO concentration at all times. Continuous sampling throughout the day can provide the lowest daily DO values; however, single "grab" samples are also used to determine compliance.

A 7-day mean minimum criterion is calculated as a moving average of daily means. A daily mean is first calculated for each of seven consecutive days. The mean of these seven values is then compared to the criterion. Data collected continuously throughout the day are needed to obtain an accurate average daily DO value.

Some agencies' water quality standards also include a 7-day minimum mean criterion. This is calculated by averaging the daily minimum DO concentrations for each of consecutive seven days. Data collected continuously throughout the day are needed to obtain the lowest daily DO value. Minimum mean criteria are not included in Table 2 because they usually apply only to the protection of salmon migration and rearing. Table 2 focuses on criteria developed to protect salmon spawning.

A 30-day mean minimum criterion is also calculated as a moving average of daily means. A daily average is first calculated for each of 30 consecutive days. The mean of these 30 values is then compared to the criterion. Data collected continuously throughout the day are needed to obtain an accurate average daily DO value.

Table 2. A comparison of Pacific Northwest state, provincial, and tribal freshwater DO criteria for the protection of salmon spawning.

Agency	Water Column Criteria				Intragravel Criteria		
	1-Day Minimum [1]	7-Day Mean Minimum [2]	30-Day Mean Minimum	Percent Saturation	1-Day Minimum [1]	7-Day Mean Minimum [2]	30-Day Mean Minimum
State of Oregon	(9.0) mg/L [3]	11.0 mg/L		95% [4]	8.0 mg/L [5]		
State of Idaho	6.0 mg/L [6]			90% [6]	5.0 mg/L	6.0 mg/L	
State of Alaska	7.0 mg/L				5.0 mg/L [8]		
State of Washington	9.5 mg/L						
British Columbia	9.0 mg/L		11.0 mg/L		6.0 mg/L		8.0 mg/L
Makah Tribe	9.5 mg/L	11.0 mg/L					
Port Gamble S'Klallam Tribe	9.0 mg/L	11.0 mg/L					
Confederated Tribes of the Umatilla Indian Reservation	(9.0) mg/L [3]	11.0 mg/L		95% [4]	8.0 mg/L [5]		
Lummi Nation	(9.0) 11 mg/L [3]			95% [4]	8.0 mg/L [5]		
Confederated Tribes of the Warm Springs Reservation	(9.0) 11 mg/L [3]			95% [4]	8.0 mg/L [5]		
Confederated Tribes of the Colville Reservation	8.0 mg/L [7]	9.5 mg/L [7]			5.0 mg/L	6.5 mg/L	

1 A 1-day minimum can also be described as an instantaneous minimum. Both descriptions are applied as a minimum concentration to be met at all times.
2 A 7-day mean minimum is calculated as a moving mean of daily averages. The data must include diel variations of DO including maximum and minimum daily values.
3 DO concentrations in parentheses supersede other water column criteria when associated intragravel criteria are met.
4 The saturation criterion applies when other water column criteria are not attained.
5 Expressed as a spatial median. The median value from samples collected at multiple locations within a spawning area.
6 Both the DO minimum concentration and minimum saturation criteria must be met.
7 The water column DO concentration is a recommendation to achieve the required intragravel criteria.
8 The criterion applies to a depth of 20 cm in spawning gravels and requires the use of the IGDO standpipe method (McNeil, 1962) for collecting IGDO values.

Percent saturation criteria require that a minimum percent of gaseous oxygen be present in the water column. Unlike DO concentration requirements, percent saturation criteria allow for comparison of DO concentration in consideration of naturally variable environmental conditions. For example, the effect of atmospheric pressure and temperature can be taken into consideration when assessing DO concentrations. Percent saturation is generally included as a secondary criterion when atmospheric pressure and temperature preclude the attainment of a DO concentration criterion. A more complete discussion of the relationship between DO concentration and percent DO saturation is provided in the *Ambient Data Review* section of this document.

Specific requirements for applying DO criteria

Specific requirements for applying mean DO criteria are described in many of the PNW criteria documents reviewed. These requirements address concerns of temporal and spatial representativeness of sample values. Examples of these are:

- Samples values must be collected from well-mixed portions of rivers and streams.
- A sufficient number of sample values must be collected to adequately represent the natural fluctuation of DO throughout a day.
- Sample values should not be taken from shallow or stagnant backwater areas.
- Sample values should be representative of the waterbody as a whole.

Requirements vary between criteria documents, but are written to ensure representative values for comparison to the standard. Most of the criteria documents included some provision to ensure representative values; therefore, these specificities are not included in this review. However, special requirements or instructions that seemed beyond common provisions are included in the discussion.

Pacific Northwest state, provincial, and tribal criteria

State of Oregon

The Oregon Department of Environmental Quality *Water Quality Standards* (Oregon, 2007) contain water column and intragravel-specific DO criteria. These criteria are set for the protection of salmonid spawning and incubation of embryos until emergence from gravels. Oregon's criteria include several exceptions and are more complex than others reviewed. Water column criteria require that a 7-day mean minimum meet 11.0 mg/L. However, when it can be shown that adjacent intragravel conditions are meeting 8.0 mg/L, the instantaneous minimum requirement shall be 9.0 mg/L. To determine that intragravel DO is meeting the criterion, a spatial median must be calculated from several samples within a spawning area.

Oregon also includes an exception to both water column and intragravel numeric criteria. When barometric pressure, altitude, and temperature preclude achievement of these criteria, the waterbody must meet at least 95% DO saturation.

State of Idaho

The Idaho Department of Environmental Quality *Water Quality Standards* (Idaho, 2008) contain water column and intragravel-specific DO criteria. As shown in Table 2 the instantaneous minimum criterion is 6.0 mg/L. This concentration requirement is significantly less than other agencies' criteria. However, Idaho's criteria document states that a one-day minimum DO concentration must not be less than 6.0 mg/L or 90% of saturation, whichever is greater. By contrast, Oregon and other agencies use the percent saturation requirement as an exception when conditions preclude attainment of other criteria. Idaho essentially requires that both the DO concentration and percent saturation criteria be met. Although it may not be clear from a cursory review, under certain conditions Idaho's criteria may be more stringent than Oregon Department of Environmental Quality criteria. Further discussion of percent saturation is provided in the *Ambient Data Review* section of this document.

Idaho's intragravel criteria requires waterbodies to meet both an instantaneous minimum criterion of 5.0 mg/L and a 7-day mean minimum criterion of 6.0 mg/L. Unlike other agencies Idaho does not specify IGDO sample collection or spatial averaging procedures.

State of Alaska

The State of Alaska Department of Environmental Conservation *Water Quality Standards* (Alaska, 2008) contain water column and intragravel-specific DO criteria. The water column instantaneous minimum criterion is 7.0 mg/L. Intragravel DO concentration must meet a 5.0 mg/L instantaneous minimum to a depth of 20 cm. These criteria apply to waterbodies used by anadromous or resident fish, for spawning. For waters not used by anadromous or resident fish the instantaneous minimum requirement is 5.0 mg/L. The State of Alaska specifies a collection method required for obtaining IGDO sample values. The criteria document designates the standpipe method described by McNeil (1962).

State of Washington

The State of Washington Surface Water Quality Criteria (Ecology, 2006) currently contain a water column DO criterion for char and core summer salmonid habitat. These waters include waterbodies designated for salmon spawning. The instantaneous minimum criterion is 9.5 mg/L.

British Columbia

The British Columbia Approved Water Quality Guidelines (British Columbia, 2006) contain water column and intragravel-specific DO criteria. The water column instantaneous and 30-day mean minimum criteria are 9.0 mg/L and 11.0 mg/L, respectively. The intragravel DO requirements include an instantaneous minimum of 6.0 mg/L and a 30-day mean minimum of 8.0 mg/L. These criteria are set to protect salmon spawning streams during the embryo and alevin life stages or 30 days after hatching. British Columbia specifies that mean intragravel DO concentration should be based on at least five evenly spaced samples. If a diurnal cycle exists, measurements should be taken when oxygen levels are lowest (usually early morning). The water column concentrations apply to these streams only when these intragravel DO concentrations are not available.

Makah Tribe

The Makah Tribe *Water Quality Standards for Surface Water* (Makah, 2006) contain DO water column criteria for the protection of salmon and trout spawning. These are shown in Table 2 and include an instantaneous minimum of 9.5 mg/L and a 7-day mean minimum of 11.0 mg/L. No intragravel-specific criteria are included in these standards.

Port Gamble S'Klallam Tribe

Port Gamble S'Klallam Tribe *Water Quality Standards for Surface Waters* (Port Gamble S'Klallam, 2002) contain DO water column criteria for the protection of salmon spawning, egg incubation, and fry emergence. These are shown in Table 2 and include an instantaneous minimum of 9.0 mg/L and a 7-day mean minimum of 11.0 mg/L. No intragravel-specific criteria are included in these standards.

Confederated Tribes of the Umatilla Indian Reservation

The *Water Quality Standards* of the Umatilla Indian Reservation (Umatilla, 2001) contain water column and intragravel-specific DO criteria. These criteria are to protect salmonids from spawning until fry emergence from gravels. The details of these criteria directly correspond with those of the Oregon Department of Environmental Quality, except that the Umatilla Tribe also designates a specific annual time period that IGDO samples should be collected (spawning season in tribal waters).

Lummi Nation

The *Water Quality Standards for Surface Waters* of the Lummi Indian Reservation (Lummi, 2007) contain water column and intragravel-specific DO criteria. The details of these criteria directly correspond with those of the Oregon Department of Environmental Quality, with one exception. Instead of requiring a 7-day mean minimum of 11.0 mg/L, the Lummi criterion requires an instantaneous minimum of 11.0 mg/L. Without an allowance for averaging daily values, this criterion is more stringent than Oregon's.

Confederated Tribes of the Warm Springs

The *Water Quality Standards, Beneficial Uses and Treatment Criteria* of the Warm Spring Tribe (Warms Springs, 2006) contain water column and intragravel-specific DO criteria. The details of these criteria directly correspond with those of the Oregon Department of Environmental Quality, with one exception. Instead of requiring a 7-day mean minimum of 11.0 mg/L, the Warm Springs criterion requires an instantaneous minimum of 11.0 mg/L. Without an allowance for averaging daily values, this criterion is more stringent than Oregon's. The Warm Springs Tribe also designates that IGDO samples should be collected during the spawning season in tribal waters.

Confederated Tribes of the Colville Reservation

The *Water Quality Standards* of the Colville Tribes Indian Reservation (Colville, 2005) contain water column and intragravel-specific DO criteria. These criteria apply to all salmonid early life stages including all embryonic and larval stages and all juveniles until 30 days after hatching. The intragravel criteria require waterbodies to meet both an instantaneous minimum criterion of 5.0 mg/L and a 7-day mean minimum of 6.5 mg/L. The Colville criteria document designates these intragravel criteria as the primary requirement. The associated water column concentrations are recommended to achieve the required IGDO concentrations. However, these water column concentrations are not specifically required. The recommended instantaneous minimum concentration for the water column is 8.0 mg/L and the 7-day mean minimum concentration is 9.5 mg/L. Unlike most other agencies, the Colville criteria document does not specify IGDO sample collection or spatial averaging procedures.

2008 Aqua Terra Literature Review

The EPA Region 10 office contracted with Aqua Terra Consultants to perform a literature review of freshwater DO research. To guide this review, EPA assigned three questions related to intragravel dissolved oxygen (IGDO) and surface water dissolved oxygen (SWDO). See Appendix A for the full memorandum.

The intent of EPA's questions was to discover new research on the relationship between IGDO and SWDO since the 1986 EPA criteria document was published. These questions included but were not limited to the following:

- What DO depressions are typical between SWDO and IGDO concentrations?
- What factors affect the magnitude of IGDO depression?
- Does the current research show trends in other environmental variables that help determine the magnitude of the DO depression?

In preparation for this document, Ecology reviewed the same research, including more recently published literature. Our review resulted in conclusions similar to those of the Aqua Terra authors. These general conclusions are summarized as follows.

- Previous literature that found DO depression between SWDO and IGDO ranges from 1.0 to 3.0 mg/L was incomplete. More recent research has found a larger degree of disparity of DO concentrations under many different environmental conditions.
- Temporal and spatial variability of IGDO concentrations results from many confounding environmental factors. These include groundwater influence, stream morphology, sediment composition, flow regime, and biochemical oxygen demand.
- Proper computer models to quantify and predict the affect of these environmental factors on IGDO concentration have not yet been developed.

Implications of Literature Review on Criteria Development

To develop water quality criteria, certain questions must be asked. These include:

- Are the proposed criteria appropriate for the protection of the use?
- How will compliance with these criteria be measured?

The literature review (Appendix A) provides information to address both of these questions. As shown in a previous section of this report, many states and tribes have adopted the 1986 EPA criteria document recommendation to be protective to the level of *no production impairment.* These include either the 11.0 mg/L water column DO criteria or the 8.0 mg/L intragravel DO criteria. Some states and tribes have adopted both of these more stringent criteria.

The high temporal and spatial variability of oxygen concentrations in stream gravels makes it difficult to ensure that IGDO criteria are attainable even under natural conditions. Streams that have little to no human influence may not attain the numeric DO standards. Low DO concentrations can be attributed to natural confounding environmental factors such as changes in groundwater, flow, and sediment in the stream. Malcolm and others (2005) recognize that basin morphology and stream-aquifer interactions predominantly influence these environmental factors. Therefore, even naturally occurring IDGO depressions characteristic in a stream tend to be site-specific. A single numeric IGDO criterion is difficult to apply on a statewide scale or to broad areas of salmon spawning waters.

Numeric criteria developed by several agencies in the Pacific Northwest take the temporally and spatially variable nature of IGDO into consideration. 7-day and 30-day IGDO and SWDO mean concentrations are set in the standards to control the effect of temporal variability. Some agencies also require that a spatial median value from several samples in a spawning area be used to determine compliance with the standard. (However, the unknown spatial variability of IGDO makes it inherently difficult to set a minimum number of samples required to determine a spatial median.)

Both approaches, when used together, can reduce the impact of temporal and spatial variability to help assess whether the salmon spawning habitat is protected. Recent research has also shown that IGDO monitoring instrumentation has improved significantly. However, implementing a sampling plan to meet these requirements would be costly and is not manageable for the amount of salmon spawning waters in Washington.

The degree to which DO criteria are protective or necessary cannot be determined on a large scale unless extensive monitoring is employed so that models can be fully developed. Recent research shows that even the 11.0 mg/L SWDO criterion described in EPA (1986b) may not be fully protective. This is because the IGDO depression varies more than the 3.0 mg/L assumed in earlier criteria guidance. When the water column concentration is meeting 11.0 mg/L there is less assurance than previously assumed that the IGDO is meeting 8.0 mg/L. Conversely, the physical principles of DO, atmospheric pressure, and temperature can preclude the ability to meet an 11.0 mg/L SWDO concentration. These principles are discussed in the next section of this report.

Considering the inconsistencies discussed above and the questions researchers are still trying to answer, it is difficult to recommend specific numeric DO criteria. It appears that current knowledge of the dynamic nature of IGDO is not complete enough to provide numeric values that can be applied broadly to salmon spawning waters.

Ambient Data Review

Physical Relationship Between Dissolved Oxygen and Percent Saturation

For practical purposes, the concentration of oxygen dissolved in water at equilibrium with air (i.e., the oxygen concentration at 100% saturation) is a function of temperature, barometric pressure, and dissolved components in the water, usually measured as salinity or conductivity. Moisture and other gases in the air, and effects of water density, also play roles, but these factors affect saturation less than the amount of precision in our routine measurements (Mortimer, 1981).

Henry's Law states that the solubility of gases in water decreases with increasing temperature and decreasing pressure. Since changes in atmospheric pressure at a given location are relatively minor, temperature has the largest impact on equilibrium oxygen concentration. Higher temperatures result in lower oxygen carrying capacity of the water.

As an illustration, the average maximum temperature at all freshwater ambient monitoring stations in Washington State with assigned supplemental spawning and incubation criteria was 13.6 ºC, and the minimum temperature was 3.0 ºC during the time periods when eggs and embryos are thought to be developing in the streambed (generally, fall, winter, and spring). For this range of temperatures, the corresponding range of theoretical oxygen concentrations at saturation is about 3 mg/L (Figure 1).

Barometric pressure, for which elevation is often used as a surrogate, also has an important effect on equilibrium oxygen concentrations. Pressure is positively correlated with oxygen; therefore, higher elevation streams, where atmospheric pressure is lower, will have lower equilibrium oxygen concentrations given the same temperature. Ninety percent of pressures measured at ambient stations during supplemental spawning seasons were greater than 724.9 mm Hg, and 90% were less than 769.6 mm Hg. This range of pressures will affect oxygen concentration at saturation by 0.6 to 0.8 mg/L, depending on the water temperature.

The effect of dissolved components in freshwater is minor, except at estuarine sites. Conductivity inversely affects the equilibrium oxygen concentration, but even the highest conductivities found in most natural freshwater systems will only reduce the oxygen concentration at saturation by a few hundredths of a milligram per liter. Conductivity will therefore be ignored for the remainder of this discussion (all calculations use 200 µS).

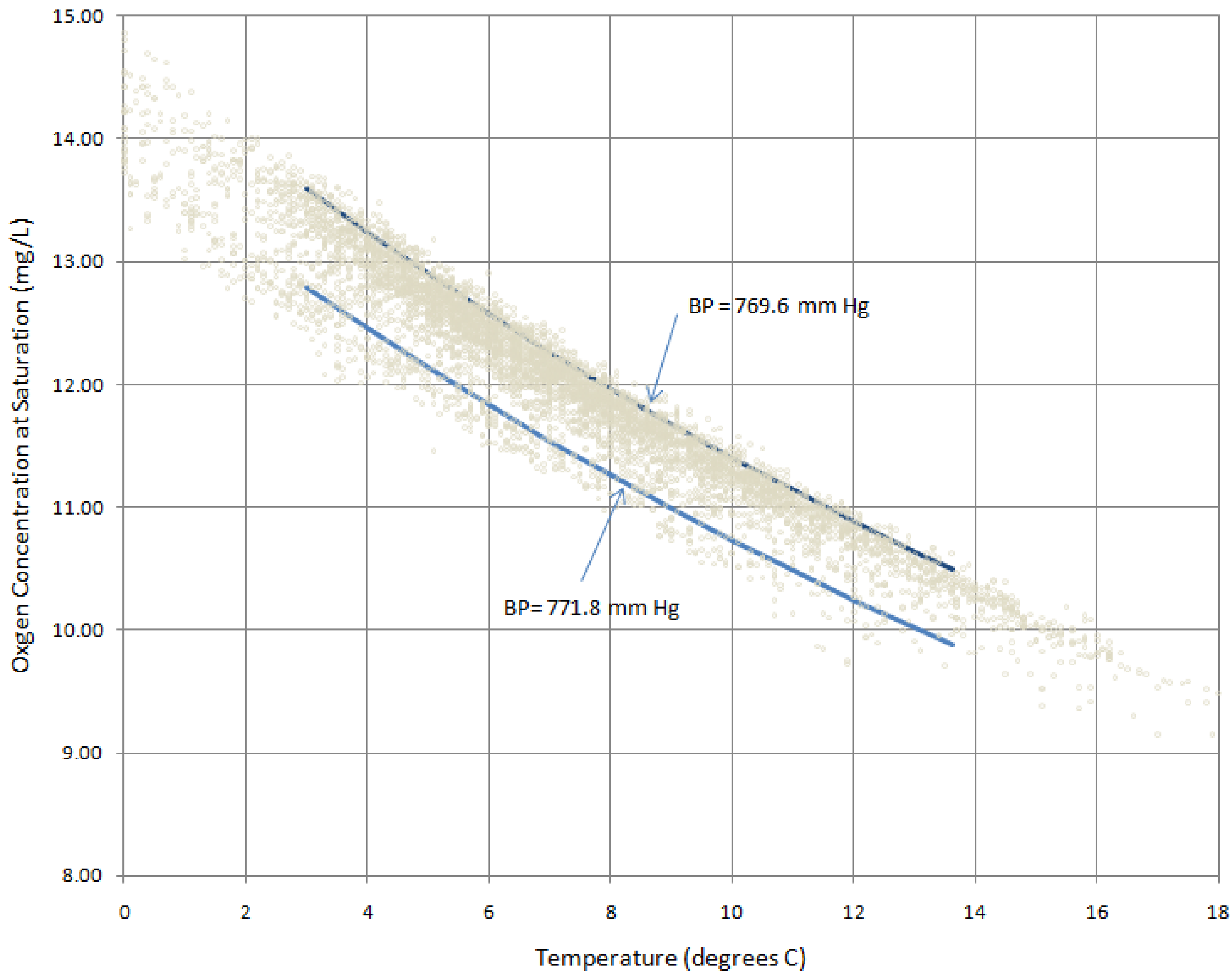

Figure 1. Oxygen concentration at saturation at various temperatures for two barometric pressures (BP; mm Hg = millimeters of mercury).

The shaded region represents 100% oxygen saturation concentrations based on measured temperatures and pressures at ambient stations with supplemental spawning criteria during the designated seasonal windows. The oxygen concentration at saturation was calculated from equations in Weiss (1970) and confirmed using tables in Lewis (2006).

In practice, most studies report the oxygen concentration and the percent oxygen saturation.

$$PctSat = \frac{Oxygen}{Oxygen_{sat}} * 100$$

where *PctSat* = percent oxygen saturation, *Oxygen* = measured oxygen concentration, and $Oxygen_{sat}$ = theoretical oxygen concentration at 100% saturation. The oxygen concentration at 100% saturation, which depends on temperature and pressure and is independent of actual oxygen concentration, is seldom reported.

As an example, the minimum measured oxygen at the Skagit River at Marblemount during the spawning and incubation period was 10.4 mg/L (on September 22, 1998) when the temperature was 10.2 ºC and the barometric pressure was 754.9 mm Hg. The oxygen was at 93% saturation. If the river had been fully saturated, the oxygen concentration would have been 11.1 mg/L.

Notice that the only way to keep *Oxygen* high is to keep *PctSat* close to 100 and to keep $Oxygen_{sat}$ high. The only way to keep $Oxygen_{sat}$ high is to keep temperature low. Besides temperature, *PctSat* is the only factor in the equation that affects oxygen concentration over which we have some control.

Deviations from 100% DO Saturation

In natural flowing waters, oxygen concentrations are rarely exactly 100% saturated over the course of a day. Changes in temperature, weather, biological activity, stream velocity and volume, and waste inputs can cause deviations from total oxygen saturation.

Factors that reduce oxygen in the system, the numerator in the percent saturation equation, will result in less than fully saturated conditions. These factors include biological respiration, chemical oxidation, and mixing with lower oxygen waters, (for example, groundwater, wastewater, and some wetland seeps). Factors that increase the denominator, such as cooling, will also result in less than fully saturated conditions. Both respiration and cooling are most pronounced in the early morning, hence percent saturation is often lowest then.

Conversely, the photosynthetic production of oxygen will increase oxygen concentration, and warming will decrease the 100% saturation concentration. Both photosynthesis and warming are most pronounced in the afternoon, hence percent saturation is often greatest then.

The rate at which oxygen concentrations return to equilibrium (aeration) also impacts percent saturation. If the exchange of oxygen between a waterbody and the atmosphere were nearly instantaneous, percent saturation would remain near 100. The slower the rate of aeration, the greater the potential difference between the actual oxygen concentration and the fully saturated concentration. Factors affecting aeration rates include turbulence and velocity, wind, rain, water depth, and the difference between the oxygen concentration and the concentration at saturation.

Together, processes like respiration, photosynthesis, warming, cooling, and aeration give us the typical sinusoidal diel patterns of oxygen concentration and percent oxygen saturation, with minima in the early mornings and maxima in the late afternoons (Figure 2).

Figure 2 illustrates the effect of biological oxygen production and consumption. Because the Black River is primarily fed by groundwater at this site, daily temperature changes were minimal. The daily cycle in percent saturation was almost entirely driven by changes in oxygen concentrations from photosynthesis and respiration. Both concentration and saturation curves are aligned. In other systems, temperature cycles may affect the saturation concentration, which can cause a delay in the oxygen concentration cycle as the system chases an equilibrium condition.

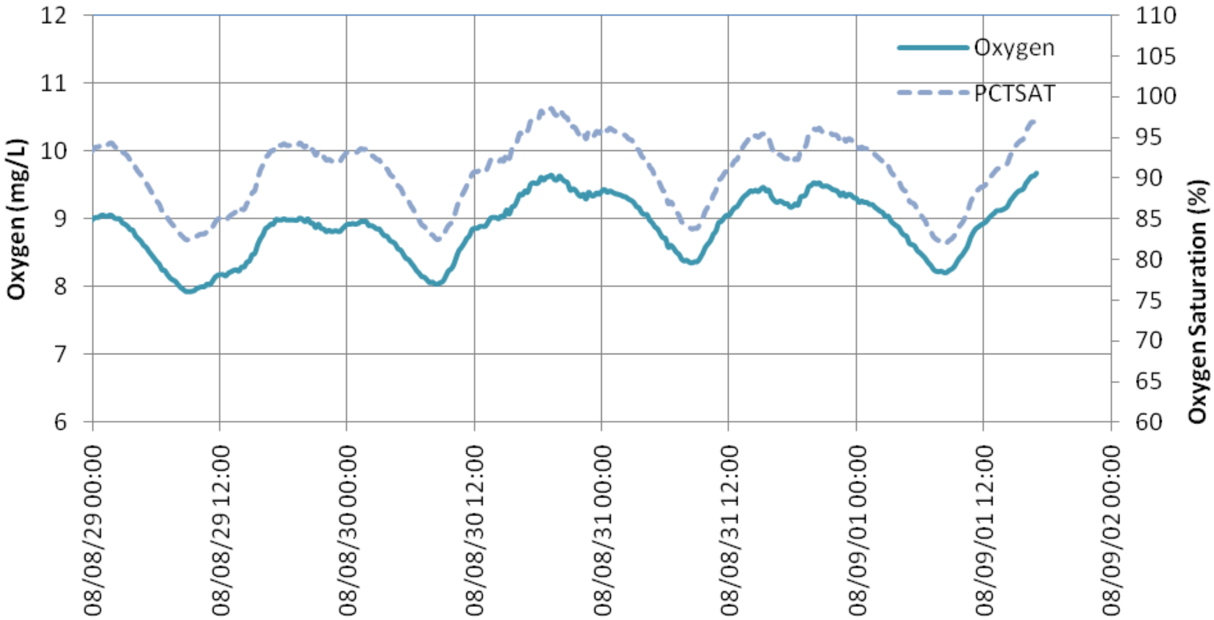

Figure 2. Oxygen concentration and percent saturation in the Black River (Lewis County).

Humans can affect ambient water oxygen concentration and saturation directly by discharging water at lower DO saturation than the receiving water. Most human uses of water, including deep discharge reservoirs, are capable of affecting downstream oxygen concentration directly.

Indirect effects on instream oxygen concentrations from human sources, however, are also common. Artificially reduced streamflows in unshaded stream channels allow more radical temperature changes that result in reduced DO concentration at saturation, increased amplitudes of daily swings, and shifting of daily maxima and minima. The addition of organic matter or reduced compounds, either from point or nonpoint sources, will increase biochemical oxygen demand and reduce DO concentration and saturation. The excessive addition of nutrients (cultural eutrophication) can increase the amplitude of the daily swings, as respiration consumes more oxygen at night and photosynthesis produces more oxygen during the day.

The combination of human impacts results in an “oxygen sag” for some distance downstream until DO saturation and concentration approach normal conditions through aeration.

The amplitude of the maximum and minimum oxygen concentration over a day can be used as an indicator of an aquatic system’s health. As demonstrated earlier, some change in oxygen concentration and saturation levels are expected over the daily cycle in any open water system. However, in a healthy environment, minimum oxygen concentrations should not decrease excessively below saturation nor rise far above saturation. Human impacts can reduce the minimum DO concentrations below critical levels for aquatic organism survival, and extreme swings from supersaturation to low saturation may cause stress to aquatic organisms. Several consecutive days of these stressful conditions can seriously harm sensitive life-stages.

Elevation and Barometric Pressure

Elevation is routinely used as a surrogate for barometric pressure in percent oxygen saturation calculations. Oxygen concentration at saturation drops about 4% for every 300 meters of increased elevation. There are several equations to adjust standard atmospheric pressure for elevation. One such equation is

$$P = P_b * \exp\left(\frac{-G_o * M * h}{R^* * T_b}\right)$$

where P is the elevation-adjusted pressure (mm Hg), P_b is the standard atmosphere, g_o is the gravitational acceleration of the earth (9.80665 m/s^2), M is the molar mass of the earth's air (0.0289644 kg/mol), h is the height above sea level (meters), R^* is the universal gas constant for air (8.31432 N-m/mol-K), and T_b is the standard temperature (288.15 K) (Wikipedia contributors, 2009).

P_b is generally 760 mm Hg but Washington's 30-year average pressure has been 763.5253 mmHg (National Climate Data Center), and we have used that value, as recommended by Mortimer (1981).

Applied to 10 years of statewide ambient data (n=13,043), oxygen at saturation based on measured pressure was strongly correlated with saturation based on elevation (r^2=0.99; Figure 3). Ninety percent of oxygen concentrations at saturation calculated from elevation were within -0.21 to +0.22 mg/L of saturation concentrations based on barometric pressure. The median concentration based on elevation was identical to the median concentration based on pressure within the limits of our ability to measure oxygen.

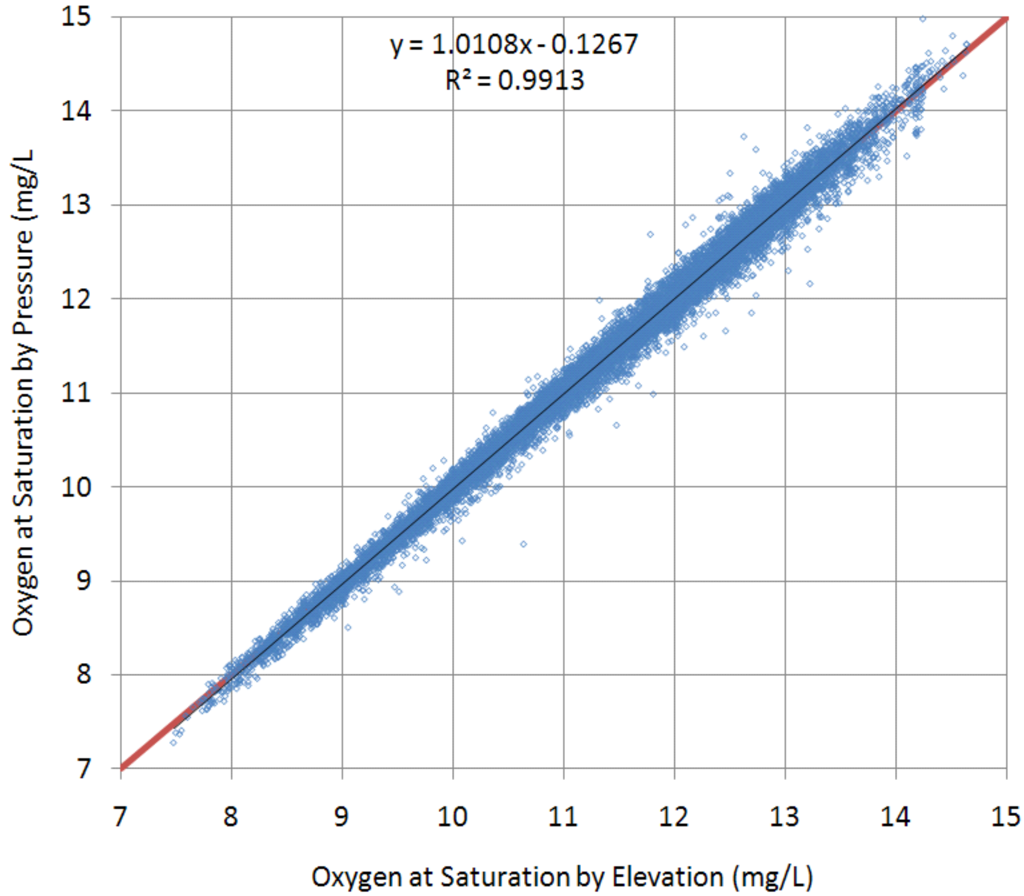

Figure 3. Comparison of oxygen concentration at saturation based on elevation (x) and measured barometric pressure (y).

The narrow black line is the regression line; the red line is 1:1.

Oxygen from Ambient Monitoring Stations

The November 2006 amendment to Washington's Water Quality Standards (WAC 173-201A) delineates stream reaches and seasons where salmon and trout spawning are known to occur and that require special temperature criteria. Ecology has measured oxygen concentration, temperature, and barometric pressure, from which oxygen saturation can be calculated, at 136 stations in these reaches since 1988 (Figure 4). All but 16 stations have been monitored for at least 2 years; 47 stations for 5 of more years, and 28 stations for at least 10 years. A few char spawning and incubation areas have also been delineated; however, we have no data from these areas.

There are some spatial gaps in the salmon and trout areas (most notably, the Blue Mountains, the upper Naches basin, higher elevation Olympic Mountain streams, and the higher headwaters). Nevertheless, coverage within designated spawning areas is reasonably broad, especially in the Puget Sound basin.

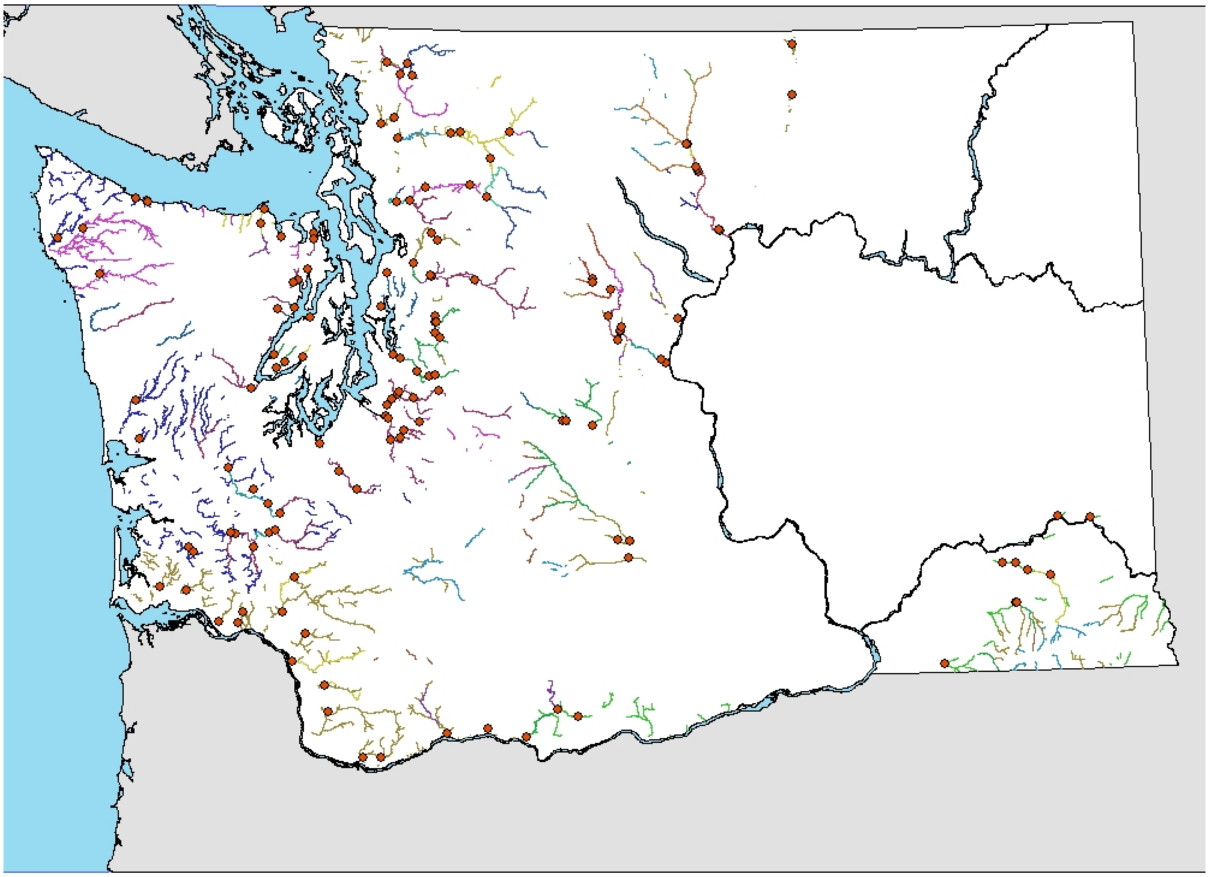

Figure 4. Washington State map showing salmon and trout spawning and incubation reaches as well as ambient monitoring stations in those reaches.

Unfortunately, we have no continuous oxygen data from ambient monitoring stations. Instead, our data are based on single grab samples with times of collection ranging from early morning, when oxygen concentrations are expected to be lower, to late afternoon when concentrations typically peak. The mean time of collection was about 11:30 AM, and the 10^{th} and 90^{th} percentiles were 8:30 AM and 3:00 PM.

In some cases, monthly grab samples may be more representative of daily averages than daily minimums. However, minimum concentrations/saturations from monthly grab samples at ambient stations can be considered high estimates of minimum oxygen conditions in the rivers and streams of Washington. Actual minimums (or 7-day average minimums) derived from continuous data would be lower, possibly much lower in degraded streams. Without continuous data, the true relationship between grab samples and daily means and minimums cannot be determined. Similarly, temperature maximums based on continuous data would be higher than the results reported here for monthly samples. Annual maximum 7-day average daily maximum temperatures (7-DADMax) based on continuous data are almost always higher than annual maximum grab sample temperatures: about 2 ºC inside Puget Sound and 4 ºC outside Puget Sound (Hallock, 2007).

The 7-DADMax is the metric specified in the WAC for supplemental spawning temperature criteria. In other words, relative to the data evaluated in this report, continuously collected temperatures would likely have been warmer, and saturated oxygen concentrations calculated from those temperatures lower. Therefore, both the measured oxygen concentrations and theoretical concentrations at saturation reported here are high estimates.

Comparisons to Water Quality Standards Criteria

The current year-round oxygen criterion for most of our ambient monitoring stations in supplemental spawning areas is 9.5 mg/L. Twenty-nine of the 136 stations (21%) sampled since October 1988 had at least one measured oxygen concentration less than 9.5 mg/L during the spawning window (Figure 5). Sixteen stations (12%) had at least one theoretical (fully saturated) concentration below 9.5 mg/L based on the maximum measured temperature. The theoretical concentration at full saturation is included to show the difference between measured oxygen and oxygen calculated from temperature and pressure.

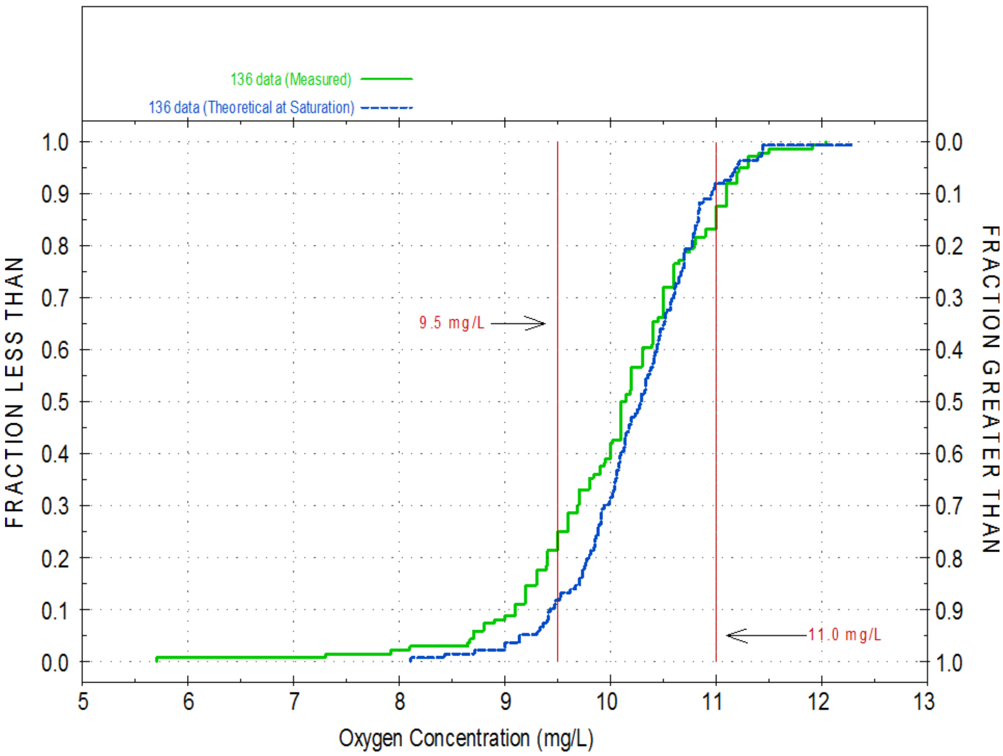

Figure 5. Cumulative frequency distribution of the minimum measured and theoretical oxygen concentrations at ambient stations in supplemental spawning areas since water year 1988 (supplemental spawning seasons only).

As seen earlier, many Northwest states and tribes use an oxygen criterion of 11.0 mg/L. Measured concentrations were less than 11.0 mg/L at least once at 113 stations (83%), and theoretical concentrations were less than 11.0 mg/L at 125 stations (92%). Fewer theoretical than measured concentrations met an 11 mg/L criterion because oxygen was super-saturated at some stations.

At about 80% of stations, the minimum oxygen concentration was above 95% saturated (Figure 6). However, the minimum saturation value for each station during the entire supplemental spawning period, which will not necessarily coincide with the minimum oxygen concentration, was quite a bit lower, with the 80th percentile closer to 87% saturated.

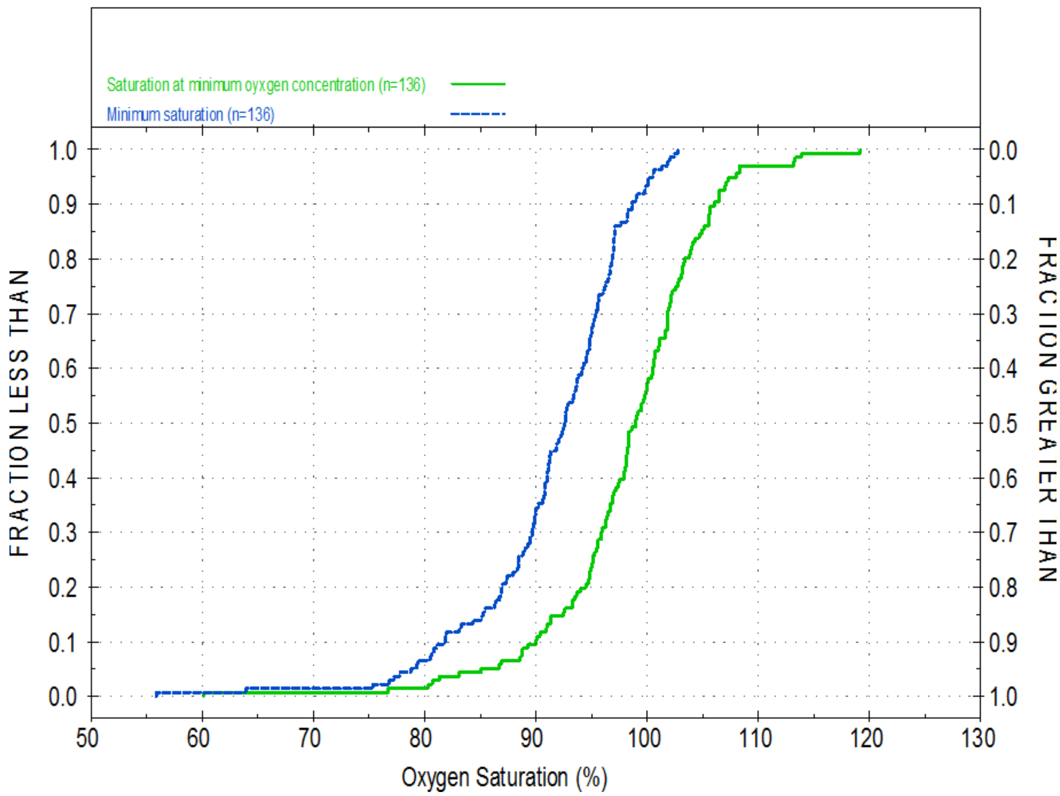

Figure 6. Cumulative frequency distribution of the minimum percent oxygen saturation (left line) and percent oxygen saturation coincident with the minimum oxygen concentrations (right line) at ambient stations with supplemental spawning criteria during the supplemental spawning season.

Spawning Seasons

Spawning periods vary greatly by stream reach, but most begin in August through September and end in May through June. Not surprisingly, lower DO concentrations tend to occur near the beginning and end of the spawning season when temperatures are more likely to be warm.

Figure 7 illustrates monthly average calculated percent saturations (A), theoretical oxygen concentration at saturation (B), measured oxygen concentration (C), and temperatures (D), for all 136 stations in supplemental spawning areas. The vertical axis of the plot is stations sorted by beginning and ending of the spawning and incubation season. The horizontal axes are the spawning season dates, beginning with August and ending with July.

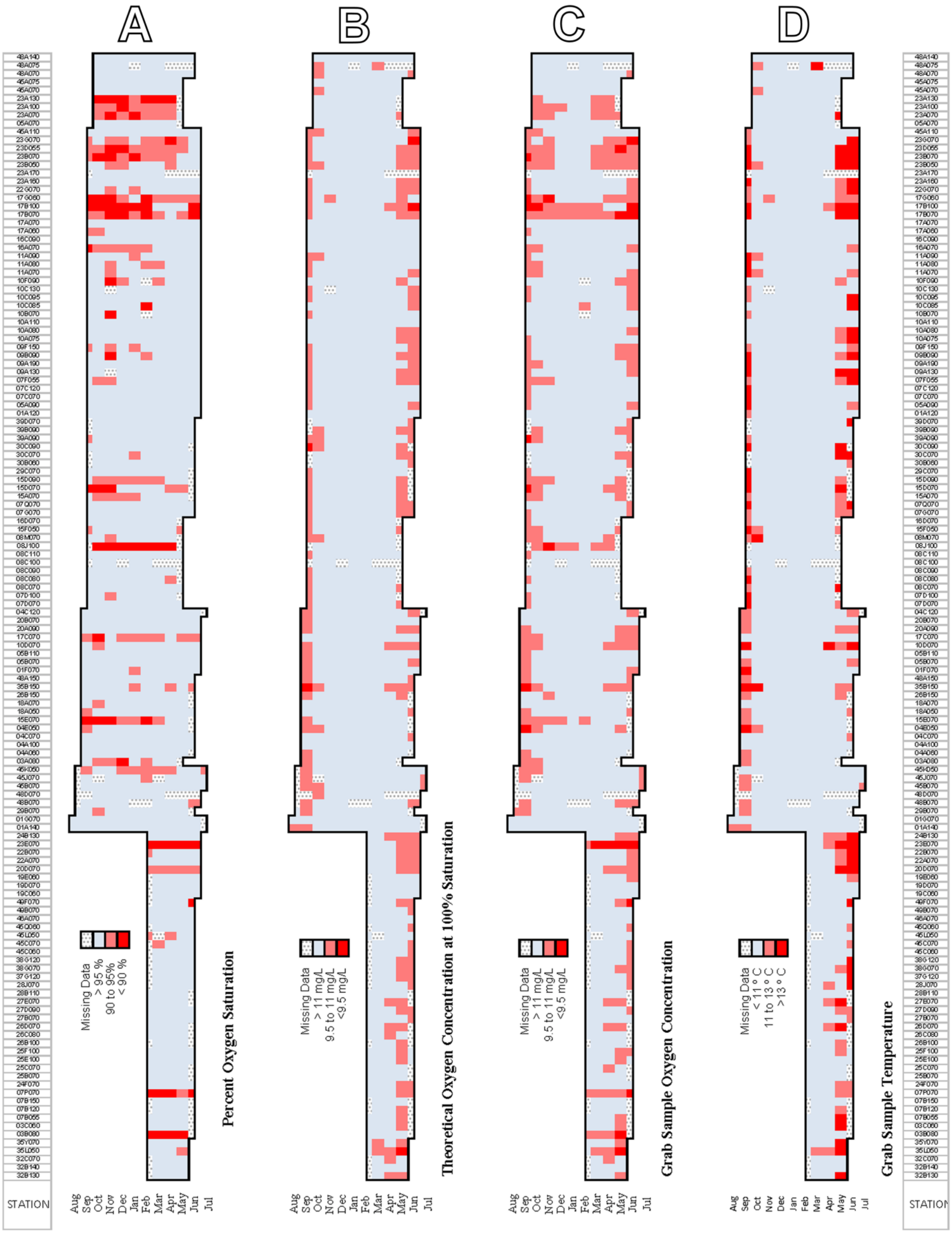

Figure 7. Average monthly percent saturation (A), theoretical oxygen at saturation (B), oxygen (C), and temperature (D) at ambient stations with supplemental spawning criteria.

Interestingly, percent saturation fell below 95% at various times throughout the season and not just when temperatures were warmest at the beginning and end of the designated seasons (Figure 7A). Furthermore, several stations had multiple saturation measurements less than 95% even though measured oxygen only rarely dropped below 9.5 mg/L.

The theoretical oxygen concentrations at saturation are the highest oxygen concentrations that can be expected given the temperatures in these streams. Most streams had at least one or two theoretical oxygen concentrations < 11 mg/L. However, most of the lower concentrations occurred in the first two weeks of the supplemental season, or in the last month or so (Figure 7B). The pattern in the measured concentration was generally similar to the pattern in the theoretical concentration at saturation, except that a few stations show low measured oxygen throughout most of the spawning season despite cool temperatures (Figure 7C).

As might be expected, the temperature plot is similar to the plot of theoretical oxygen concentration at saturation (Figure 7D versus. 7B). We used a temperature of 11ºC as a criterion because that is the approximate temperature required to reach an 11 mg/L oxygen concentration at sea level. For some stations at higher elevations, the theoretical oxygen concentrations were < 11 mg/L even when temperatures were <11 ºC. The current 13ºC 7-DADMax temperature criterion at supplemental spawning stations and times is not consistent with an 11 mg/L oxygen criterion. That is, temperatures can be cooler than the temperature requirement, yet still be too warm to allow 11.0 mg/L of oxygen to dissolve, even at full saturation. Also, 82 stations (60%) failed to meet even the 13ºC criterion, based on monthly average grab sample temperatures.

The results represented in Figure 7 show more optimistic conditions (reporting cooler temperatures and higher oxygen concentrations and saturations) than may actually exist. There are several reasons for this:

- Annual maximum grab sample temperatures are typically 2-4 º C cooler than annual maximum 7-DADMax temperatures. The discrepancy during the spawning season may not be as large as this, but theoretical oxygen at saturation could be overestimated by as much as 0.4 to 0.8 mg/L.
- Grab-sample oxygen concentrations will be higher than a 7-day average daily minimum calculated from continuous data. Had continuous oxygen data been available, there would likely be far more red in Figure 7A and C.
- 28 of the 136 stations are long-term stations, and all but 16 have been monitored for more than one year. Figure 7 is based on the average monthly value for each station, not the minimum value.

The preceding discussion is based on all 136 stations sampled since Water Year 1988. In any given year, we sample about 40 stations in supplemental spawning and incubation areas. On average, 64% of these will have at least one theoretical oxygen concentration at 100% saturation below 11 mg/L (Appendix B).

Effects of Elevation

There was little relationship between the minimum measured or theoretical oxygen concentration and elevation (Figure 8). This may be in part because the effect that reduced pressure at higher elevations has on oxygen concentration is balanced by the cooler temperatures typically found at higher elevations. Also, higher elevation streams tend to have steeper gradients, which increase aeration rates.

Together, temperature and pressure explain 34% of the variance in the minimum measured oxygen concentration (and all the variance in theoretical oxygen, of course). The remaining 66% unexplained variance is partly due to natural diel cycling of temperature. Because aeration is not instantaneous, the measured oxygen concentration lags behind the theoretical concentration. However, part of the unexplained variance is also due to those factors of interest to water quality managers discussed earlier, such as the addition of nutrients or oxygen-consuming substances. Identifying those stations with large deviations from the oxygen concentration predicted by temperature and pressure should be a goal of an oxygen water quality standard.

Evaluating the difference between measured oxygen concentration and an oxygen concentration prediction based on temperature and pressure is similar but less direct than simply evaluating percent saturation.

Figure 8 also shows a slight increase in minimum percent saturation as a function of elevation, and it appears that lower elevation streams are more likely to have minimum saturations less than 90%.

Effects of Ecoregion

There was no statistically significant difference among ecoregions (Omernik and Gallant, 1986) in minimum measured DO concentrations, at least among stations with supplemental criteria during the spawning and incubation period (Figure 9, top). However, because temperature, elevation (pressure), and factors affecting oxygen production and consumption all affect oxygen concentration, comparisons of measured concentration are difficult to interpret.

There was a statistically significant difference between ecoregions in minimum oxygen saturation (Figure 9, bottom). In particular, saturation tended to be lower in Puget Sound (ecoregion 2) and higher in the Columbia basin (ecoregion 7). Unfortunately, because these data are based on grab samples, one cannot conclude that oxygen is usually nearer saturation in the Columbia Basin than in Puget Sound. It is also possible that saturation is higher in the Columbia Basin during the day (when we collect our samples) because of greater primary production, and that night-time saturation may be lower there than in other ecoregions due to correspondingly high respiration. We need continuous data to verify and interpret the causes of these differences.

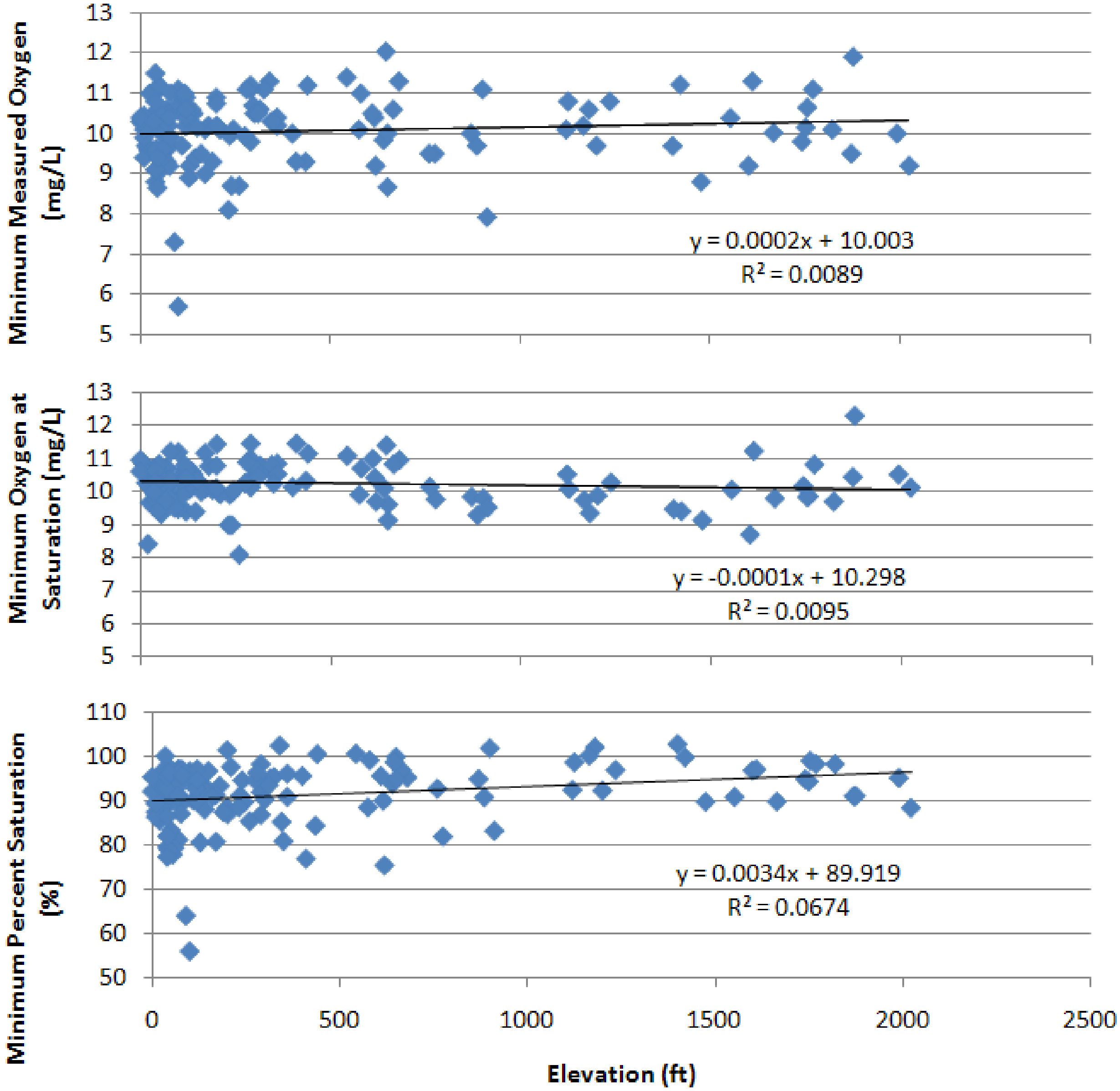

Figure 8. Minimum measured (top) and theoretical (middle) oxygen concentration and minimum percent saturation (bottom) as a function of elevation from ambient stations in supplemental spawning areas during the spawning and incubation season.

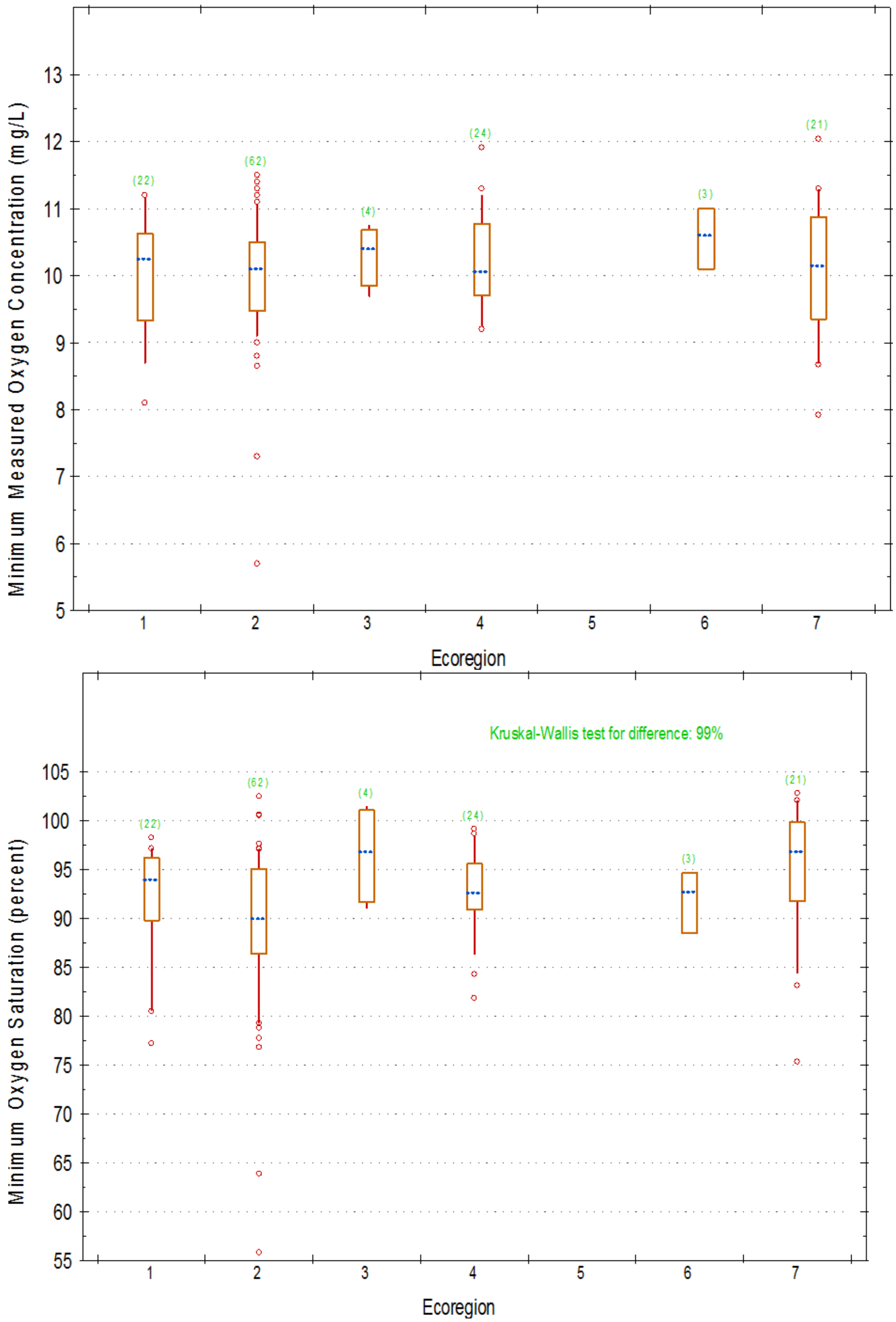

Figure 9. Minimum measured DO concentration (top) and minimum oxygen saturation (bottom) by ecoregion.

Ecoregions are 1=Coast Range; 2=Puget Lowlands; 3= Willamette Valley; 4=Cascades; 5=not applicable; 6= Eastern Slopes and Foothills; and 7=Columbia Basin.
The whiskers extend to the 10th and 90th percentiles, and the numbers above the boxes are the number of data points from that ecoregion.

Implications of a One-Day Minimum 11.0 mg/L Oxygen Concentration Criterion

An 11.0 mg/L oxygen criterion has been suggested for areas and seasons designated in *Waters Requiring Supplemental Spawning and Incubation Protection for Salmonid Species* (WAC 173-201A). The current one-day minimum criterion for most of these waters is 9.5 mg/L. The justification for this proposed criterion is based on the needs of sensitive and important biota, as discussed earlier.

EPA (1986a) suggests that if slight production impairment is unacceptable, then two criteria be set: (1) an 11 mg/L 7-day average mean minimum (i.e., the running 7-day average of daily averages should not drop below 11) and (2) a 9 mg/L absolute minimum.

An 11.0 mg/L daily minimum or 7-day average minimum criterion for Washington waters designated for salmon and trout spawning and incubation would likely result in most monitored stations being included on the state's 303(d) list for failing to meet the oxygen criterion (e.g., Figure 7). A 7-day average mean criterion, as recommended by EPA, could also result in a high proportion of listed stations, but relatively few stations would likely meet the data requirement for a true daily mean criterion, which would presumably require continuous data.

The physical relationship between oxygen concentration, stream temperature, and barometric pressure cannot be uncoupled. An oxygen concentration of 11.0 mg/L would require super-saturation at the observed temperatures at 91% of ambient stations with supplemental spawning criteria sampled since 1988. The effect of requiring that oxygen concentrations be super-saturated is both physically not possible but also misleading in terms of water quality management. This direct correlation among temperature, barometric pressure, and oxygen concentration is such that the temperature would have to be reduced to support 11.0 mg/L oxygen at saturation.

Figure 10, which is based entirely on Henry's law and not monitoring data, shows that maximum temperatures required to meet an 11.0 mg/L oxygen criterion at 100% saturation must be <11.2ºC at sea level, and <7ºC above 2750 feet elevation. Requiring 11.0 mg/L but allowing a reasonable deviation from saturation (say, 95%) would require temperatures 2ºC cooler than shown in Figure 10.

This disparity between stream temperature and desired oxygen can be resolved by allowing an exception to the oxygen concentration criterion if oxygen saturations are > 90 or 95%. About 53% of ambient stations had at least one grab sample with concentrations < 11 mg/L and saturation < 95% (Table 3). However, pairing a concentration and a saturation criterion would not protect against oxygen depressions due to high temperatures.

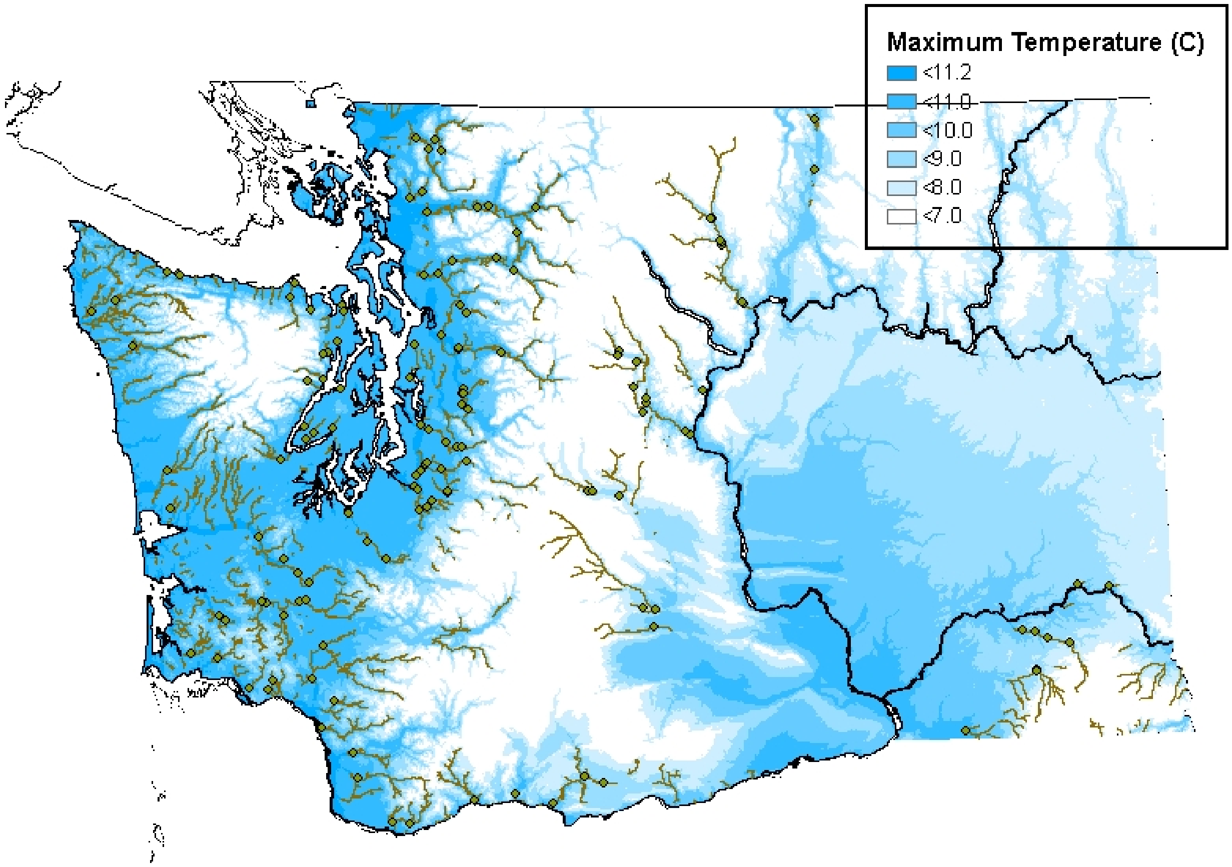

Figure 10. Maximum permissible stream temperatures to meet an 11.0 mg/L oxygen criterion at 100% saturation at different elevations.

Table 3. Percent of 136 ambient stations that would fail to meet various hypothetical criteria.
Based on at least one grab sample exceeding the criterion except where otherwise noted.
Details are in Appendix C.

Criterion	Percent of stations not meeting criterion
9.5 mg/L minimum	21
11 mg/L minimum	83
11 mg/L minimum unless saturation >95%	53
11 mg/L minimum unless saturation >90%	26
11 mg/L 30-day mean[a]	48
95% saturation	67
90% saturation	34

[a] Assessed by requiring that 2 consecutive grab samples do not meet the criterion.

Discussion of a Percent Saturation Criterion

EPA (1986b) states that compared to percent oxygen saturation, oxygen concentration criteria are more direct and easier to administer. Percent saturation criteria could also result in unnecessarily stringent criteria during cold months (i.e., when concentrations can be high despite low percent saturation).

Ecology has traditionally used one-day minimum DO concentration criteria to protect aquatic biota rather than percent saturation criteria. From the perspective of the biota, using concentration is reasonable and more direct. The concentration is more critical than the saturation (though oxygen uptake is more difficult if saturation is low), and critical concentrations are fairly well established. Concentration criteria address the question "how will oxygen affect the biota?"

Human Activities

However, if the question is "how are humans affecting the oxygen?" then concentration criteria may not be the most direct approach. For detecting and managing human effects on oxygen in water, percent saturation may be more straightforward.

Human activities that affect the amount of oxygen in a system can be classified into two groups: (1) activities that affect the theoretical saturated concentration, and (2) activities that affect the amount of deviation from the saturated concentration.

Activities in the first category (the denominator in the percent saturation equation) are those that affect stream temperature. An oxygen concentration criterion would offer protection against impacts from these activities, and a percent saturation criterion would not. However, if the goal is to protect water bodies from the effects of temperature increases, a temperature criterion is easier to develop, easier to monitor and assess, and more directly related to the cause of impairment than is an oxygen criterion.

Hence, to evaluate anthropogenic effects on oxygen, we are more interested in activities in the second category, those that affect percent saturation, such as:

- Activities that affect aeration rates (such as artificially changing streamflows).
- The addition of a low-oxygen discharge.
- The addition of nutrients, which increases productivity and can lead to both positive and negative deviations from full oxygen saturation.
- The addition of substances with biochemical oxygen demand, which reduce oxygen saturation.

In general, these activities affect the magnitude of deviation from saturated conditions but not the theoretical concentration at full saturation (though some affect both). For activities that affect the amount of deviation from the saturated concentration, it is the amount of deviation that indicates impairment, not the actual concentration.

Natural Deviations in Saturation

Although unpolluted flowing waters typically have oxygen concentrations near saturation (Allan, 1995) and a large deviation of oxygen saturation in either direction from 100% generally indicates impaired conditions, low saturation can occur naturally. Natural causes of low percent saturation must be considered when determining impairment. For example, in larger more productive streams, saturation may be well above 100% during warm sunny afternoons when the oxygen production by algae and aquatic macrophytes reaches its maximum, and drop below 80% in cool early morning hours when respiration is greatest. In small headwater streams, the decomposition of autumn leaves consumes oxygen (Hynes, 1970). Merritt (in draft) found lower than expected oxygen in wadeable streams in Washington, which he attributed to the influence of groundwater.

Saturation Criteria

Even though aquatic species may benefit from oxygen levels higher than 100% saturation (Hicks, 2002), setting a concentration criterion higher than the amount of oxygen the system is physically capable of holding at equilibrium is misleading. A concentration criterion should ideally clarify that concentrations are not expected to exceed 100% saturation.

Oregon's standards include 95% and 90% saturation provisions for "salmonid spawning" and "cold waters," respectively, when temperature and pressure preclude achievement of concentration criteria. In practice, however, at temperatures greater than 9ºC (at sea level), the primary concentration part of this two-part standard is irrelevant because 11 mg/L is not attainable at 95% saturation.

For example, Table 4 shows that oxygen concentration in the Snoqualmie River in September 1998 was well below an 11 mg/L criterion, yet still 100% saturated. A concentration criterion alone would report this as an oxygen problem when, in fact, the temperature is too high to support 11 mg/L oxygen. A saturation criterion would not report this as an oxygen problem.

As pointed out by EPA (1986b), at colder temperatures, a saturation criterion could be more stringent than a concentration criterion because a concentration criterion could allow significant oxygen consumption when the concentration at full saturation is above the concentration criterion. For example, in February 2000, oxygen in Nookachamps Creek was 11.4, yet saturation was only 82% (Table 4). The concentration is sufficient to protect aquatic life; but does the relatively low saturation indicate beneficial uses are not being met? Oregon's two-part standard implies "no": the percent saturation component is only relevant when concentration is less than 11.0 mg/L.

Table 4. Examples of different oxygen/temperature/elevation combinations and whether results would fail to meet theoretical percent saturation and concentration criteria.

Station	Date	Stream Temp (ºC)	Ele-vation (ft)	Measured Oxygen (mg/L)	Percent Satu-ration	Violate 11 mg/L Concen-tration Criterion?	Violate 95% Satu-ration Criterion?	Comment
Snoqualmie River @ Snoqualmie	9/21/98	12	400	9.4	100	Yes	No	100% saturation, therefore cause is high temperature.
Nookachamps Creek near mouth	2/16/00	2.1	15	11.4	82	No	Yes	Concentration is OK despite low saturation because temperature is low.
Nooksack River near Brennan	5/16/00	9.1	10	10.9	94	Yes	Yes	Concentration and saturation criteria both indicate slight impairment.
Nooksack River near Brennan	11/13/01	8.1	10	11.4	98	No	No	Neither concentration nor saturation criteria indicate impairment.

In summary, the relationship between stream temperature, barometric pressure, and oxygen concentration at saturation is determined by the laws of physics and is unaffected by human actions, which, except for actions that affect temperature, affect only the amount of deviation from a saturated condition. The effects of temperature on oxygen may best be managed, monitored, and assessed directly through temperature criteria. The amount of deviation from 100% saturation can be directly assessed with saturation criteria, though this may be overly stringent at low temperatures.

- *Concentration criteria*: Protect against warmer temperatures resulting in unattainable oxygen concentrations, but will often identify a temperature problem as an oxygen problem instead.
- *Saturation criteria*: Don't protect against temperature effects on oxygen (which could be protected through separate temperature criteria) and may be overly stringent at cooler temperatures. But saturation criteria directly identify potential oxygen problems.
- *Concentration plus saturation criteria*: Effectively a saturation criterion above a certain temperature, but less stringent than saturation alone at low temperatures.

Conclusions

- For supplemental spawning areas and seasons, measured stream temperatures were typically too warm to support an 11 mg/L oxygen criterion during the full seasonal windows.
- The current temperature criterion for supplemental spawning at most streams (13ºC) is too warm to support an 11 mg/L oxygen criterion.
- Requiring 11 mg/L at 95% saturation would require that temperatures be below about 9ºC at sea level and cooler at higher elevations during the supplemental spawning seasons.

- An oxygen concentration criterion is directly related to impacts on aquatic biota, but it fails to recognize the physical influence of temperature and is harder to monitor and assess than temperature.
- Percent oxygen saturation may be a more meaningful measure of oxygen impairment for management purposes than concentration, but it would not protect against temperature effects on oxygen concentration and it could be overly stringent at cooler temperatures.
- A two-part concentration plus saturation criterion would be similar to a saturation criterion alone for warmer temperatures, but would not be overly stringent at cooler temperatures.

Recommendations

As a result of this study, we offer the following recommendations regarding monitoring and the use of monitoring data:

- Although our monitoring station placement appears fairly well distributed around the state among salmon waters with supplemental spawning and incubation criteria, we have little data from some areas, especially headwaters, and no data from waters designated for char spawning and incubation. The availability of data from spawning and incubation areas should be one of our ambient monitoring program's selection criteria for basin stations.
- We have begun a continuous dissolved oxygen monitoring program on a pilot basis. This program should be supported and expanded.
- The preceding evaluation is based on grab sample data. With representative continuous stream temperature data, it may be possible to use grab sample data to estimate 7-day average minimum oxygen concentrations at saturation with a known level of confidence. The modeled estimates could then be used to better identify attainable temperatures and oxygen concentrations in spawning areas and seasons with supplemental criteria. Our nascent probabilistic monitoring program should consider collecting year-round continuous temperature data.
- When revising water quality standards, consideration should be given to monitoring requirements. For example:
    - A criterion based on the 7-day average of daily average oxygen concentrations might be more appropriate than a daily minimum criterion, but would require continuous monitoring data that are seldom available. If such a criterion is set, an additional daily minimum criterion should also be identified.
    - If managers determine that stream temperatures should be sufficiently low to support 11 mg/L dissolved oxygen, appropriate temperature criteria would more directly reflect the cause of impairment, and would be easier to monitor and assess than would an oxygen criterion.

Literature Cited

Alaska, 2003. Alaska Water Quality Standards (18 AAC 70), Alaska Department of Environmental Conservation, Division of Water. Juneau, AK. www.dec.state.ak.us/water/wqsar/wqs/index.htm.

Allan, D.J., 1995. Stream Ecology: Structure and function of running waters. Kluwer Academic Press, Dordrecht, Holland. 388 p.

British Columbia, 2006. British Columbia Approved Water Quality Guidelines, 2006 Edition, British Columbia Ministry of Environment. Victoria, BC. Canada. www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html.

Colville, 2005. Colville Confederated Tribes Indian Reservation Water Quality Standards, [40 CFR Sec. 131.35 (7-1-08 Edition)]. Washington D.C.

Ecology, 2006. Water Quality Standards for Surface Waters of the State of Washington. Washington State Department of Ecology, Olympia, WA. Publication No. 06-10-091. www.ecy.wa.gov/biblio/0610091.html.

EPA, 1986a. Quality Criteria for Water. Office of Water, Regulations and Standards Division. U.S. Environmental Protection Agency, Washington, D.C. EPA 440/5-86-001.

EPA, 1986b. Ambient Water Quality Criteria for Dissolved Oxygen. Office of Water, Regulations and Standards Division. U.S. Environmental Protection Agency, Washington, D.C. EPA 440/5-86-003.

Hallock, D., 2007. River and Stream Water Quality Monitoring Report for Water Year 2006. Washington State Department of Ecology, Olympia, WA. 34 p. + appendices. Publication No. 07-03-022. www.ecy.wa.gov/biblio/0703022.html.

Hicks, M., 2002. Part II: The Effect of Dissolved Oxygen on the Freshwater Aquatic Life of Washington. In: Evaluating Criteria for the Protection of Freshwater Aquatic Life in Washington's Surface Water Quality Standards: Dissolved Oxygen. Draft Discussion Paper and Literature Summary. Revised December 2002. Washington State Department of Ecology, Olympia, WA. Publication No. 00-10-071. www.ecy.wa.gov/biblio/0010071.html.

Hynes, H.B.N., 1970. The Ecology of Running Waters. Liverpool University Press. 555 p.

Idaho, 2008. Idaho Surface Water Quality Standards, Idaho Department of Environmental Quality. Boise, ID. http://adm.idaho.gov/adminrules/rules/idapa58/0102.pdf.

Lewis, M.E. (Revised by), 2006. Dissolved Oxygen (version 2.1): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6., section 6.2. Accessed October, 8, 2008. http://water.usgs.gov/owq/FieldManual/Chapter6/6.2_v2.1.pdf.

Lummi, 2007. Water Quality Standards for Surface Waters of the Lummi Indian Reservation, Lummi Nation. Bellingham, WA. www.epa.gov/waterscience/standards/wqslibrary/tribes/lummi.pdf.

Malcolm I.A., Soulsby et al., 2005. Catchment-scale Controls on Groundwater-Surface Water Interactions in the Hyporheic Zone: Implications for Salmon Embryo Survival. River Research and Applications. 21:977-989.

Makah, 2006. Water Quality Standards for Surface Waters, Makah Tribe. Neah Bay, WA. www.epa.gov/waterscience/standards/wqslibrary/tribes/makah.pdf.

McNeil, W.J., 1962. Variations in the Dissolved Oxygen Content of Intergravel Water in Four Spawning Streams of Southeastern Alaska. USDA Fish & Wildlife Service Special Science Report No. 402. 20 p.

Merritt, G. (Draft). An Assessment of Washington Wadeable Streams, Environmental Assessment Program. Washington State Department of Ecology, Olympia, WA.

Mortimer, C.H., 1981. Oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. Mitt. Int. Ver. Limnol. No. 22, p. 1-22.

National Climate Data Center, 2009. Climate Atlas of the United States. Accessed March 25, 2009. http://gis.ncdc.noaa.gov/website/ims-climatls/index.html.

Omernik and Gallant, 1986. Ecoregions of the Pacific Northwest. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/3-86/003.

Oregon, 2007. Water Quality Standards: Beneficial Uses, Policies, and Criteria for Oregon. (OAR 340-041). Oregon Department of Environmental Quality, Portland, OR. http://arcweb.sos.state.or.us/rules/OARs_300/OAR_340/340_041.html.

Port Gamble S'Klallam, 2002. Water Quality Standards for Surface Waters, Port Gamble S'Klallam Tribe. Kingston, WA. www.epa.gov/waterscience/standards/wqslibrary/tribes/s-klallam-10-wqs.pdf.

Umatilla, 2001. Water Quality Standards, Beneficial Uses, and Treatment Criteria. Confederated Tribes of the Umatilla Indian Reservation of Oregon. Pendleton, OR. www.epa.gov/waterscience/standards/wqslibrary/tribes/umatilla.pdf.

Warm Springs, 2006. Water Quality Standards, Beneficial Uses, and Treatment Criteria. Confederated Tribes of the Warm Springs Indian Reservation of Oregon. Warm Springs, OR. www.epa.gov/waterscience/standards/wqslibrary/tribes/warmsprings.pdf.

Wikipedia Contributors, 2009. Atmospheric pressure. In Wikipedia, The Free Encyclopedia. Retrieved March 24, 2009, from http://en.wikipedia.org/w/index.php?title=Atmospheric_pressure&oldid=279025665.

Weiss, R.F., 1970. The solubility of nitrogen, oxygen and argon in water and seawater: Deep Sea Research, v. 17, p. 721–735.

Appendices

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Appendix A. Aqua Terra Consultants Technical Memorandum Prepared for EPA, February 2008.

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MEMORANDUM

To: Lisa McGuire
Date: Feb 29, 2008
From: John Imhoff
Client: EPA Region 10
Copies: Lillian Herger, Region 10, Project No.: 20610-124
Tony Donigian, AQUA TERRA
Subject: Summary of Work Assignment Findings

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1.0 Background

The spawning and incubation stages of cold water fishes are directly dependent on the dissolved oxygen (DO) concentrations *in the gravel beds* in which the eggs are laid. Direct measurement of these *intergrave*l dissolved oxygen (IGDO) concentrations is difficult, and hence there is a need to relate IGDO concentrations to the DO concentrations of the water column above them. Research suggests that IGDO concentrations tend to be depressed approximately 3.0 mg/l from those in the water column. EPA has established 7-day mean and 1-day minimum water column dissolved oxygen concentration recommendations to protect cold water fisheries based on this approximate relationship.

However, EPA recognizes that the relationship between water column DO and IGDO is not simplistic; environmental factors such as stream morphology, stream flow, sediment deposition and re-suspension, and upwelling come into play in the actual DO depression that occurs.

Much of the literature that was considered in establishing the current recommendations was generated during the 1980’s and 1990’s. The objective of this work assignment was to provide EPA Region 10 with a summary of the last ten to fifteen years of scientific literature that relates water column dissolved oxygen to intergravel dissolved oxygen and specific aspects of this relationship.

2.0 Work Assignment Methodology

EPA established three questions/directives that defined the focus for literature review:

1. Describe the current state of knowledge regarding the relationship between water column DO and intergravel DO. Past literature suggests the DO depression effect between water column and intergravel ranges from 1.0 to 3.0 mg/l. Determine if the body of recent literature supports this finding in relatively sediment-free gravels. Qualitatively describe
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variability and any noticeable trends or patterns in the body of literature regarding the relationship of water column DO to intergravel DO.

2. Sources of variability that may explain the difference in water column DO versus intergravel DO are well known (degree of upwelling, sedimentation characteristics, channel morphology, temporal flow regime). From the literature, provide insight on whether or not the relationship between water column DO and intergravel DO varies in a consistent manner due to characteristics of substrate/sediment, channel morphology, or flow.

3. From the literature summarize the justifications authors have developed for using a particular metric (i.e., the 'mg/l DO in water column' metric or the 'percent saturation in water column' metric) in studies related to aquatic life, especially salmonid spawning and incubation.

The work assignment was comprised of three tasks. The Task 1 effort consisted of designing a summary sheet that could be used to capture relevant findings in a consistent format and applying the summary sheet to a collection 21 articles previously identified and collected by EPA Region 10.

The objective of Task 2 was to expand the search for relevant literature beyond those documents that were identified by means of the initial searches that Region 10 had performed, i.e. the literature that was reviewed in the Task 1 effort. The summary sheet used to perform the evaluation of each document in Task 1 was once again used for the Task 2 evaluations.

Task 2 documents originated from three sources:

1. Region 10 assembled and provided ten additional documents after completion of Task 1. Some of these documents were identified by the contractor from the reference lists of the original Task 1 documents. Others were newly acquired documents of interest to Region 10.

2. Based on search criteria suggested by the contractor, Region 10 performed supplemental searches on their available databases (Dialog, ScienceDirect). Search criteria were as follows:
    a. intragravel DO and stream DO
    b. intragravel dissolved oxygen and stream dissolved oxygen
    c. intragravel DO and stream dissolved oxygen
    d. intragravel dissolved oxygen and water column
    e. intergravel DO and stream DO
    f. intergravel dissolved oxygen and stream dissolved oxygen
    g. (intergravel dissolved oxygen or intergravel DO) and water column
    h. intragravel DO or intragravel dissolved oxygen

    The positive results of the searches were limited, because the search engines were not able to search the full text of the manuscripts. Therefore, searches were limited to manuscript titles and abstracts. Nonetheless, one additional relevant document was identified.

3. In response to a subsequent Technical Directive for Region 10 the contractor conducted targeted Google searches in an attempt to identify additional literature that supports the objective of the work assignment. The Google searches enabled full-text searches, but generated many items that were irrelevant. Professional judgment was exercised in selecting the links that were followed, and the documents that were screened for relevance.

   Search criteria that were used included the following:
   i. intergravel DO depression
   j. IGDO depression
   k. intragravel DO
   l. intergravel DO
   m. IGDO/DO
   n. intergravel depression
   o. intergravel Soulsby

Typically approximately 40 results were explored for each search. As expected, many of the results were project reports, gray literature and regulations and/or regulatory discussions. Seven additional documents relevant to the work assignment questions were obtained through this effort.

The final task (Task 3) of this work assignment is to summarize the findings of all the literature that was identified and evaluated.

3.0 Memorandum Objective

This memorandum comprises the Task 3 effort to summarize findings related to Region 10's three questions/directives based upon all relevant literature reviewed under Tasks 1 and 2. By technical directive EPA requested that AQUA TERRA place greatest priority on addressing question 1, but also briefly address questions 2 and 3.

4.0 Summary of Literature Relevance

Table I provides a basis for overview of all findings. Within the table red stars are used to indicate which documents contain information useful to each of the work assignment questions. In the case of question #2, columns are provided for indicating relevancy to each of four confounding factors that can influence the relationship between stream DO and intergravel DO (IGDO): upwelling/ downwelling, surface water flow variability, sedimentation/substrate, and channel morphology. For question #3, separate columns are included for each of the two metrics that can be used for expressing the DO/IGDO relationship. The information needed to assign red stars was derived directly from the summary sheets for the documents.

Once the documents had all been characterized, Table 1 provided a 'map' for re-visiting the relevant summary sheets for each the three questions to summarize findings in Sections 5 through 7 of this memorandum. Often the documents themselves were re-visited as well to obtain specific information or graphics that warranted inclusion.

TABLE 1. LITERATURE RELEVANCY TO EACH OF THE IGDO RESEARCH QUESTIONS

Manuscript ID	Question #1: Data for DO/IGDO Relationship	Question #2: Confounding factors	Upwelling/downwelling	Surface water flow variability	Sedimentation/Substrate	Channel morphology	Question #3: Metric for DO/IGDO Relationship	Mg/l metric	% saturation metric used
Argent and Flebbe (1999).	★				★			★	
Armstrong et al. (2002)									★
Baxter and Hauer (2000)									
B.C. Ministry of Environment (1999)	★		★	★	★			★	★
Bowen and Nelson (2003)	★		★	★	★			★	
Carl Mesick Consultants (2002)								★	
DeVries (1997)									
Finkenbine et al. (2000)	?		?	?	?	?		?	?
Gately (2005)									
Geist et al. (2006)									
Geist et al. (2002)	★		★					★	
Greig et al. (2007)			★	★	★	★			
Greig et al. (2005)				★	★			★	
Greig et al. (2006)			★	★	★	★		★	
Groves and Chandler (2005)	★		★	★	★			★	
Groves and Chandler (2003a)									
Groves and Chandler (2003b)	★		★		★	★		★	★
Guimond and Burt (2007)	★				★			★	★
Heywood and Walling (2006)	★				★			★	
Horner et al. (2000)									
Ice (2007)	?		?	?	?	?		★	?
Ingendall (2001)					★			★	
Kondolf (2000)								★	
Kondou et al. (2005)			★		★				
Malcolm et al. (2006)	★		★	★		★			★
Malcolm et al. (2005)	★		★	★		★		★	★
Malcolm et al. (2004a)	★		★	★		★		★	
Malcolm et al. (2004b)	★		★	★		★			★
Malcolm et al. (2003a)	★		★	★		★		★	
Malcolm et al. (2003b)	★		★					★	
Merz and Seika (2004)	★							★	
Meyer (2003)	★				★				
Moir et al. (2006)	?		?	?	?	?		?	?
Peterson and Quinn (1996)	★		★		★	★		★	★
Rubin (1998)					★			★	
Soulsby et al. (2001)									
Soulsby et al. (2005)	★		★			★		★	
Zimmerman and Lapointe (2001)									

5.0 Findings for Question #1

Describe the current state of knowledge regarding the relationship between water column DO and intergravel DO. Past literature suggests the DO depression effect between water column and intergravel ranges from 1.0 to 3.0 mg/l. Determine if the body of recent literature supports this finding in relatively sediment-free gravels. Qualitatively describe variability and any noticeable trends or patterns in the body of literature regarding the relationship of water column DO to intergravel DO.

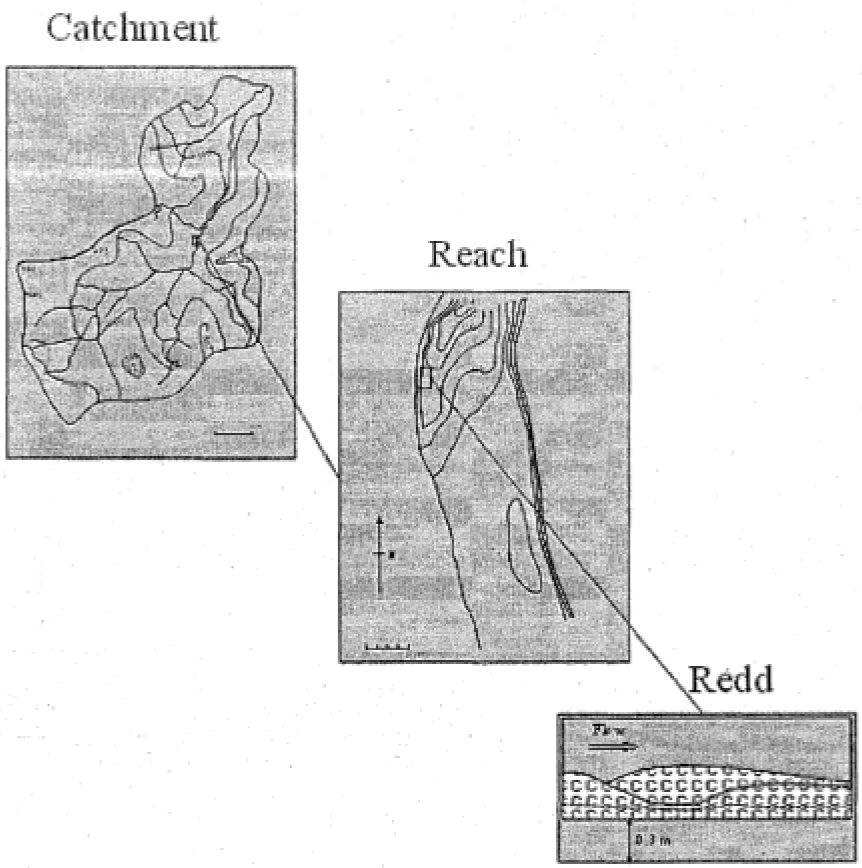
We have drawn several conclusions as a result of the literature reviewed for this work assignment:

1. Monitoring instrumentation and strategies for intergravel DO have improved significantly over the past decade. Literature reports instrumentation that can provide high frequency (if desired) in-situ IGDO measurement that enables a much better understanding of IGDO response to environmental forcing functions (e.g., variable flow).
2. Recent researchers have become increasingly focused on the multiple spatial scales (catchment, stream reach, individual redd) that must be considered in investigating IGDO.
3. Data sets have been developed in the past decade that provide a much broader spatial and temporal definition of IGDO than was previously available (Figure 1). To expand spatial scale some researchers have combined results from multiple stream reaches to characterize catchments. At the same time other researchers have further reduced and discretized spatial scale to investigate IGDO differences between redds and adjacent undisturbed sediments. Still others have performed testing to differentiate between the head, run, and tail areas of individual redds. Unfortunately, the results of these investigations indicate large differences in DO depression (comparable or greater than the 1.0 to 3.0 target range) at the large or very small spatial scales that they investigate. Likewise, high frequency measurements of DO depression at a single location over the duration of a single storm runoff event indicate large differences in DO depression in certain geomorphological settings.
4. The body of literature relating the magnitude of DO depressions to confounding factors has also increased significantly over the past decade. The literature convincingly documents the time- and space-variability of the confounding factors. Recognition of this variability, in particular with respect to fine sediment, makes the task of deciding whether or not a reported DO depression can justifiably be considered representative of a "relatively sediment-free gravel" (see question #1) quite challenging.

The following results from specific documents are relevant to question #1.

Argent & Flebbe (1999) developed artificial redds with initial fine sediment percentages ranging from zero to 25%. The evaluations were performed in a laboratory hydraulic chamber with saturated DO imposed. Result: In the absence of fine sediment, **no IGDO depression** occurred.

B.C. Ministry of Environment (1999) provided comprehensive discussion of previous research relevant to establishing DO criteria, including those for intergravel DO in British Columbia streams. All literature cited was developed pre-1990's and was available for consideration in EPA's previous DO criteria for cold water fisheries.



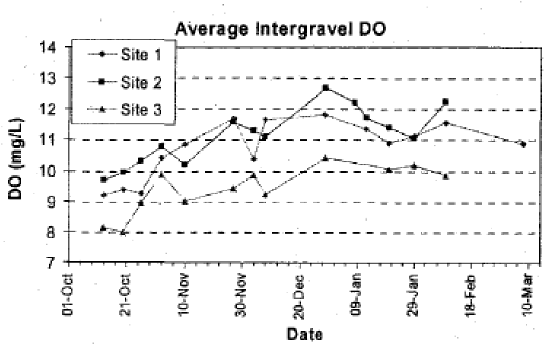
Relevant spatial scales for investigating IGDO. (from Malcolm et al. (2004b)

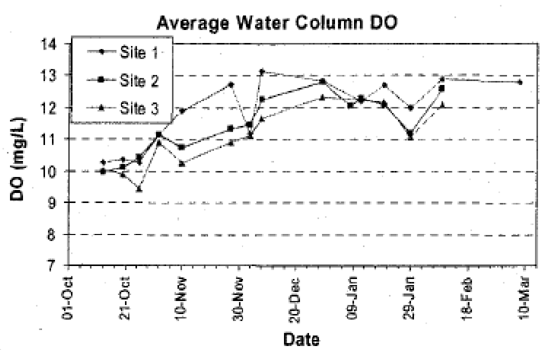
Bowen & Nelson (2003) measured DO depression at depths of 30 cm and 46 cm for one redd on three occasions (Nov, Dec, Mar).

Nov: DO depression at 30 cm = **0.4 mg/l**; DO depression at 46 cm = **0.4 mg/l**
Dec: DO depression at 30 cm = **0.3 mg/l**; DO depression at 46 cm = **0.7 mg/l**
Mar: DO depression at 30 cm = **7.3 mg**/l; DO depression at 46 cm = **6.6 mg/l**

In November and December the gravel beds were low in fine sediments; in March significant amounts of fine sediment had been introduced by storm runoff.

Guimond & Burt (2007) collected paired water column/intergravel DO measurements at three sites. Each sampling day at each site included 12 water column DO samples and 12 intergravel DO samples. Two sites were sampled on 14 days throughout the salmon incubation season, and the third site was sampled on 12 days. The data were not presented in a manner that made it easily interpreted for our purposes. One time series plot was used to display site-averaged intergravel DO at each of the 3 sites on each sampling day, and a separate plot was used to display the same information for water column DO 9 see below). It is recommended that Region 10 request the raw data in order to compute a time series of DO depression values for each of the 3 sites.





Finkenbine et al. (2000) [results will be summarized in final version of memo – not yet evaluated]

Geist et al. (2002) report DO depression values of **0.8 and 1.7 mg/l** for two upstream *downwelling* sites. For three downstream *upwelling* sites DO depression values are **5.5 mg/l; 6.7 mg/l; and 9.4 mg/l**, respectively.

Groves & Chandler (2005) collected data suitable for monthly measurements of DO depression throughout a spawning/emergence period. Two annual cycles were measured and evaluated at the 3 different sites. Intergravel measurements were taken in both undisturbed gravels and in artificial redds, allowing development and comparison of two different DO depression metrics. Results were presented graphically (2 annual graphics for water column DO and undisturbed gravel DO, 2 annual graphics for water column DO and artificial redd DO). DO depression varies significantly from year to year, from month to month, and from site to site. By comparing pairs of monthly water column and intergravel DO concentrations, frequent depressions that are significantly **in excess of 3 mg/l** can be inferred. However, these appear to correspond with seasonal high flows and possibly high sediment loads.

As was the case with the Guimond and Burt data presented above, it is recommended that Region 10 request the raw data in order to compute a time series of DO depression values for each of the 3 sites.

Groves and Chandler (2003b) reports DO depressions derived from multiple samples collected and analyzed at four sites in September 2000. Data included paired DO values for river and 30 cm gravel depth. 35 pairs of river DO and gravel DO were collected.

Mean DO depression at Site #1: (7.98 – 3.53) = **4.45. mg/l**
Site #2: (9.01 – 4.89) = **4.12 mg/l**
Site #3: (8.80 – 5.73) = **3.07 mg/l**
Site #4: (9.86 – 1.45) = **8.41 mg/l**

The authors noted that the large depression at Site #4 was apparently due to joint condition of downwelling plus high levels of fine sediment, so this result falls outside of the constraints imposed by Region 10 on Question 1.

Heywood & Walling (2006) documented DO depression for two streams during two multi-month sampling periods. These results are for artificial redds that had no fine sediment at the beginning of sampling period. During the sampling period, the mean DO depression for each stream showed a general increase over time likely due to natural introduction of fine sediments. Results are as follows:

Stream #1

During runoff season (Sep-Dec 1999): mean DO depression **5.9 mg/l**, with a range of 1.8 to 8.4 mg/l

During spawning season (Jan-Mar 2000): mean DO depression **4.2 mg/l**, with a range of 1.0 to 6.8 mg/l

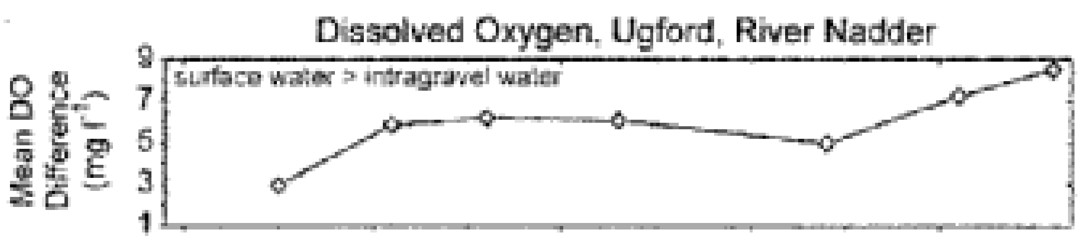
Stream #2

During runoff season (Sep-Dec 1999): mean DO depression **1.1 mg/l**, with a range of 0.6 to 3.9 mg/l

During spawning season (Jan-Mar 2000): mean DO depression **1.8 mg/l**, with a range of 1.0 to 3.0 mg/l

Stream #1 carries a significantly higher sediment load (i.e., 7 to 8 times greater) than Stream #2, and likely cannot be considered sediment-free for the purposes of answering Region 10's Question #1.

The authors developed/used a novel graphical technique for presenting results, that being a time line of mean DO depression within a study stream (see example below).



Ice (2007) [results will be summarized in final version of memo – not yet evaluated]

Malcolm et al. (2006) collected high-frequency data over a full 5 month spawn-to- emergence period including measurements of surface water DO and DO at 150 and 300 mm redd depth. Surface water and 150 mm depth DO measurements stayed consistently in the range of **90 to**

100% saturation with diurnal variation within the range. At 300mm depth there were significant variations in DO saturation with low DO values occurring on the recession leg of hydrographs when contribution from upwelling was greatest.

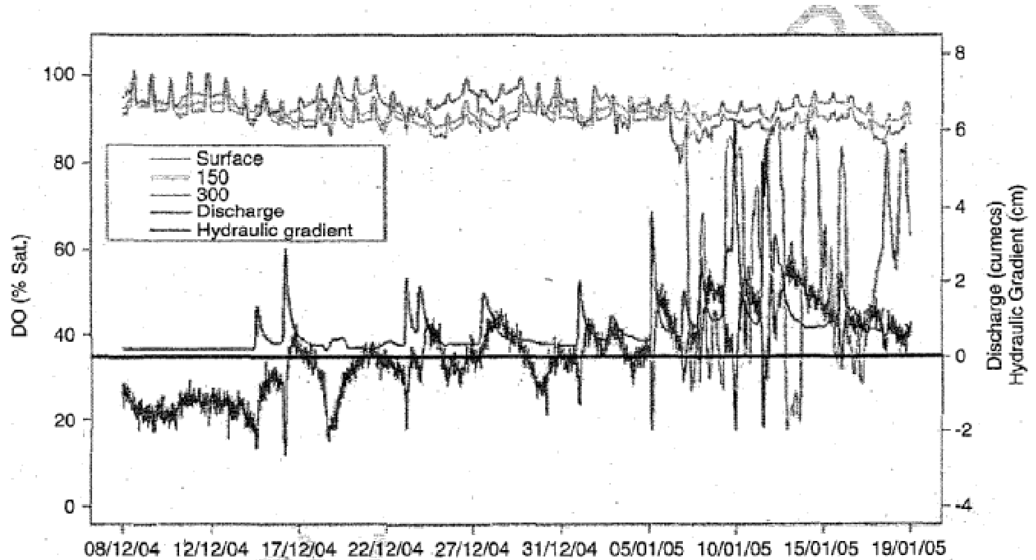
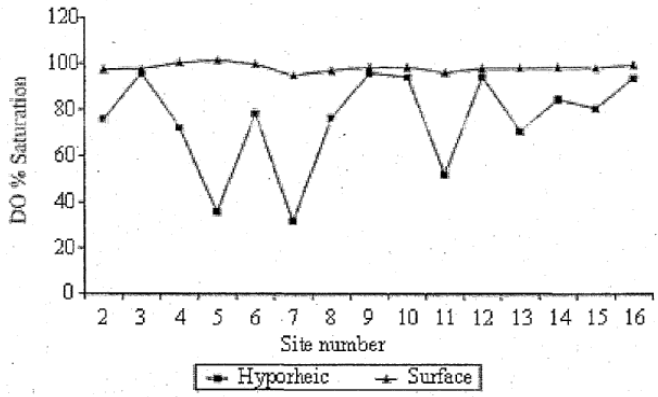


Figure 3. DO concentrations in stream and hyporheic water (150 and 300 mm), relative to discharge and hydraulic gradient. Streamward gradients are indicated where the difference in head between 70 and 38 cm exceeds unity, as indicated by the solid horizontal line

Malcolm et al. (2005) investigated DO depressions on a larger catchment scale, including data from a number of research sites. The focus was on the impact of geomorphic/hydraulic differences within a drainage on variable DO depression. The spatial variability of intergravel DO concentrations greatly exceeded that of surface water. DO depressions within the catchment ranged from 0.7 mg/l to 9.1 mg/l. Larger depressions corresponded with settings dominated by GW upwelling.

Malcolm et al. (2004a) reported temporal and spatial data available over the full 5 month spawn to emergence period as 26 discrete sampling episodes including measurements of surface water DO and DO at 150 and 300 mm redd depth. The study examined DO depression a spatial micro-scale, taking measurements at head, free run and tail of riffles. Surface water and 150 mm depth DO measurements were similar (i.e., there were near-zero DO depression) in the free run of riffles. At 300mm depth there were significant variations in DO saturation with low DO values occurring particularly at the head and tail of riffle.

Malcolm et al. (2004b) presented data that enable the determination of DO depression for 16 sites within a catchment on one sampling day to demonstrate spatial variability (see graph below).



Data were also collected and provided for selected sites for 8 times over the spawn-emergence period to demonstrate temporal variability.

Malcolm et al. (2003a) reports data for DO depression in a degraded bed stream and hence cannot be considered sediment-free for the purposes of answering Region 10's Question #1.

Malcolm et al. (2003b) reported the results of measuring water column and intergravel DO concentrations 18 times at three different redds. Hyporheic DO concentration was measured at depths of 150 mm and 300 mm at upstream and downstream boundaries of each redd. The hyporheic zone of each redd was affected differently by mix of downwelling and upwelling conditions. DO depression values are reported in the table below.

Mean DO (mg/l)	Upstream 150 mm depth	Upstream 300 mm depth	Downstream 150 mm depth	Downstream 300 mm depth
Redd #1	-1.8	-2.3	-1.0	-2.7
Redd #2	-1.7	-5.1	-1.8	-3.7
Redd #3	-1.6	-3.4	-1.8	-2.0

Merz and Seika (2004) provides yet another data set of measurements (see below) that are useful for estimating DO depression values at three depths within the hyporheic zone of a river sampling site. Different columns reflect different sampling dates and conditions. Depressions measured at 15 gravel depth range from **0.2 to 0.5 mg/l**; at 30 cm DO depressions vary from **0.3 to 0.9 mg/l**; and at 45 cm depth the DO depressions vary from **0.1 to 2.0 mg/l**.

Dissolved oxygen (mg/L)						
Ambient	8 5	8 6	8 6	8 2	8 2	7.8
15 cm	8 0 (0.1)	8 3 (0 3)	8 1 (0 1)	8 0 (0 2)	8 0 (0.1)	8 1 (0 2)
30 cm	7 6 (0 4)	8.1 (0 1)	8 1 (0 1)	7 8 (0 1)	7 6 (0 4)	7 5 (0 3)
45 cm	6 7 (1 4)	7 2 (1 2)	6 6 (0 7)	7 5 (0.3)	6 8 (0 1)	7 7 (0 3)

Meyer (2003) suggests that the lower redd is the critical area, and that surface conditions on redd itself can protect lower area from deterioration. The study suggests that most critical factor in survivability is the absence of large amounts of fine sediment in the lower redd, and that DO and permeability correlations with egg death are not as significant. The study reported DO depression that was relatively small (mean depression of **~ 0.6 mg/l**).

Moir et al. (2006) [results will be summarized in final version of memo – not yet evaluated]

6.0 Findings for Question #2

Sources of variability that may explain the difference in water column DO versus intergravel DO are well known (degree of upwelling, sedimentation characteristics, channel morphology, temporal flow regime). From the literature, provide insight on whether or not the relationship between water column DO and intergravel DO varies in a consistent manner due to characteristics of substrate/sediment, channel morphology, or flow.

As Table 1 indicates, the majority of the documents that were reviewed contained at least descriptive information regarding the confounding factors identified in the question #2. Upwelling/downwelling was the most frequently addressed factor followed in descending order by sedimentation, flow variability and finally channel morphology. It is noteworthy that recent studies have also indicated and investigated an additional confounding variable that affects IGDO: organic sediment. In coldwater fishery streams that carry high organic and nutrient loads, these materials can accumulate in the interstitial spaces of the gravel bed through the incubation period and result in microbial action and biochemical oxygen demand that further depresses the intergravel DO concentrations.

The issue of whether and/or how one can relate the confounding factors that affect DO depression in spawning gravels is clearly on the minds of researchers. The approaches that individual researchers are utilizing and the applicability of their results to management and regulation vary. Researchers such as Argent and Flebbe (1999) have developed regression analyses that relate IGDO to fine sediment, but such relationships are site-specific and cannot be reliably transferred to other streams.

Greig et al. (2006) have developed a conceptual model (next page) of IGDO and embryonic survival that identified phenomena influencing IGDO, but no mechanistic processes are defined. Models that represent intergravel flow, sedimentation and DO processes are not currently available, and hence cannot be used as an aid to understanding or predicting DO depressions. And the potential for such models to support regulatory activities is questionable. It is abundantly clear from the literature that was reviewed for this work assignment that the interplay of all the confounding factors varies profoundly over time and space - the relationships are highly dynamic, and hence very difficult to deal with in a regulatory context.

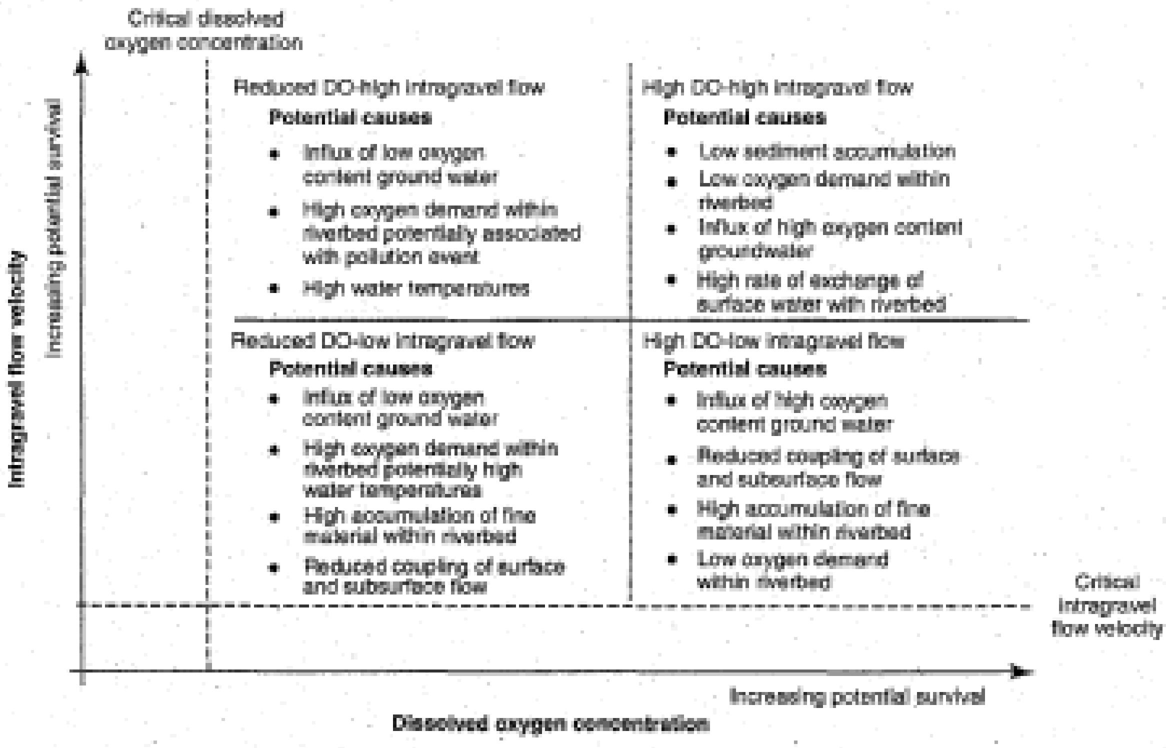
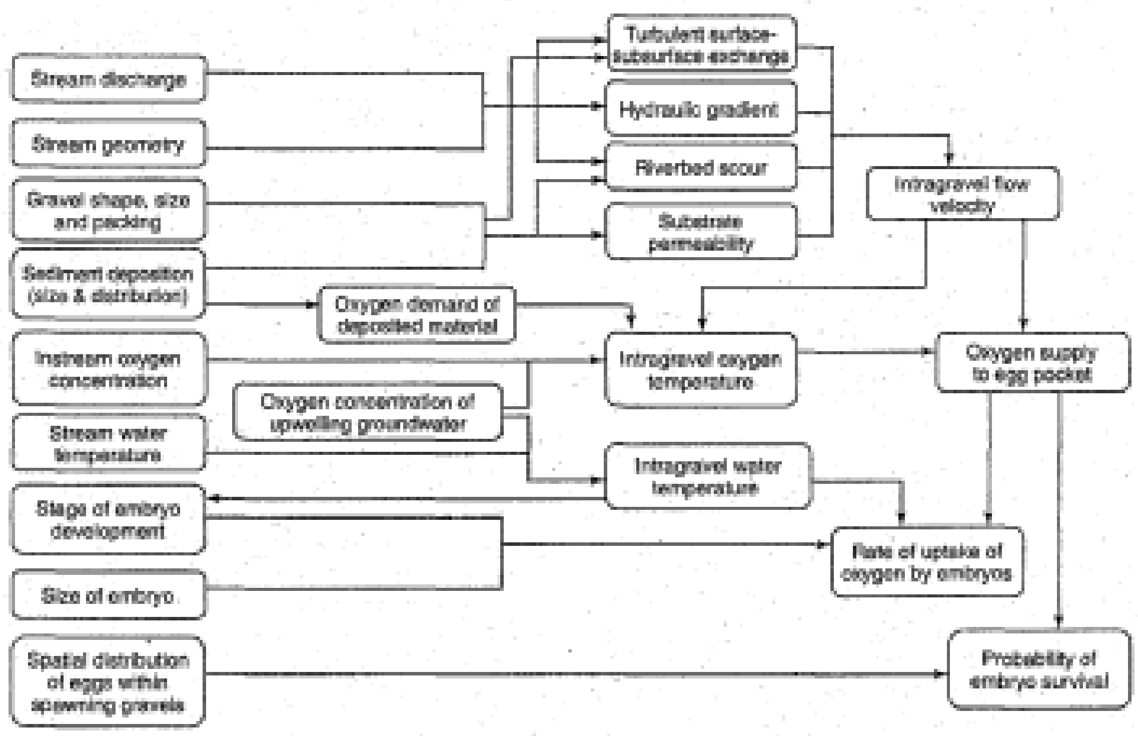


Figure 8. Overview of factors influencing the availability of oxygen to incubating salmonid embryos



From Greig et al. (2006)

7.0 Findings for Question #3

From the literature summarize the justifications authors have developed for using a particular metric (i.e., the 'mg/l DO in water column' metric or the 'percent saturation in water column' metric) in studies related to aquatic life, especially salmonid spawning and incubation.

All DO measurements are initially expressed in units of 'mg/l', and this likely explains why researchers continue to predominantly express their findings using the mg/l metric. The authors of less than a fourth of the documents that were reviewed expressed or referenced results that were expressed as % saturation. Authors are not inclined to offer justification for expressing their research results in the same terms as their instrumentation reports results to them, and accordingly no justification for using this metric was offered in the literature that was reviewed.

Conversion of instrumentation results to "percent saturation" is a conscious decision made by researchers under circumstances where they believe that expression of their results as 'mg/l' does not properly express their findings. Differences in stream elevation and stream temperature affect the DO saturation value (and hence the necessary interpretation one may attach) to specific DO values that are expressed as 'mg/l'. The circumstance of most concern to authors of the literature that was reviewed is when 'coldwater' fisheries are not consistently cold. Two examples follow.

Groves and Chandler (2001) chose to express DO and IGDO values for reaches below the Hells Canyon Complex in the Snake River in both in mg/l and as % saturation. While they did not discuss this decision, the data contained in the report shows many low DO values (in terms of mg/l) for both the river and the gravel that might be misconstrued in terms of cause and effect. Expressed as % saturation, the same values correspond to between 85 and 105% saturation, and are more a result of relatively warm water conditions that they are of any other confounding factors. It should be noted that to a large extent the opportunity to misinterpret DO values expressed in mg/l is reduced when pairs of DO and IGDO measured under the same temperature condition are used to calculate a DO depression.

The second example of a circumstance/application in which conversion of DO concentration values to % saturation may be beneficial is provided in Malcolm et al. (2005). The issue of concern in this study is comparing DO values that are collected over a larger spatial area (i.e., a catchment). Malcolm notes the benefit of converting to % saturation when one is making comparisons between sites of markedly different hyporheic (or surface water) temperatures, a phenomenon which is likely to increase in frequency and magnitude with increasing scale of a study area or an area of regulation.

It is noteworthy that in recent literature a third metric for expressing DO depression appears to be increasing in popularity: the ratio of water column concentration to intergravel DO (i.e., DO/IGDO). The search for expressions of DO depression by the ratio IGDO/DO produced a number of reports and articles suggesting that certain governmental institutions are adopting the use of this metric. Included among these are the Washington Center for Urban Water Resources Management and The Greater Vancouver Regional District. The rationale for using this metric appears to be normalizing the expression of DO depression.

8.0 Full list of Literature Identified and Reviewed

Argent, D.G and P.A. Flebbe. 1999. "Fine sediment effects on brook trout eggs in laboratory Streams." Fisheries Research **39**: 253-263

Armstrong, J.D., P.S. Kemp, G.J.A. Kennedy, M. Ladle and N.J. Milner. 2002. "Habitat requirements of Atlantic salmon and brown trout in rivers and streams." Fisheries Research 62:143-170.

Baxter, C.V. and F.R. Hauer. 2000. "Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (Salvelinus confluentus)." Canadian Journal of Fisheries and Aquatic Research **57**: 1470-1481.

B.C. Ministry of the Environment. 1997. "Water quality: ambient water quality criteria for dissolved oxygen." Chapter 3: Occurrence in the Environment. **In**: Report to the Water Management Branch, Environment and Lands Headquarters Division, Ministry of Environment, Lands and Parks. Prepared pursuant to Section 2(e) of the Environmental Management Act

Bowen, M.D. and S.M. Nelson. 2003. "Environmental variables associated with a Chinook salmon redd in Deer Creek, California." California Fish and Game **89**(4): 176-186.

Carl Mesick Consultants. 2002. "Knights Ferry gravel replenishment project." Report prepared for CALFED Bay Delta Program, Sacramento, CA. 13pp.

DeVries, P. 1997. "Riverine salmonid egg burial depth: review of published data and implications for scour studies." Canadian Journal of Fisheries and Aquatic Sciences **5**4: 1685-1698.

Finkenbine, J.K., J.W. Atwater and D.S. Mavinic. 2000. "Stream health after urbanization." Journal of American Water Resources Association, Vol. 35 Issue 5 pages 1149-1160.

Gately, G. 2005. Water Quality Screening Report July 2003-June 2005: Water quality implementation Grant 04-02-IM-01, Puget Sound Grant 04-02-IM-01, CREP Grant 05-02-CR-01, Jefferson County Conservation District for Washington State Conservation Commission. Olympia, WA.

Geist, D.R., C.S. Abernathy et al. 2006. "Survival, development, and growth of fall Chinook salmon embryos, alevins, and fry exposed to variable thermal and dissolved oxygen regimes." Transactions of the American Fisheries Society 135 1462-1477.

Geist, D.R., T.P. Hanrahan, E.V. Arntzen, G.A. McMichael, C.J. Murray and Y.J. Chien. 2002. "Physiochemical characteristics of the hyporheic zone affect redd site selection by chum salmon and fall Chinook salmon in the Columbia River." North American Journal of Fisheries Management. **22**: 1077-1085.

Greig, S.M., D.A. Sear and P.A. Carling. 2007. "A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos." Hydrological Processes. **21**: 323-334.

Greig, S.M., D.A. Sear, et al. 2005. "The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management." Science of the Total Environment **344**: 241-258.

Greig, S.M., D.A. Sear, et al. 2006. "A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos." *Hydrological Processes*. In Press.

Groves, P.A. and G. Chandler. 2005. "Habitat quality of historic Snake River fall Chinook salmon spawning locations and implications for incubation survival. Part 2: Intra-gravel water quality." River Research and Applications **21**(5): Page: 469-483.

Groves, P.A. and J.A. Chandler. 2003a. "The quality and availability of fall Chinook salmon spawning and incubation habitat downstream of the Hells Canyon complex." Chapter 1, Technical Report Appendix E.3.1-3. Idaho Power Company. 38pp.

Groves, P.A. and J.A. Chandler. 2003b. "The quality and availability of fall Chinook salmon spawning and incubation habitat downstream of the Hells Canyon complex." Chapter 3, Technical Report Appendix E.3.1-3. Idaho Power Company. 122pp.

Guimond, E. and D.W. Burt. 2007. "Puntledge River Egg Incubation Assessment, 2006-2007 Results." Prepared for BC Hydro, Campbell River BC. 45p.

Horner, R.R., C.W. May, E.H. Livingston and J. Maxted. 2000. "Impervious cover, aquatic community health, and stormwater BMPs: Is there a relationship?" Riparian Buffer Conference sponsored by North Carolina Department of Environment and Natural Resources. Raleigh, NC, May 2000.

Heywood, M.J.T. and D.E. Walling. 2006. "The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content on intragravel water and embryo survival." Hydrol. Process. 770-788. (2007)

Ice, G.W. 2007. "Hydrological and Biological Responses to Forest Practices: The Alsea Watersehd Study." In: Stream Temperature and Dissolved Oxygen (ISSN 0070-8356) Volume 199. (ISBN 978-0-387-94385-5)

Ingendahl, D. 2001. "Dissolved oxygen concentration and emergence of sea trout fry form natural redds in tributaries of the Rhine River." Journal of Fish Biology **58**: 325-341.

Kondolf, G.M. 2000. "Assessing salmonid spawning gravel quality." Trans. Amer. Fisheries Soc. 129:262-281.

Kondou, T., N.Takeshita, et al. 2001. “Egg Survival in a fluvial population of masu salmon in relation to intergravel conditions in spawning redds.” Transactions of the American Fisheries Society **130**: 969-974.

Malcolm I.A., C. Soulsby, et al. 2006. “High-frequency logging technologies reveal state-dependent hyporheic process dynamics: implications for hydroecological studies. Hydrological Processes (Wiley InterScience online) 20 (In press).

Malcolm I.A., C. Soulsby, et al. 2005. “Catchment-scale controls on groundwater-surface water interactions in the hyporheic zone: implications for salmon embryo survival.” River Research and Applications **21**:977-989.

Malcolm I.A., C. Soulsby, et al. 2004a. “Hydrologic influences on the hyporheic water quality: implications for salmon egg survival.” Hydrological Process (Wiley InterScience online) In Press.

Malcolm I.A., C. A.F. Youngson, et al. 2004b. “Spatial and temporal variability of groundwater/surface water interactions in upland salmon spawning stream: implications for egg survival.” Hydrology: science and practice for the 21st century, Volume II. Proceedings of the Britsih Hydrological Society International Conference, Imperial College, London, July 2004 Paper no. 4.16.

Malcolm I.A., A.F. Youngson, et al. 2003a. “Survival of salmonid eggs in a degraded gravel-bed stream: Effects of groundwater-surface water interactions.”

Malcolm, I.A, C. Soulsby, A.F. Youngston. 2003b. “Heterogeneity in groundwater-surface water interactions in the hyporheic zone of a salmonid spawning area.” Hydrol. Process. **17**: 601-617.

Merz, J.E. and J.D. Seika (2004). “Evaluation of a spawning habitat enhancement site for Chinook salmon in a regulated California river.” North American Journal of Fisheries Management 24: 397-407.

Meyer, C.B. 2003. “The importance of measuring biotic and abiotic factors in the lower egg pockets to predict coho salmon egg survival.” Journal of Fish Biology **62**: 534-548.

Moir, H.J., C.N. Gibbins, C. Soulsby, and J.H. Webb. 2006. “Discharge and hydraulic interactions in contrasting channel morphologies and their influence on site utilization by spawning Atlantic salmon (Salmo salar).” Can. J. Fish. Aquat. Sci. 63(11): 2567–2585 (2006).

Moir, H.J. and C. Soulsby. 1998. “Hydraulic and sedimentary characteristics of habitat utilized by Atlantic salmon for spawning in the Girnock Burn, Scotland.” Fisheries Management and Ecology **5**:241-254.

Peterson, N.P. and T.P. Quinn. 1996. “Spatial and temporal variation in dissolved oxygen in natural egg pockets of chum salmon in Kennedy Creek, Washington.” Journal of Fish Biology **48**: 131-143.

Rubin, J.F. 1998. “Survival and emergence pattern of sea trout fry in substrata of different compositions.” Journal of Fish Biology **53**: 84-92.

Soulsby, C., I.A. Malcolm, A.F. Youngson, D. Tetzlaff, C.N. Gibbons and D.M. Hannah. 2005. “Groundwater-surface water interactions in upland Scottish rivers: hydrological, hydrochemical and ecological implications.” Scottish Journal of Geology. 41, {1}, 39-49.

Soulsby, C., A.F. Youngston, et al. 2001. “Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment.” The Science of the Total Environment. 265: 295-307.

Zimmerman, A.E. and M.F. Lapointe. 2005. “Intergranular flow velocity through salmonid redds: sensitivity to fines infiltration from low intensity sediment transport events.” River Research and Applications **21**: 865-881.

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Appendix B. Stations, Counts of Theoretical Dissolved Oxygen < 11 mg/L, and Total Counts by Calendar Year During Supplemental Spawning Seasons.

In Table B-1, N is the total number of temperature measurements taken during the supplemental spawning and incubation period since Water Year 1989. The first two digits of the station ID field indicate the Water Resource Inventory Area.

In the year columns, the first value is the number of temperatures in the year that resulted in a theoretical oxygen concentration at 100% saturation < 11 mg/L. (If available, measured pressure was used in the calculation, otherwise elevation was used to estimate pressure.) The second value is the total number of measured temperatures.

Station ID and Name Fields are shaded if no theoretical DO concentrations were < 11 mg/L (during the entire data record). Year fields are shaded if no values were < 11 mg/L. No number indicates no data for that year.

Table B-1. Stations, counts of theoretical DO < 11 mg/L, and total counts by calendar year during supplemental spawning seasons.

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
188	01A120	Nooksack R @ North Cedarville	1/9	1/11	1/8	0/3	0/8	0/3	1/9	0/10	1/10	0/10	0/12	0/10	3/10	1/11	2/10	0/10	0/10	0/10	0/10	0/10
33	01A140	Nooksack R above the MF								0/3	1/8				0/3	2/8				0/3	2/8	
33	01F070	SF Nooksack @ Potter Rd								0/3	1/9				0/3	1/7				0/4	2/7	
34	01G070	MF Nooksack R								0/4	1/8				0/3	0/8				0/3	0/8	
15	03A080	Skagit R above Sedro Woolley											0/3	1/5				0/2	1/5			
5	03B080	Samish R near Prairie							0/5													
8	03C060	Friday Cr below Hatchery					1/4		1/4													
34	04A060	Skagit R @ Concrete	2/8	1/8	1/6	0/3	2/9															
193	04A100	Skagit R @ Marblemount	0/7	1/10	0/12	0/10	0/10	1/9	0/9	0/10	0/9	0/9	0/9	0/9	1/10	0/10	0/8	0/10	0/10	0/9	0/9	0/9
45	04C070	Sauk R near Rockport	0/7	1/10	1/7	0/4	0/6											0/3	1/8			
10	04C120	Sauk R @ Backman Park																0/3	2/7			
10	04E050	Finney Cr near Birdsview						2/4	1/6													
146	05A070	Stillaguamish R near Silvana	0/5	0/7	0/7	0/7	0/8	0/7	0/7	0/6	0/8	0/8	0/7	0/7	0/7	1/7	1/7	0/7	0/8	0/8	0/8	0/7
188	05A090	SF Stillaguamish @ Arlington	1/10	1/12	1/8	0/3	4/8	0/3	2/9	0/10	2/10	2/10	1/10	1/12	3/10	2/10	2/10	2/10	3/10	2/10	2/10	0/10

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
193	05B070	NF Stillaguamish @ Cicero	0/9	1/11	1/7	0/4	3/7	0/3	1/9	0/11	2/10	2/10	1/12	1/9	3/10	3/12	3/10	2/10	4/11	3/11	2/11	0/10
170	05B110	NF Stillaguamish near Darrington				0/3	1/9	0/3	1/10	0/10	0/10	0/10	0/10	1/10	1/12	1/11	4/12	1/11	4/11	1/10	2/11	0/10
22	07B055	Pilchuck R @ Snohomish	2/4	2/4	1/4	2/6				1/4												
3	07B120	Pilchuck R @ Robe-Menzel Rd																		1/3		
3	07B150	Pilchuck R @ Menzel Lake Rd																		0/3		
188	07C070	Skykomish R @ Monroe	1/8	1/7	2/9	4/11	2/6	0/3	1/8	2/10	1/11	2/13	1/10	1/10	2/10	2/10	2/9	1/10	1/10	1/9	1/10	1/10
50	07C120	Skykomish R near Gold Bar	1/8	1/11	1/11	2/8								0/3	2/8							
38	07D070	Snoqualmie R near Carnation	3/8	1/7	2/9	1/6			0/3	1/5												
10	07D100	Snoqualmie R above Carnation												0/5	1/5							
21	07F055	Woods Cr @ Monroe			0/3	3/7			0/3	4/8												
11	07G070	Tolt R near Carnation			0/4	3/7																
9	07P070	Patterson Ck near Fall City				2/5				0/4												
19	07Q070	Raging R @ Fall City			0/3	3/7								0/3	2/6							
174	08C070	Cedar R @ Logan St/Renton	1/6	2/9	1/10	3/9	0/9	1/8	1/7	0/9	1/8	2/8	1/10	1/8	1/8	1/9	2/8	2/9	2/8	3/9	1/8	1/9
9	08C080	Cedar R @ Maplewood					0/3	1/6														
8	08C090	Cedar R @ Maple Valley					0/3	1/5														
4	08C100	Cedar R @ RR Grade Rd																				0/2
138	08C110	Cedar R near Landsburg	1/7	1/8	0/5		0/4	1/8	0/9	0/6	1/8	1/7	0/8	0/5	1/8	1/8	3/8	1/7	1/7	2/6	0/8	1/8
9	08J100	Swamp Cr above Lynnwood										0/3	0/6									
8	08M070	SF Thornton Cr @ 107th Ave NE															1/3	1/5				
10	09A130	Green above Big Soos/Auburn					0/3	3/7														
213	09A190	Green R @ Kanaskat	3/8	1/10	2/11	4/11	3/11	6/13	2/10	2/11	1/10	4/12	1/10	2/10	1/11	2/10	3/10	3/10	4/11	3/10	2/10	2/9
23	09B090	Big Soos Cr near Auburn					0/4	5/8				0/4	2/7									
10	09F150	Newaukum Creek near Enumclaw										0/3	2/7									
10	10A075	Puyallup R @ East Main St																0/3	2/7			
12	10A080	Puyallup R near Sumner															0/3	3/9				
50	10A110	Puyallup R @ Orting	0/9	0/13	0/8	0/3	0/6		0/3	1/8												
12	10B070	Carbon R near Orting				0/4	1/8															

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
11	10C085	White R near Sumner							0/3	2/8												
95	10C095	White River @ R Street										0/3	1/12	2/10	4/10	2/10	3/10	3/10	3/12	2/7	0/3	0/7
11	10C130	White R @ Buckley				0/3	2/8															
10	10D070	Boise Cr @ Buckley												0/3	4/7							
9	10F090	South Prairie Ck near S. Prairie				0/3	1/6															
213	11A070	Nisqually R @ Nisqually	4/9	2/12	2/9	3/12	2/12	5/13	2/10	3/10	2/10	2/10	0/10	4/12	3/10	3/10	3/10	4/10	3/10	3/11	2/10	1/10
23	11A080	Nisqually R @ McKenna		2/7	1/6	0/3	1/7															
13	11A090	Nisqually R above Powell Cr	2/9	0/4																		
18	15A070	Dewatto R near Dewatto									0/3	2/6									0/3	2/6
10	15D070	Tahuya R @ Tahuya River Rd																			0/3	2/7
9	15D090	Tahuya R near Belfair									0/3	2/6										
20	15E070	Union R near Belfair									0/3	1/6				0/5	1/6					
41	15F050	Big Beef Cr @ mouth																0/3	3/11	2/8	1/8	0/8
217	16A070	Skokomish R near Potlatch	0/10	0/11	0/10	4/12	0/12	0/9	2/11	1/11	0/12	0/10	0/12	0/10	3/10	1/10	2/12	3/10	1/12	0/9	0/10	0/10
165	16C090	Duckabush R near Brinnon					0/3	2/11	1/10	0/9	0/11	0/9	0/10	0/10	0/12	0/9	0/10	1/11	0/12	0/13	0/9	0/12
8	16D070	Dosewallips R @ Brinnon					0/3	1/5														
20	17A060	Big Quilcene R near mouth											0/3	0/10	1/7							
22	17A070	Big Quilcene R near Quilcene					0/4	1/8				0/3	0/7									
10	17B070	Chimacum Cr near Irondale					0/3	3/7														
12	17B100	Chimacum Cr @ Chimacum					0/4	4/8														
22	17C070	Jimmycomelately Cr near mouth											0/3	1/12	1/7							
12	17G060	Tarboo Cr near mouth																		2/4	2/8	
64	18A050	Dungeness R near mouth												0/5	1/11	0/9	1/11	3/11	1/10	1/7		
38	18A070	Dungeness R near Sequim					0/3	2/6				0/3	0/9	0/9	2/8							
20	19C060	West Twin R near mouth																	0/4	2/4	0/5	0/5
16	19D070	East Twin R near mouth																	0/4	2/4	1/3	0/4
17	19E060	Deep Cr near mouth																	0/4	1/4	1/4	0/4
12	20A090	Soleduck R near Forks					0/3	3/9														

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
162	20B070	Hoh R @ DNR Campground					0/3	2/10	3/10	1/11	0/11	2/10	0/10	0/10	3/10	2/10	2/10	1/10	1/13	1/9	1/11	0/11
5	20D070	Dickey R near La Push									2/5											
106	22A070	Humptulips R near Humptulips	3/4	2/6	2/8	2/5	2/5	3/7	2/5	1/5	2/5	1/6	0/6	1/7	2/5	2/5	1/5	2/5	1/4	2/4	1/4	0/4
5	22B070	WF Hoquiam R near Hoquiam						2/5														
37	22G070	Satsop R near Satsop	2/8	3/12	1/6	0/4	3/7															
153	23A070	Chehalis R @ Porter	2/5	1/7	1/7	1/7	0/8	0/7	0/7	0/8	0/7	0/7	0/9	0/9	0/7	0/7	1/7	1/7	1/7	3/10	1/7	0/9
53	23A100	Chehalis R @ Prather Rd						1/3	0/8	0/8	0/4				0/5	0/7	2/7	1/7	0/4			
8	23A130	Chehalis R @ Claquato								0/3	0/5											
227	23A160	Chehalis R @ Dryad	6/9	4/10	4/12	5/11	4/11	5/14	4/11	1/12	2/13	3/10	1/10	3/12	4/10	3/11	3/12	3/11	6/11	3/10	3/12	3/10
7	23A170	Chehalis R near Doty																				0/4
10	23B050	Newaukum @ mouth				1/3	3/7															
10	23B070	Newaukum R near Chehalis								0/3	3/7											
21	23D055	Skookumchuck R @ Centralia				1/3	3/8			0/3	3/7											
29	23E070	Black River @ Moon Road Bridge			5/7		3/6		2/5	2/5	3/6											
18	23G070	SF Chehalis R @ Beaver Creek Rd								0/3	4/9											0/3
15	24B130	Willapa R @ Lebam	2/4	2/5		3/6																
68	24F070	Naselle R near Naselle				2/4			1/4	0/4	0/4	0/6	0/4	0/6	2/4	1/4	1/4	1/4	2/5	1/4	0/4	2/5
4	25B070	Grays R near Grays River										0/4										
6	25C070	Elochoman R near Cathlamet										0/4										
16	25E100	Abernathy Cr @ DNR																	0/5	0/3	0/4	1/4
16	25F100	Mill Cr @ DNR																	0/5	0/3	0/4	1/4
3	26B100	Cowlitz R @ Castle Rock																		1/3		
9	26B150	Cowlitz R @ Toledo			0/3	2/6																
4	26C080	Coweeman R av Goble Cr										1/4										
15	26D070	Toutle R near Castle Rock	2/3	1/4	1/4	3/4																
75	27B070	Kalama R near Kalama	0/4	0/4	0/5	1/4			1/4	0/4	0/4	1/4	0/4	0/4	2/4	0/4	0/4	1/4	1/5	1/3	1/4	0/4
79	27D090	EF Lewis R near Dollar Corner	2/3	1/4	0/4	2/4			1/5	0/5	1/4	1/4	0/6	1/6	2/4	0/4	0/4	1/4	2/5	1/3	1/4	0/4
4	27E070	Cedar Cr near Etna							2/4													

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
13	28B110	Washougal R below Canyon Ck							1/5			0/4		0/4								
4	28J070	Little Washougal Cr @ Blair Road																			1/4	
10	29B070	White Salmon R near Underwood						0/3	1/7													
9	29C070	Wind R near Carson						0/3	1/6													
18	30B060	Klickitat R near Lyle					0/3	1/9	0/6													
21	30C070	Little Klickitat near Wahkiacus					0/4	3/11	2/6													
11	30C090	Little Klickitat R @ Olson Rd																		1/3	2/7	
8	32B130	Touchet R @ Dayton			2/3	3/5																
3	32B140	Touchet R above Dayton									0/3											
3	32C070	Mill Cr @ Swegle Rd															1/3					
12	35B150	Tucannon R near Marengo								1/3	4/9											
4	35L050	Almota Cr @ mouth																			3/4	
4	35Y070	Penewawa Cr near mouth																			2/4	
11	37G120	Ahtanum Cr @ 62nd Ave													2/5	1/5						
8	38G070	Cowiche Cr @ Powerhouse Rd																	3/4	1/4		
9	38G120	Cowiche Cr @ Zimmerman rd													2/4	1/4						
182	39A090	Yakima R near Cle Elum	0/2	3/13	2/11	1/7		1/3	2/9	3/11	2/14	2/9	2/9	2/9	2/9	4/11	2/9	3/10	3/10	2/9	2/11	1/11
9	39B090	Cle Elum R near Roslyn			1/3	2/6																
11	39D070	Teanaway R near Cle Elum			0/3	1/8																
171	45A070	Wenatchee R @ Wenatchee	2/8	0/10	1/9	1/7	2/7	1/8	1/7	1/10	0/8	1/8	1/8	0/10	1/8	1/9	3/9	1/8	1/8	0/8	1/8	1/8
8	45A075	Wenatchee R @ Sleepy Hollow Br																		0/3	0/5	
191	45A110	Wenatchee R near Leavenworth	2/9	0/11	0/12	2/10	2/9	2/9	1/8	1/9	1/9	1/9	0/9	0/9	4/13	1/9	1/9	2/9	2/9	0/10	1/9	1/8
12	45B070	Icicle Cr near Leavenworth				1/3	3/9															
8	45C060	Chumstick Cr near mouth															1/4	2/4				
19	45C070	Chumstick Cr near Leavenworth									1/4	1/6	1/4	1/4		1/1						
10	45J070	Nason Cr near mouth																			0/2	2/7
11	45K050	White R @ Road 6500 Bridge																			0/3	1/8
4	45L050	Little Wenatchee @ 2 Rvr Grav.Pit																				0/4

N	Station ID	Station Name	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
8	45Q060	Eagle Cr near mouth															1/4	1/4				
84	46A070	Entiat R near Entiat	1/7	0/6	0/4			0/7	0/5	2/4	0/4	0/3	1/5	0/4	2/4	1/4	1/4	1/4	0/5	0/4	0/4	0/5
188	48A070	Methow R near Pateros	3/7	1/9	0/9	3/11	5/12	1/10	1/9	2/10	0/13	0/8	1/9	1/9	3/11	2/9	2/8	2/9	2/8	1/11	2/9	1/5
5	48A075	Methow R near Pateros @ Metal Br.																				1/3
178	48A140	Methow R @ Twisp	3/8	0/9	0/6	0/3	3/7	0/3	1/9	2/10	0/9	0/10	0/13	0/10	3/11	1/9	1/10	1/10	1/8	1/9	1/9	2/9
11	48A150	Methow R @ Winthrop																			0/4	2/7
9	48B070	Chewuch R @ Winthrop																			0/3	2/6
7	48D070	Twisp River near mouth																				¼
92	49B070	Similkameen R @ Oroville	2/4	0/5	0/4	1/5	2/4	2/7	1/5	2/4	1/4	1/3	0/4	1/6	2/6	1/4	1/4	1/5	2/4	2/4	1/4	2/4
4	49F070	Bonaparte Cr @ Tonasket																			2/4	
		Percent of stations with ≥1 results < 11	76%	71%	58%	68%	51%	71%	71%	49%	56%	51%	38%	44%	83%	76%	86%	79%	73%	67%	60%	50%

Appendix C. Stations Failing to Meet Several Hypothetical Criteria.

In Table C-1, The first two digits of the station ID field indicate the Water Resource Inventory Area.

Hypothetical criteria column headings are defined as follows:

9.5	=	9.5 mg/L
11	=	11.0 mg/L
11+95%	=	11 mg/L unless saturation >95%
11+90%	=	11 mg/L unless saturation >90%
30Day11	=	11 mg/L 30-day mean
95%	=	95% saturation
90%	=	90% saturation

Cells shown in pink indicate that at least one grab sample result was less than the criterion except 30Day11, where pink indicates that two consecutive monthly samples were less than the criterion. (This matrix is for illustration only; grab samples are neither daily minimums nor averages. Ecology's 303(d) listing policy may require that grab sample data be interpreted differently than they have been in this matrix.)

Water quality standards should not be set based on how many stations might meet a theoretical criterion, and this matrix is not intended for that purpose. However, it may be instructive to see how particular stations presumed to be either impaired or relatively unimpaired might be assessed against different theoretical criteria.

Table C-1. Stations failing to meet several hypothetical criteria.

Station ID	Station Name	9.5	11	11+ 95%	11+ 90%	30Day 11	95%	90%
01A120	Nooksack R @ North Cedarville							
01A140	Nooksack R above the MF							
01F070	S.F. Nooksack @ Potter Rd							
01G070	M.F. Nooksack R							
03A080	Skagit R above Sedro Woolley							
03B080	Samish R near Prairie							
03C060	Friday Cr below Hatchery							
04A060	Skagit R @ Concrete							
04A100	Skagit R @ Marblemount							
04C070	Sauk R near Rockport							
04C120	Sauk R @ Backman Park							
04E050	Finney Cr near Birdsview							
05A070	Stillaguamish R near Silvana							
05A090	SF Stillaguamish @ Arlington							
05B070	NF Stillaguamish @ Cicero							
05B110	NF Stillaguamish near Darrington							
07B055	Pilchuck R @ Snohomish							
07B120	Pilchuck R @ Robe-Menzel Rd							
07B150	Pilchuck R @ Menzel Lake Rd							
07C070	Skykomish R @ Monroe							
07C120	Skykomish R near Gold Bar							
07D070	Snoqualmie R near Carnation							
07D100	Snoqualmie R above Carnation							
07F055	Woods Cr @ Monroe							
07G070	Tolt R near Carnation							
07P070	Patterson Ck near Fall City							
07Q070	Raging R @ Fall City							
08C070	Cedar R @ Logan St/Renton							
08C080	Cedar R @ Maplewood							
08C090	Cedar R @ Maple Valley							
08C100	Cedar R @ RR Grade Rd							
08C110	Cedar R near Landsburg							
08J100	Swamp Cr above Lynnwood							
08M070	SF Thornton Cr @ 107th Ave NE							
09A130	Green above Big Soos/Auburn							
09A190	Green R @ Kanaskat							
09B090	Big Soos Cr near Auburn							
09F150	Newaukum Cr near Enumclaw							
10A075	Puyallup R @ East Main St.							
10A080	Puyallup R near Sumner							
10A110	Puyallup R @ Orting							
10B070	Carbon R near Orting							
10C085	White R near Sumner							
10C095	White R @ R Street							
10C130	White R @ Buckley							
10D070	Boise Cr @ Buckley							
10F090	South Prairie Ck near S. Prairie							
11A070	Nisqually R @ Nisqually							
11A080	Nisqually R @ McKenna							
11A090	Nisqually R above Powell Cr							

Station ID	Station Name	9.5	11	11+ 95%	11+ 90%	30Day 11	95%	90%
15A070	Dewatto R near Dewatto							
15D070	Tahuya R @ Tahuya R Rd							
15D090	Tahuya R near Belfair							
15E070	Union R near Belfair							
15F050	Big Beef Cr @ mouth							
16A070	Skokomish R near Potlatch							
16C090	Duckabush R near Brinnon							
16D070	Dosewallips R @ Brinnon							
17A060	Big Quilcene R near mouth							
17A070	Big Quilcene R near Quilcene							
17B070	Chimacum Cr near Irondale							
17B100	Chimacum Cr @ Chimacum							
17C070	Jimmycomelately Cr near mouth							
17G060	Tarboo Cr near mouth							
18A050	Dungeness R near mouth							
18A070	Dungeness R near Sequim							
19C060	West Twin R near mouth							
19D070	East Twin R near mouth							
19E060	Deep Cr near mouth							
20A090	Soleduck R near Forks							
20B070	Hoh R @ DNR Campground							
20D070	Dickey R near La Push							
22A070	Humptulips R near Humptulips							
22B070	WF Hoquiam R near Hoquiam							
22G070	Satsop R near Satsop							
23A070	Chehalis R @ Porter							
23A100	Chehalis R @ Prather Rd							
23A130	Chehalis R @ Claquato							
23A160	Chehalis R @ Dryad							
23A170	Chehalis R near Doty							
23B050	Newaukum R @ mouth							
23B070	Newaukum R near Chehalis							
23D055	Skookumchuck R @ Centralia							
23E070	Black R @ Moon Road Bridge							
23G070	SF Chehalis R @ Beaver Cr Rd							
24B130	Willapa R @ Lebam							
24F070	Naselle R near Naselle							
25B070	Grays R near Grays R							
25C070	Elochoman R near Cathlamet							
25E100	Abernathy Cr @ DNR							
25F100	Mill Cr @ DNR							
26B100	Cowlitz R @ Castle Rock							
26B150	Cowlitz R @ Toledo							
26C080	Coweeman R above Goble Cr							
26D070	Toutle R near Castle Rock							
27B070	Kalama R near Kalama							
27D090	EF Lewis R near Dollar Corner							
27E070	Cedar Cr near Etna							
28B110	Washougal R below Canyon Ck							
28J070	Little Washougal Cr @ Blair Rd							
29B070	White Salmon R near Underwood							
29C070	Wind R near Carson							

Station ID	Station Name	9.5	11	11+ 95%	11+ 90%	30Day 11	95%	90%
30B060	Klickitat R near Lyle							
30C070	Little Klickitat near Wahkiacus							
30C090	Little Klickitat R @ Olson Rd							
32B130	Touchet R @ Dayton							
32B140	Touchet R above Dayton							
32C070	Mill Cr @ Swegle Rd							
35B150	Tucannon R near Marengo							
35L050	Almota Cr @ mouth							
35Y070	Penewawa Cr near mouth							
37G120	Ahtanum Cr @ 62nd Ave							
38G070	Cowiche Cr @ Powerhouse Rd							
38G120	Cowiche Cr @ Zimmerman Rd							
39A090	Yakima R near Cle Elum							
39B090	Cle Elum R near Roslyn							
39D070	Teanaway R near Cle Elum							
45A070	Wenatchee R @ Wenatchee							
45A075	Wenatchee R @ Sleepy Hollow							
45A110	Wenatchee R near Leavenworth							
45B070	Icicle Cr near Leavenworth							
45C060	Chumstick Cr near mouth							
45C070	Chumstick Cr near Leavenworth							
45J070	Nason Cr near mouth							
45K050	White R @ Road 6500 Bridge							
45L050	Little Wenatchee @ 2 Rvr Grav.Pit							
45Q060	Eagle Cr near mouth							
46A070	Entiat R near Entiat							
48A070	Methow R near Pateros							
48A075	Methow R near Pateros @ Metal Br							
48A140	Methow R @ Twisp							
48A150	Methow R @ Winthrop							
48B070	Chewuch R @ Winthrop							
48D070	Twisp R near mouth							
49B070	Similkameen R @ Oroville							
49F070	Bonaparte Cr @ Tonasket							
	Number of stations failing to meet criterion	29	113	91	72	36	65	46

Appendix D. Glossary, Acronyms, and Abbreviations.

Aeration: Process by which are is circulated through, mixed with or dissolved in a water.

Ambient: Background (environmental). Away from point sources of contamination.

Anadromous: Types of fish, such as salmon, that go from the sea to freshwater to spawn.

Anthropogenic: Human-caused.

Biological oxygen demand: Rate of uptake of dissolved oxygen by biological organisms.

Biota: Flora (plants) and fauna (animals).

Char: Char (genus *Salvelinus*) are distinguished from trout and salmon by the absence of teeth in the roof of the mouth, presence of light colored spots on a dark background, absence of spots on the dorsal fin, small scales, and differences in the structure of their skeleton. (Trout and salmon have dark spots on a lighter background.)

Clean Water Act: Federal Act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Designated uses: Those uses specified in Chapter 173-201A WAC (Water Quality Standards for Surface Waters of the State of Washington) for each waterbody or segment, regardless of whether or not the uses are currently attained.

Diel: Of, or pertaining to, a 24-hour period.

Diurnal: Of, or pertaining to, a day or each day; daily. (1) Occurring during the daytime only, as different from nocturnal or crepuscular, or (2) Daily; related to actions which are completed in the course of a calendar day, and which typically recur every calendar day (e.g., diurnal temperature rises during the day, and falls during the night).

Eutrophication: An increase in productivity resulting from nutrient loads from human activities such as fertilizer runoff and leaky septic systems.

Grab sample: A discrete sample from a single point in the water column.

Hyporheic: The area under and along the river channel where surface water and groundwater meet

Intergravel dissolved oxygen (IGDO) depression: The difference in dissolved oxygen concentration between the dissolved oxygen found in surface water and the dissolved oxygen found in the underlying gravel substrate. Hydraulic, chemical, and biochemical processes often contribute to a lower dissolved oxygen concentration found in the intragravel habitat.

Intergravel/ intragravel: Gravel in the bottom of a stream. The interstitial spaces of a stream substrate. (These two descriptions seem to be used interchangeably in the literature on this topic.)

Median: The number separating the higher half of a sample, a population, or a probability distribution from the lower half.

Morphology: Shape (e.g., channel morphology).

mm Hg: millimeters of mercury.

Nonpoint source: Unconfined and diffuse sources of contamination. Pollution that enters water from dispersed land-based or water-based activities. This includes, but is not limited to, atmospheric deposition, surface water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the National Pollutant Discharge Elimination System program.

Nutrient: Substance such as carbon, nitrogen, and phosphorus used by organisms to live and grow. Too many nutrients in the water can promote algal blooms and rob the water of oxygen vital to aquatic organisms.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Photosynthesis: The process by which plants and other photoautotrophs generate carbohydrates and oxygen from carbon dioxide, water, and light energy in chloroplasts.

Reach: A specific portion or segment of a stream.

Redd: An individual nest or depression in the gravel excavated by fish in the trout and salmon family for depositing eggs. Multiple redds make up a bed.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Any fish that belong to the family *Salmonidae*. Basically, any species of salmon, trout, or char. www.fws.gov/le/ImpExp/FactSheetSalmonids.htm

Seep: A place where small flows of water exit the ground or other solid surface.

Spatial: How concentrations differ among various parts of the river.

Spawning and incubation period: The season during which salmonid species are spawning or incubating the gravel.

Supplemental spawning season: The spawning and incubation periods identified in WAC 173-201A for supplemental temperature criteria.

Temporal trends: Characterize trends over time.

Water year: October 1 through September 30. For example, WY07 is October 1, 2006 through September 30, 2007.

303(d) List: Section 303(d) of the federal Clean Water Act requires Washington State periodically to prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality-limited waterbodies (ocean waters, estuaries, lakes, and streams) that fall short of state surface water quality standards, and are not expected to improve within the next two years.

1-DMax or 1-day maximum temperature: The highest water temperature reached on any given day. This measure can be obtained using calibrated maximum/minimum thermometers or continuous monitoring probes having sampling intervals of thirty minutes or less.

7-DADMax or 7-day average of the daily maximum temperatures: The arithmetic average of seven consecutive measures of daily maximum temperatures. The 7-DADMax for any individual day is calculated by averaging that day's daily maximum temperature with the daily maximum.

7-day mean minimum or 7-day average mean minimum: The arithmetic average of seven consecutive daily mean dissolved oxygen values. Daily mean values should be calculated from multiple daily values that capture the maxima and minima of the dissolved oxygen diel cycle in a waterbody.

7-day minimum mean or 7-day average of daily minimum: The arithmetic average of seven consecutive measures of daily minimum dissolved oxygen values.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms and Abbreviations

BP	Barometric pressure
CFR	Code of Federal Regulations
DO	Dissolved oxygen
EAP	Environmental Assessment Program (Ecology)
Ecology	Washington State Department of Ecology
EF	East Fork
EPA	U.S. Environmental Protection Agency
Hg	Mercury
IGDO	Intragravel dissolved oxygen
MF	Middle Fork
mm	Millimeters
mg/L	Milligrams per liter
NOAA	National Oceanic and Atmospheric Administration
NOAA Fisheries	National Marine Fishery Service
OAR	Oregon Administrative Rules
SF	South Fork
SWDO	Surface water dissolved oxygen
USFWS	U.S. Fish and Wildlife Service
WAC	Washington Administrative Code
WF	West Fork
WQP	Water Quality Program (Ecology)
WRIA	Water Resources Inventory Area