To: **Washington Citizens**

From: **Megan White, P.E., Manager**
Water Quality Program
Department of Ecology

Subject: **Proposed Dissolved Oxygen Criteria**
Decision Process for Ecology's Proposed Rule

This memorandum constitutes the decision-making process that resulted in the Washington Department of Ecology's (Ecology) proposal for changes to the dissolved oxygen (D.O.) criteria.

Proposed Alternative

Ecology's proposal is to apply limits for D.O. to protect salmonids and other aquatic species using a long-term, 90-day average coupled with a one-day minimum. D.O. limits are proposed to protect key aspects of aquatic life including: char; salmon, steelhead, and trout spawning/rearing; salmon, steelhead, and trout rearing only; non-indigenous interior redband trout; and indigenous warm-water fish habitats.
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Background

Ecology administers the state's surface water quality standards regulations (Chapter 173-201A WAC). These regulations establish minimum requirements for the quality of water that must be maintained in lakes, rivers, streams, and marine waters. This is done to ensure that all beneficial uses associated with these waterbodies are protected.

As part of a public review of its water quality standards in the early 1990's, Ecology convened a technical work group to evaluate the water quality criteria established to protect fresh water aquatic communities. One of the recommendations of the work group was for Ecology to re-evaluate the existing criteria for D.O.

The existing state surface water quality standards group all fresh waters in the state into classes that are protected at different levels. The standards contain three D.O. criteria levels that are applied to fresh waters throughout the state:

Class AA - 9.5 mg/l
Class A - 8.0 mg/l
Class B - 6.5 mg/l

Class AA and Class A standards provide two different levels of protection for the same set of beneficial uses and are intended to protect salmonid spawning, rearing, and migration. Class AA waters are predominately established within forested upland areas, but Class A waters are found broadly throughout the state. Class B waters are designed only to protect salmonid rearing and migration, and was not intended to fully protect spawning. There are only a small number of waterbodies in the state that have been assigned the Class B designation. With each class, the criteria are applied as the lowest single daily minimum measurement of D.O. occurring in the waterbody. The current rule also has a Lake Class which does not apply numeric D.O. criteria limits but requires that lakes are maintained at natural levels.

Basis for Proposed Alternative

Ecology's proposed alternative for D.O. is based upon a review of the technical literature and in consideration of the species and environmental conditions existing in Washington. Consideration was also given to the ability to implement the criteria in a feasible and reasonable manner. Available scientific and technical literature were assessed to establish D.O. recommendations that will maintain healthy and productive populations of the state's aquatic species and not hinder efforts to recover populations of fish species that are threatened with extinction.

In determining draft D.O. criteria numbers for the proposal, Ecology focused on making technical recommendations that would not knowingly result in a predictable increase in the mortality of incubating eggs or a significant change in sub-lethal factors such as spawning period, fish growth, or maintenance of maximum swimming speeds. Because conditions such as sedimentation can completely eliminate oxygen reaching the developing eggs, however, the state cannot guarantee that oxygen would never be a limiting factor. And because of the gaps and variability in the available data and our knowledge of how some sublethal changes affect the ultimate well being of aquatic species, we cannot always establish with complete confidence a single fixed value beyond which detrimental effects would always occur.

In recommending the D.O. limits, Ecology summarized conclusions from the scientific literature on what would be expected to provide full protection for specific life stages of: 1) salmon, char, and trout; 2) warm water non-salmonid species, and 3) macroinvertebrates (i.e., aquatic insects).

Where appropriate, D.O. values common to the overlapping ranges of minimum D.O. requirements of individual life-stages were identified and used to create the synthesis recommendations for individual species or life-stages. This allowed a recommendation for non-salmonids that combined all life stages into single criteria for non-salmonid waters. Adherence to the proposed minimum D.O. criteria should be expected to provide full protection for Washington's native aquatic life communities.

Of all water quality parameters, D.O. is possibly the most affected by the actions of humans. Human actions increase the biological oxygen demand by contributing organic and inorganic materials that are metabolized by stream organisms (who use available oxygen to process the waste), and by actions that raise the temperature of the waterbodies (increasing water temperature reduces the ability of the water to hold oxygen in saturation). Against this backdrop of human influence, the available technical information generally demonstrates that aquatic species would benefit from oxygen levels that are higher than what can often be held naturally in saturation and that any reduction in oxygen can have some biological effect that can be measured by researchers. These two factors, one biologic and one human, when considered together introduce serious practical and scientific challenges for the state in recommending water quality criteria for D.O. Ecology's recommendation seeks to identify levels of effect that, while a departure from the experiential optimal levels, will still fully protect (or allow for the re-establishment of) healthy, robust aquatic communities. The reviewer is asked to keep this critical factor in mind as they examine the foundation for the recommendations.

Standard Units for Measuring Dissolved Oxygen

Two standards are used in Ecology's proposed alternative: 1) a longer-term average daily minimum (called the 90-Day Average of the Daily Minimum or 90-DADMin), and 2) a short-term single daily minimum. These two metrics work together to provide for a healthy oxygen environment and to allow full use of the existing methods for collecting field samples for D.O. (predominantly monthly grab samples). The basis for having two metrics is that the health of aquatic species depends upon maintaining both high longer-term (>90-day) average oxygen levels and preventing unhealthy short term (1-day) depressions of oxygen.

Including both the long-term daily minimum average and the single daily minimum criteria was found to achieve the biological goal with a minimum increase in stringency over the state's current oxygen criteria. The average daily minimum value is based on long-term laboratory and field testing and on recognizing the biological importance of the daily minimum oxygen concentrations to long-term performance. The limit on the single daily minimum values acts in essence as an insurance policy against short-term (e.g., 30-60 days) depressions of oxygen that could otherwise negate the benefits of maintaining more favorable long-term average minimum oxygen levels. The single daily minimum values generally represent oxygen levels that have had mixed performance in long-term laboratory tests, sometimes showing strong protection for the biota but sometimes significantly reducing biological performance.

Year-round Criteria Applied to Protect both Spawning and Rearing

For all key species identified, Ecology is proposing a single "healthy stream" criterion that is designed to protect both spawning and rearing to a high degree instead of having separate criterion for rearing periods and for spawning periods. This simplifies application of the criteria and also avoids the costly and complex task of needing to identify the spawning seasons for all of the state's streams and rivers. This decision is based upon finding that maintaining oxygen levels in the summer above certain critical minimum values will result in the higher oxygen levels needed in the fall to protect spawning.

The focus of this review was to try and identify summer dissolved oxygen concentrations that could be depended upon to generally provide full protection for the more sensitive life stage of spawning which tends to occur in the fall through spring when oxygen concentrations are naturally higher. Determining a single year-round criterion to protect both spawning and rearing for salmonids was done by comparing dissolved oxygen data with known spawning periods to determine the percentage of time dissolved oxygen criteria protective of spawning were met. The discussion document for dissolved oxygen analysis showed that dissolved oxygen levels during spawning should be greater than 9.0-11.5 mg/L as a 90-DADMin – with the highest probability of protection occurring at concentrations above 10.5 mg/L.

Ecology evaluated monthly grab samples from its ambient monitoring program at 84 sites. This involved examining 11,000 dissolved oxygen records collected between 1978 and 2001 at 84 ambient monitoring stations across the state. Ecology also used the Washington Department of Fish & Wildlife's Salmonid Stock Inventory (SaSI) to identify dates when spawning occurred in individual waterbodies.

Based on this comparative analysis from available data and ranges of protection for salmonid spawning, a determination was made that summer minimum dissolved oxygen levels of 9.5 mg/L as a 90-DADMin or more were necessary to ensure that spawning criteria will be predicted to be met at the appropriate spawning times. From this analysis, Ecology is proposing a single year-round spawning and rearing criterion of 9.5 mg/L as a 90-DADMin.

Another factor considered in setting a year-round criterion to protect spawning and rearing is that conditions for oxygen rapidly improve as fall approaches and continues to be high throughout the spawning season. Thus even where the earliest portion of a spawning season is less than fully protected, the rest of the season will be substantially better off. Further, with the help of the criterion limiting daily minimum oxygen levels, we can be reasonably sure that unnatural trends in oxygen depletion will be identified and corrected, thus also tending to protect the early spawning seasons as well.

Characteristics of Water in Relation to D.O.

Waterbodies come in a wide range of sizes and flow characteristics. Source waters may be cold and plentiful or they may be fed only by infrequent rains. They may be supplied by well-established surface water streams or dominated by shallow or deep ground water seeps and upwelling. The soil and biologic input material may be rich in biologically and chemically active materials or may be composed mostly of inert rock types. The temperature and altitude may also vary considerably based on where the waterbody occurs. All of these factors can strongly influence the ability of a waterbody to meet established water quality criteria for D.O., even without any human activity involved. Aquatic systems are often naturally limited for D.O. Thus the needs of aquatic species will not always be fully met even under natural conditions.

Natural D.O. and Human Actions

Human actions, almost invariably, reduce the oxygen potential of natural waters. They do this through actions that increase the temperature of the waterbody or that contribute input materials that must be broken down through biologic and chemical action thus exerting a demand for oxygen. While in many cases our waters are capable of maintaining oxygen at saturation even with moderate changes in the oxygen demand, in some cases they cannot. Where waters are naturally unable to attain the established water quality criteria for D.O., the system will be even less capable of absorbing any added oxygen demand without some measurable decline in ambient oxygen levels occurring. This describes an important dilemma that must be accommodated, or at least considered, in setting water quality criteria. Unless some formal allowance is made otherwise, any time a water quality criterion is not met, no further action would be allowed that would make the condition any worse even if the original source of the problem is entirely natural. Thus no human action would be allowed that would result in an increase in temperature or the discharge or drainage of materials that may exert an increased demand for oxygen.

Since few human actions occur that do not at least to some extent reduce oxygen levels, a complete moratorium on further oxygen depletion has very serious economic consequences. For this reason, it is proposed that a small allowance for oxygen depletion beyond natural levels be included in any oxygen standard developed. If no allowance is made for further lowering of naturally sub-optimal water quality, then even the best treated wastewater runoff would not be permitted.

To avoid unnecessary and unreasonable impacts to regulated industry and others, Ecology believes some allowance needs to be provided even where a waterbody naturally cannot meet the established criteria. Ecology is recommending that a cumulative allowance value of 0.2 mg/l be applied when determining a D.O. allowance in a waterbody that is naturally lower in D.O. than the established criteria. A 0.2 mg/l limit would be based on restricting any further allowance for lowering oxygen levels to amounts that would essentially be undetectable using current field methods. This allowance is currently granted in the state water quality standards for marine water oxygen levels.

A similar issue exists with regard to rivers that have had their dissolved oxygen characteristics changed due to human structural and hydrologic changes (such as dams). In such cases the 0.2 mg/L allowance would be applied below the estimated attainable dissolved that is calculated given that such permanent human modifications are in place. Thus the 0.2 mg/L applies either to: (1) natural conditions that are below water quality criteria, or (2) a revised estimate of a system's potential that recognizes that some human changes must effectively be considered permanent.

Accompanying Documents & Information

This decision memo is accompanied by 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."

Draft language for D.O. in fresh water can be found in the proposed rule at WAC 173-201A-200(1)(d).

A discussion of alternatives for D.O. in fresh water can be found in the draft Environmental Impact Statement for the proposed rule on page 62.

Additional questions on the proposed revisions to the dissolved oxygen criteria can be directed to Mark Hicks in the Water Quality Program at (360) 407-6477.

Additional information on proposed revisions to the rule, including draft Administrative Procedures Act (APA) materials and the draft Implementation Plan, can be found by visiting our Web site at www.ecy.wa.gov/programs/wq/swqs.

Recommended Criteria

The following table shows the criteria in Ecology proposed alternative:

Category	1-day minimum	90-day average of the daily minimum
Char	7.0 mg/L	9.5 mg/L

Salmon, Steelhead, and Trout Spawning and Rearing	7.0 mg/L	9.5 mg/L
Salmon, Steelhead, and Trout Rearing-Only	6.0 mg/L	8.5 mg/L
Non-anadromous Interior Redband Trout	6.0 mg/L	8.5 mg/L
Indigenous Warm Water Species	5.0 mg/L	7.0 mg/L

Additional notes to apply and implement D.O. criteria

The following statements are proposed for inclusion into the water quality standards' regulation to guide implementation of the D.O. criteria. These notes include direction on how to apply the dual criteria, how to deal with waterbodies where the D.O. is naturally lower than the established criteria, dealing with probability frequencies in data, where measurements should occur, and what criteria apply when waters with different criteria limits meet.

1. The health of aquatic species depends upon maintaining both high longer-term average D.O. levels and preventing unhealthy short-term depressions of D.O. The 90-day average of the daily minimum and the 1-day minimum criteria in the table above must both be applied to ensure protection of a healthy aquatic system.
2. When a waterbody's D.O. is lower than the criteria in the table 200(1)(d) [or within 0.2 mg/L of the criteria] and that condition is due to natural conditions or human structural changes that cannot be effectively remedied (as determined consistent with the federal regulations at 40 CFR 131.10), then human actions considered cumulatively may not cause the 90-DADMin to decrease more than 0.2 mg/L.
3. Concentrations of D.O. are not to fall below the criteria in the table at a probability frequency of more than once every ten years on average.
4. Unless site-specific knowledge of the patterns of aquatic life use in a waterbody dictate otherwise, D.O. measurements should represent the water segment as a whole and should:
    a. be taken from well mixed portions of rivers and streams; and
    b. not be taken from shallow stagnant backwater areas, within isolated thermal refuges, at the surface, or at the water's edge.
5. D.O. must be maintained to fully protect all existing and designated aquatic life uses of downstream waters. Where an upstream water segment having less stringent criteria enters a downstream segment having more stringent criteria, an area of mixing may occur wherein the water quality is lower than the more stringent D.O. criteria. Mixing is allowed only where a localized change in D.O. would not have the potential to impair the aquatic life use of the downstream waters.
6. It is important to average data for comparison with the 90-day average of the daily minimum D.O. criteria in a manner that would not unreasonably bias the results.

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

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
Publication Number 00-10-071

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Dissolved Oxygen

Draft Discussion Paper and Literature Summary

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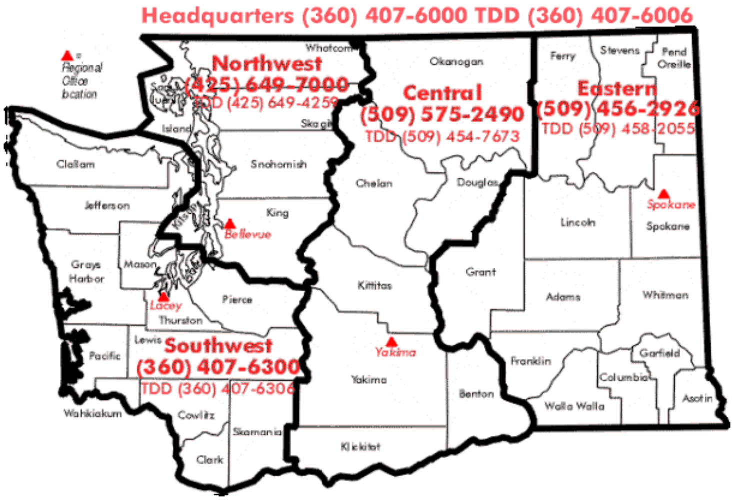

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Abstract

This document evaluates and presents information necessary to develop freshwater dissolved oxygen criteria for Washington waters. In addition to evaluating scientific research and waterbody characteristics, the review discusses some of the important policy issues addressed during criteria development and gives a technical assessment and some specific technically-based recommendations on each of these issues.

Part one of the document explains the existing dissolved oxygen criteria. Part two reviews the underlying science on the effects of dissolved oxygen on fish and other aquatic life. Based on this review, it is clear that dissolved oxygen levels must be maintained near or above saturation to provide “optimal” conditions year-round for the growth and survival of fish and other aquatic life. In the review of the technical literature, levels of dissolved oxygen that would result in the protection of native aquatic species were identified. Wherever possible the review included numerical estimates of the relative levels of biological effect. This is done to allow an assessment of the probable effects of dissolved oxygen concentrations below physiologically optimal levels.

Part three reviews the patterns of dissolved oxygen in the state’s rivers and streams. The purpose of the evaluation was to provide information on potential compliance scenarios and levels of protection that would be afforded by different potential dissolved oxygen criteria. Understanding the regulatory effect of selecting one value over another can help assist in selecting among values determined to be protective in the scientific review contained in part one.

Part I

Background and Technical Summary

1. Background

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

As part of a public review of its water quality standards, Ecology convened a technical workgroup to evaluate the water quality criteria established to protect freshwater aquatic communities. One of the recommendations of the workgroup was for Ecology to re-evaluate the existing criteria for dissolved oxygen. This document reviews the technical literature supporting freshwater dissolved oxygen criteria and establishes a basis for recommending changes to the state's existing criteria.

2. Current Dissolved Oxygen Requirements

The current surface water quality standards (WAC 173-201A-030) have four dissolved oxygen criteria levels that are applied to freshwaters throughout the state:

Class AA - 9.5 mg/l
Class A - 8.0 mg/l
Class B - 6.5 mg/l
Lake Class - No change from natural levels

Class AA and Class A provide two different levels of protection for the same set of beneficial uses, and are intended to protect salmonid spawning, rearing, and migration. Class AA is predominately established within forested upland areas, but Class A waters are found broadly throughout the state. Class B is designed only to protect salmonid rearing and migration and was not intended to fully protect spawning. There are only a small number waterbodies in the state that have been assigned the Class B designation. With each class, the criteria are applied as the lowest single daily minimum measurement of dissolved oxygen occurring in the waterbody.

3. Organization of this Review Document

Part I: Provides a brief background discussion on the effort to revise the state's existing water quality criteria for dissolved oxygen in freshwater systems.

Part II: Reviews available scientific research on the effects of dissolved oxygen on aquatic life, with a particular focus on species occurring in Washington.

Part III: Summarizes the patterns of dissolved oxygen in freshwaters that occur across the state using data from Ecology's ambient monitoring program

4. The Challenge of Selecting Protective Criteria

Of all water quality parameters, dissolved oxygen is possibly the most ubiquitously affected by the actions of humans. Human actions increase the biological oxygen demand by contributing organic and inorganic materials that are metabolized by stream organisms (that use available oxygen to process the waste), and by actions that raise the temperature of the waterbodies (increasing water temperature reduces the ability of the water to hold oxygen in saturation). Against this backdrop of human influence, the available technical information generally demonstrates that aquatic species would benefit from oxygen levels that are higher than what can often be held naturally in saturation, and that any reduction in oxygen can have some biological effect. These two factors, one biologic and one human, when considered together create serious practical and scientific challenges for the state in recommending water quality criteria for dissolved oxygen.

Part II

The Effect of Dissolved Oxygen on the Freshwater Aquatic Life of Washington

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1. The Goal of This Technical Review

The goal of this review is to use the available scientific literature to identify dissolved oxygen recommendations that will maintain healthy and productive populations of the state’s aquatic species and not hinder efforts to recover populations of fish species that are threatened with extinction.

In trying to support this goal, levels of dissolved oxygen that prevent any impairment of fish and other aquatic life species are identified. The level of potential impairment is also established for alternative levels of dissolved oxygen to further assist policy makers and others to evaluate the relative risks of potential harm in selecting specific criteria values.

2. Summary of Technical Findings

Salmonid Species and Associated Macroinvertebrates:

A summary of the technical recommendations for oxygen concentrations for individual life-stages and activities of salmonid species expected to confidently provide for full protection (approximately less than 1% lethality, 5% reduction in growth, and 7% reduction in swimming speed). Other possibly acceptable alternatives for criteria are contained in the text of the analysis document.

Life-Stage or Activity	Oxygen Concentration (mg/l)	Intended Application Conditions
Incubation through Emergence	**≥9.0-11.5** (30 to *90-DADMin*) **and** No measurable change when waters are above 11°C (weekly average) during incubation.	• Applies throughout the period from spawning through emergence. • Assumes 1-3 mg/l will be lost between the water column and the incubating eggs.
Growth of Juvenile Fish	≥ **8.0-8.5** (*30-DADMin*) **and** ≥**5.0-6.0** (*1-DMin*)	• In areas and at times where incubation is not occurring.
Swimming Performance	≥ **8.0-9.0** (*1-DMin*)	• Year-round in all salmonid waters.
Avoidance	≥ **5.0-6.0** (*1-DMin*)	• Year-round in all salmonid waters.
Acute Lethality	≥ **3.9** (*1-DMin*) ≥**4.6** (*7 to 30-DADMin*)	• Year-round in all salmonid waters.
Macro-invertebrates (*stream insects*)	≥ **8.5-9.0** (*1-DMin or1-DAve*)	➢ Mountainous Headwater Streams
	≥ **7.5-8.0** (*1-DMin or1-DAve*)	➢ Mid-Elevation Spawning Streams
	≥ **5.5-6.0** (*1-DMin or1-DAve*)	➢ Low-Elevation Streams, Lakes, and Non-Salmonid Water
Synergistic Effect Protection	≥ **8.5** (***1-DAve***)	• Year-round in all salmonid waters to minimize synergistic effect with toxic substances.

Abbreviations:

1-DMin = annual lowest single daily minimum oxygen concentration.
1-DAve = annual lowest single daily average concentration.
90-DADMin = lowest 90-day average of daily minimum concentrations during incubation period.

Non-Salmonid Species and Associated Macroinvertebrates:

A summary of the technical recommendations for oxygen concentrations for individual life-stages and activities of non-salmonid species expected to confidently provide for full protection. Other possibly acceptable alternatives for criteria are contained in the text of the analysis document.

Life-Stage or Activity	Oxygen Concentration (mg/l)	Intended Application Conditions
Incubation through Emergence	≥ **6.5-7.0** (30 to 60-*DADMin*) **and** ≥ **5.5-6.0** (*1-DMin*)	- Throughout the period of incubation.
Growth of Juvenile Fish	≥ **6.0-7.5** (*30-DADMin*) **and** ≥ **5.0-6.0** (*1-DMin*)	- Year-round in non-salmonid waters.
Swimming Performance	≥ **6.0-6.5** (*1-DMin*)	- Year-round in non-salmonid waters.
Avoidance	≥ **5.0-5.5** (*1-DMin*)	- Year-round in non-salmonid waters.
Acute Lethality	≥ **3.5-4.0** (*1-DAve*)	- Year-round in non-salmonid waters.
Macro-invertebrates (*stream insects*)	≥ **5.5-6.0** (*1-DMin*)	- Year round. Assumes sensitive mayfly species are absent.
Synergistic Effect Protection	≥ **8.5** (*1-DAve*)	- Year-round in non-salmonid waters to minimize synergistic effect with toxic substances.

Abbreviations:
1-DMin = annual lowest single daily minimum oxygen concentration.
1-DAve = annual lowest single daily average concentration.
90-DADMin = lowest 90-day average of daily minimum concentrations during incubation period.

3. Incubation Requirements

A. Salmon, Char, and Trout:

Mortality During Incubation

Siefert and Spoor (1974) found that survival until first feeding in coho held at 7.4-10°C decreased with decreasing dissolved oxygen concentrations. Highest survival (79.6%) occurred in the controls at 11.6 and 10.4 mg/l with survivals dropping (73.1%) in the test conditions of 6.0 and 5.5 mg/l, and (70.4%) in tests at 2.9 and 1.7 mg/l. This represents a 6.5% reduction in survival at 5.5-6 mg/l and a 9.2% reduction at 1.7-2.9 mg/l. No individuals survived at 1.4 mg/l.

Mason (1969) found similar survival in coho, where survival until yolk absorption was highest (82%) in the control at 11.45 mg/l and lower in the test conditions of 5.14 mg/l (77.3%) and 3.12 mg/l (57.9-60.3%). This represents a 4.7% reduction in survival at 5.14 mg/l and as much as a 24.1% reduction at 3.12 mg/l. However, the mean temperatures during incubation increased slightly with each succeeding decrease in oxygen level from 8.84, to 9.56, to 10.68°C, which may also have influenced survival rates since temperatures greater than 11°C may not to be optimal for coho (Hicks, 2002).

Herrmann (1958) reported unpublished data as suggesting that very small coho (yolk-sac fry) may require levels above 4 mg/l for survival at 10-11°C.

Garside (1966) incubated embryos of brook and rainbow trout in the laboratory and found that for a specified level of hypoxia there is a progressive increase in the relative effect with increasing temperature. Garside notes that in his earlier work with lake trout (1959), 2.5 and 3.3 mg/l of oxygen at 10°C induced teratologic development and eventual mortality in all embryos of lake trout.

Carlson and Siefert (1974 as cited in ODEQ, 1995) reportedly found that in laboratory studies of lake trout, embryonic survival was affected at all concentrations below saturation at incubation temperatures of 7-10°C. It was noted, however, that this effect was only slight at approximately 6 mg/l. They also noted that at 6 mg/l development of lake trout through first feeding was inhibited.

Siefert and Spoor (1974) found variable results in tests of brook trout at 8°C. They found that survival rates were high at both 10.5 (90.5%) and 2.9 mg/l (91.5%) but slightly depressed at both 5.8 and 4.2 mg/l (averaging 85.5%). They also noted that the time to first feeding increased with subsequent reductions in oxygen from 10.5 to 5.8, 4.2, and 2.9 mg/l.

Baroudy and Elliott (1993; as cited in Elliott and Baroudy, 1995) found in a laboratory setting that Windemere Arctic char alevins required at least 9 mg/l (70% saturation) for maximum survival over 7 days or longer at 5°C, and all died at less than 30% saturation (estimated as 3.9 mg/l).

Shumway et al. (1964) reared coho salmon and steelhead trout from fertilization of the eggs to hatching, at about 10°C, at dissolved oxygen concentrations averaging 11.5, 8.0, 5.6, 4.0, 2.5, and 1.6 mg/liter, and at different water velocities ranging from about 3 to 750 cm/hour. Complete mortality occurred at 1.6 mg/liter, the lowest concentration tested. However, in tests at higher concentrations mortality rates were inconsistent. High mortality occurred sporadically in test chambers at mean concentrations of 4.1 mg/l or less, but less markedly in test chambers at higher mean oxygen levels. At these higher concentrations mortalities ranged from 17 to 27 percent and were reported to show no clear relation to oxygen concentration. The authors noted it cannot be assumed that nearly all, or equal percentages, of the eggs used in their experiments were fertile and viable. This unaccounted mortality factor complicates any effort to determine effects levels and to determine statistical significance. Deformed fry were found in cylinders having mean oxygen concentration up to 4.1 mg/liter. Even under conditions that are not lethal for embryos, the authors note that a delay of hatching and reduction in size of fry at hatch may result in mortality because emergence from the gravel of small and weak fry or their subsequent success in the natural environment may be impossible.

Silver et al. (1963) found that the hatching rates of steelhead at 9.5°C and averaged across four different flow conditions (6-750 cm/hr) were 79, 78, 85, 81, and 81% at oxygen concentrations of 11.2, 7.9, 5.7, 4.2, and 2.6 mg/l; with no survival at 1.6 mg/l. Silver et al. (1963) found that the hatching rates of chinook salmon at 11.0-11.4°C and averaged across three different flow conditions (88-1,360 cm/hr) were 97, 97, 96, 100, and 97% at oxygen concentrations of 11.7, 8.0, 5.6, 3.9, and 2.5 mg/l; with no survival at 1.6 mg/l. Except for the complete mortality observed for both steelhead and chinook salmon, the work of Silver et al. does not show any predictable pattern of survival. Silver et al. (1963) noted that temperature increases of 2 to 3°C beyond 10°C may increase by several milligrams per liter the oxygen requirements for survival of salmonid embryos to the hatching stage. The authors also noted that mortalities within 7 days after hatching of chinook at concentrations of 2.5 mg/l were 29.3, 23.7, and 8.5 percent at the three velocities tested. The post-hatching mortalities at all other concentrations were summarized as ranging from 6.9 to 0 percent. In neither the work with steelhead or that with chinook salmon are there any clear relationships between oxygen concentrations above 2.6 mg/l and the number of surviving hatchlings. The methods documented do not clarify if the eggs were examined to ensure they were all fertilized or not, so this study could possibly be confounded by unaccounted losses due to less than full fertilization rates of eggs.

Eddy (1971) reared chinook salmon from fertilization to several weeks after complete yolk absorption at dissolved oxygen concentrations of 3.5, 5.0, and 7.3 mg/liter and air saturation (10.1-11.0 mg/l) at temperatures of 10.5, 12.0, 13.5, and 15°C. Eddy concluded that increased incubation mortality can be expected with any substantial reduction of dissolved oxygen concentration below the air saturation level at temperatures as low as 13.5°C and possibly even 12°C. Survival was high (91.66-100%) between replicates at all dissolved oxygen levels tested at 10.5°C. Survival rates were 99.6-100% at 7.4 mg/l and 10.8-11.0 mg/l, and was 94.6-99.5 in replicates at 5.2 mg/l.

Figure 1 below uses the data of Eddy (1971) to demonstrate that temperature may exert a greater influence on survival rates than dissolved oxygen when incubation occurs at the upper temperature boundary for safe incubation. It also suggests that chinook salmon incubation should generally occur at mean temperatures below 10.5°C to eliminate any reasonable chance of oxygen induced mortality. In the tests of Eddy, it can be seen that at 10.5°C, dissolved oxygen concentrations from 3.5 to 11 mg/l had consistently high survival rates. At higher test temperatures (12 and 13.5°C) mortality rates increase irrespective of the specific level of oxygen, but as temperatures move further from the optimal incubation temperature the mortality rate increased dramatically with successive decreases in available oxygen. However, as reported below by Siefert and Spoor (1974), Mason (1969), and Raleigh, Miller, and Nelson (1986), even at temperatures within the range of optimal (less than 10-10.7°C), survival rates may decline with a reduction in oxygen from saturation levels.

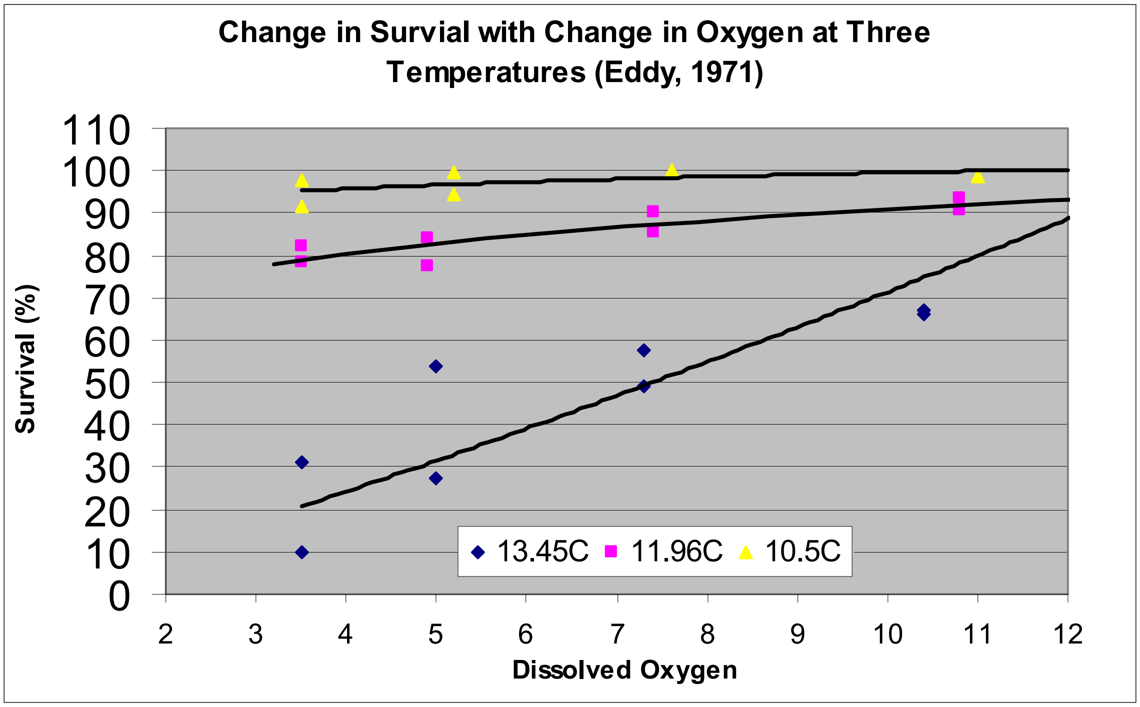

Figure 1. Relationship between incubation survival rates of chinook salmon at three temperatures (10.5, 12, and 13.5°C) and four oxygen concentrations (based on the data from Eddy, 1971).

Examining the data from Eddy (1971) for incubation tests conducted at a favorable temperature (10.5°C), an estimate can be made of the impact of lowering oxygen levels on survival to hatch (Figure 2). While the statistical relationship is too weak to gain much confidence in the specific estimates, it can be seen that survival remains high at oxygen concentrations above 6 mg/l. The equation for the line of best fit would predict that dissolved oxygen losses would remain less than 1% at an average incubation concentration of 9 mg/l or greater, less than 2% at 7mg/l, be 2.5% at 6 mg/l, and remain below approximately 4% at concentrations as low as 4 mg/l.

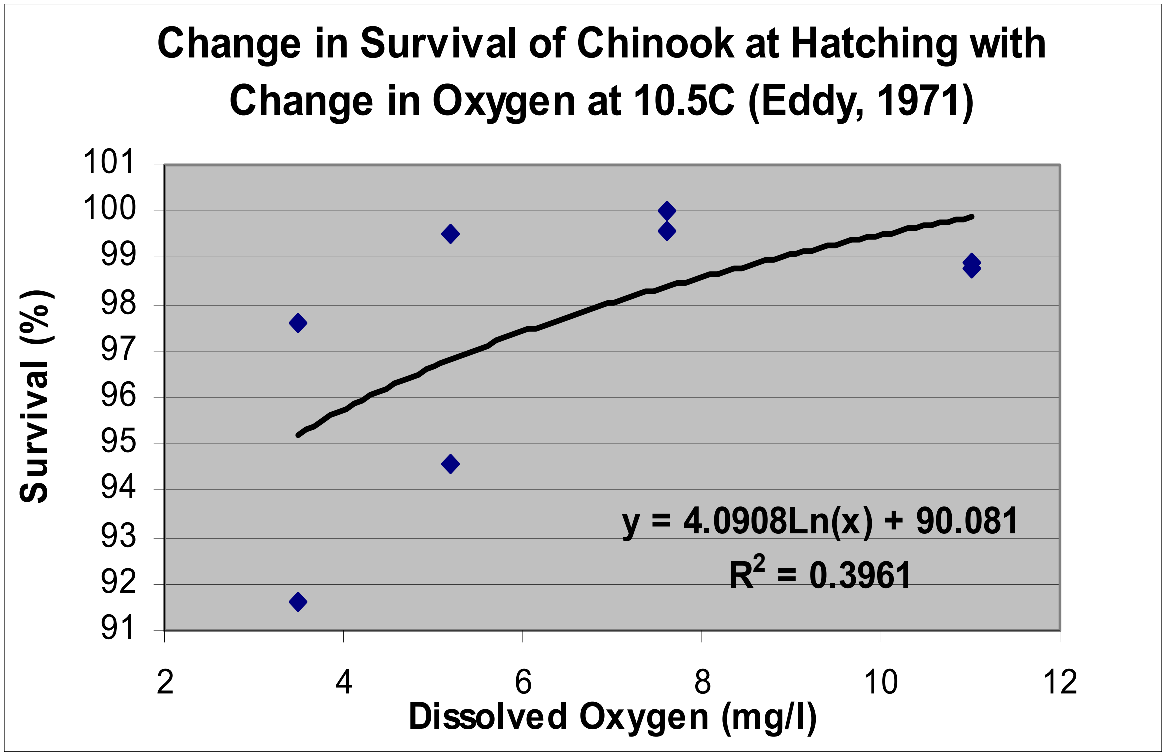

Figure 2. Survival to hatching of chinook salmon with changes in dissolved oxygen level at 10.5°C (Eddy 1971).

At unfavorable incubation temperatures, however, the impact of reducing oxygen concentrations is notably more severe (Figure 3). For example, the same studies by Eddy (1971) can be used to predict the effect of lowering oxygen at a less favorable temperature of 13.5°C. In this case, the number of surviving hatchlings begins at 70% at 11 mg/l and is reduced by an additional 4% at 10 mg/l and by an additional 19% at 7 mg/l. At 4 mg/l survival rates are reduced by 42% compared to higher oxygen levels (11 mg/l). Thus the effect of lower oxygen concentrations is magnified at unhealthy incubation temperatures.

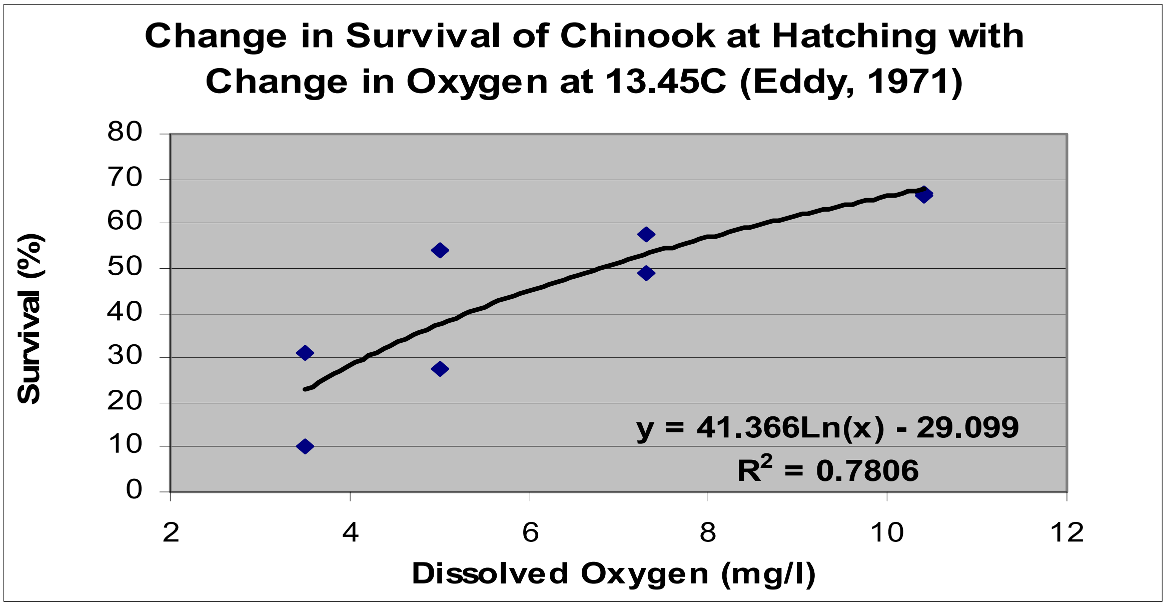

Figure 3. Change in survival at hatching of chinook salmon with changes in dissolved oxygen level at 13.45°C (Eddy 1971).

Figure 4 displays the survival rates reported in all of the cited studies. The regression coefficient created in this exercise is too small to reasonably use for predicting survival rates, but combining the data is useful in graphically supporting the overall results of Eddy (1971). While survivals are inconsistent, overall the frequency of low survival rates is noticeably increased at oxygen concentrations below about 6.5 mg/l.

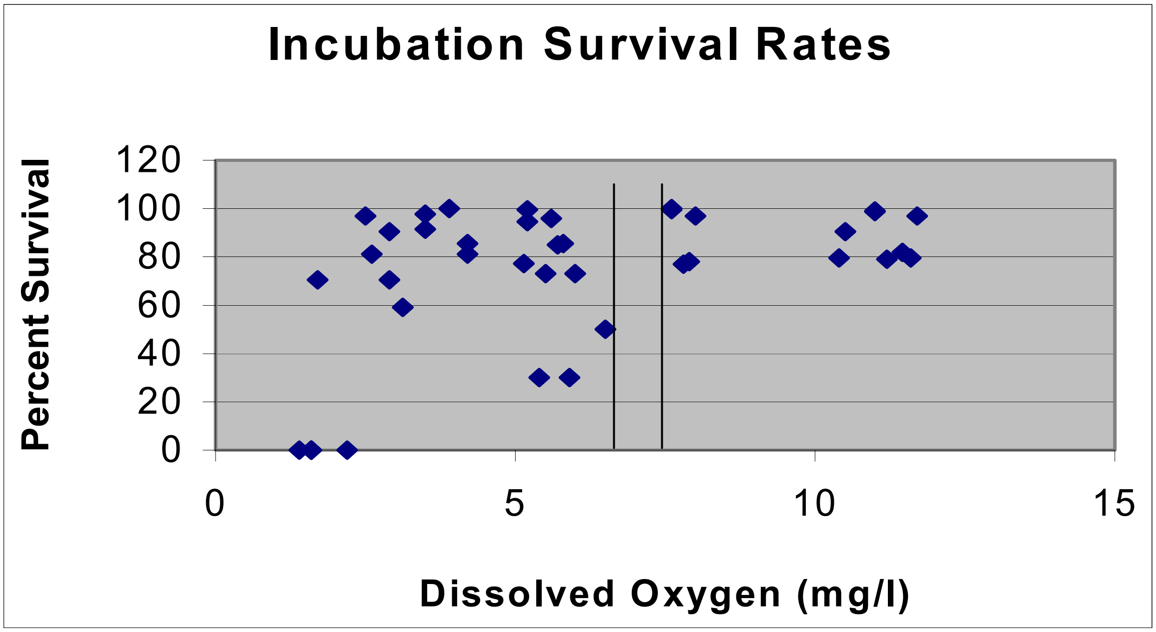

Figure 4. Incubation survival rates versus dissolved oxygen levels reported in the literature

Summary of Incubation Mortality through Hatching: Based upon the research reviewed above, at favorable incubation temperatures mortality rates should be expected to remain less than 1% at a concentration of 9 mg/l or greater, less than 2% at a concentration of 7 mg/l, and between 2-6% percent at a concentration of 6 mg/l. While mean oxygen concentrations over the development period below 6 mg/l are sometimes associated with significant increases in mortality rates, the overall pattern is for mortality rates and the occurrence of abnormalities to remain low (less than 7%) at concentrations above 4 mg/l. Survival rates at oxygen concentrations below 4 mg/l are highly variable. While mortality rates were low (4-7%) in some studies, they ranged from 25% to 100% in others. All tests at concentrations below 1.7 mg/l resulted in 100% mortality.

While mortality rates related to low oxygen concentrations remain relatively minor at favorable incubation temperatures (averages below 11°C), they increase rather substantially at temperatures that are warmer than ideal. In warmer waters (13.45°C) even a decrease from 11 to 10 mg/l would be associated with causing a 4% reduction in survival through hatching. A decrease to 7 mg/l would be associated with a 19% reduction in survival. Thus an important policy decision when setting oxygen criteria will be whether or not to take into account the very real risk that temperatures will commonly be above ideal levels.

An important point to recognize is that in the laboratory studies the developing alevin did not need to push their way up through gravel substrate as would wild fish. The studies above focused on survival through hatching and did not consider this rather substantial final act for emerging through the redds. Optimal fitness will likely be required for optimal emergence in the natural environment, and the metabolic requirements to emerge would be expected to be substantial. Thus higher oxygen levels may be needed to fully protect emergence than to just fully support hatching alone.

Growth Rates During Incubation

Nikiforov (1952) is cited by Herrman (1958) as showing that salmonid yolk-sac fry may have critical concentrations for growth as high as 7 mg/l or more. Rombough (1988) found that the critical concentration necessary to fully supply the oxygen demands of developing steelhead was 7.5-7.9 mg/l at the stage of development just prior to hatch, and noted that at 15°C, the critical conditions would exceed the level of oxygen available at full saturation.

Alderdice et al. (1958) estimated the critical concentration for chum salmon to be 7.19 mg/l just prior to hatch, which is very similar to that determined for steelhead by Rombough.

ODEQ (1995) cites Rombough (1986) and Carlson (1980) as demonstrating that the greatest oxygen requirements for embryos occurs just prior to hatching, and at temperatures near 15°C oxygen requirements will exceed 10 mg/l.

Reiser and Bjornn (1979) cited Lindroth (1942) as finding that the critical concentration for chum salmon is 10 mg/l at initiation of hatching.

Reiser and White (1983; Oregon Department of Environmental Quality (ODEQ), 1995) noted compensatory growth (time needed to catch up to the size of the control fish) occurring for 8 weeks in chinook salmon and 8.5 weeks for steelhead during rearing of test and control eggs.

Chapman (1988) citing Brannon (1965) noted significant decreases in the size of newly hatched embryos at test concentrations of 6 and 3 mg/l compared with a control at 12 mg/l. He noted that the period to full yolk absorption was extended by three weeks in the test concentration at 6 mg/l. Chapman (1988) concluded that any incremental reduction in dissolved oxygen levels from saturation probably reduces survival to emergence or post-emergent survival.

Chapman (1969; as cited in ODEQ, 1995) is reported to have found that the maximum size attained by juvenile steelhead alevins held at 3 and 5 mg/l was only slightly less than those held at 10 mg/l. Chapman also found that the time required to reach maximum size increased with decreasing dissolved oxygen.

Eddy (1971) reared chinook salmon from fertilization to several weeks after complete yolk absorption at dissolved oxygen concentrations of 3.5, 5.0, and 7.3 mg/liter and air saturation (10.1-11.0 mg/l) at temperatures of 10.5, 12.0, 13.5, and 15°C. Mean dry weight consistently decreased (with a 19% decrease with a change from 11 to 7.6 mg/l and 66% reduction with a change to 3.5 mg/l at 10.5°C). The work of Eddy (Figure 5) is useful in showing the impact of changing oxygen levels at different incubation temperatures.

Silver et al. (1963) examined the incubation growth of steelhead at 9.5°C under four different flow conditions and six oxygen concentrations (11.2, 7.9, 5.7, 4.2, 2.6, and 1.6 mg/); with no survival at l.6 mg/l. Mean lengths at hatching decreased 3.6 % with a reduction from 11.2 to 7.9 mg/l, and 7% with a reduction from 11.2 to 5.7 mg/l. Silver et al. (1963) also studied chinook salmon at 11.0-11.4°C and averaged across three different flow conditions (88-1,360 cm/hr) at oxygen concentrations of 11.7, 8.0, 5.6, 3.9, and 2.5 mg/l; with no survival at 1.6 mg/l. Mean lengths at hatching decreased 5% with a reduction from 11.7 to 8.0 mg/l, and 8% with a reduction from 11.7 to 5.6 mg/l. Discussing the interrelationship between temperature and dissolved oxygen; Silver et al. (1963) cited unpublished research that determined growth was limited at concentrations as high as 11.7-11.9 mg/l in chinook salmon and as high as 11.2 mg/l in steelhead at incubation temperatures of 11 and 12.5°C respectively.

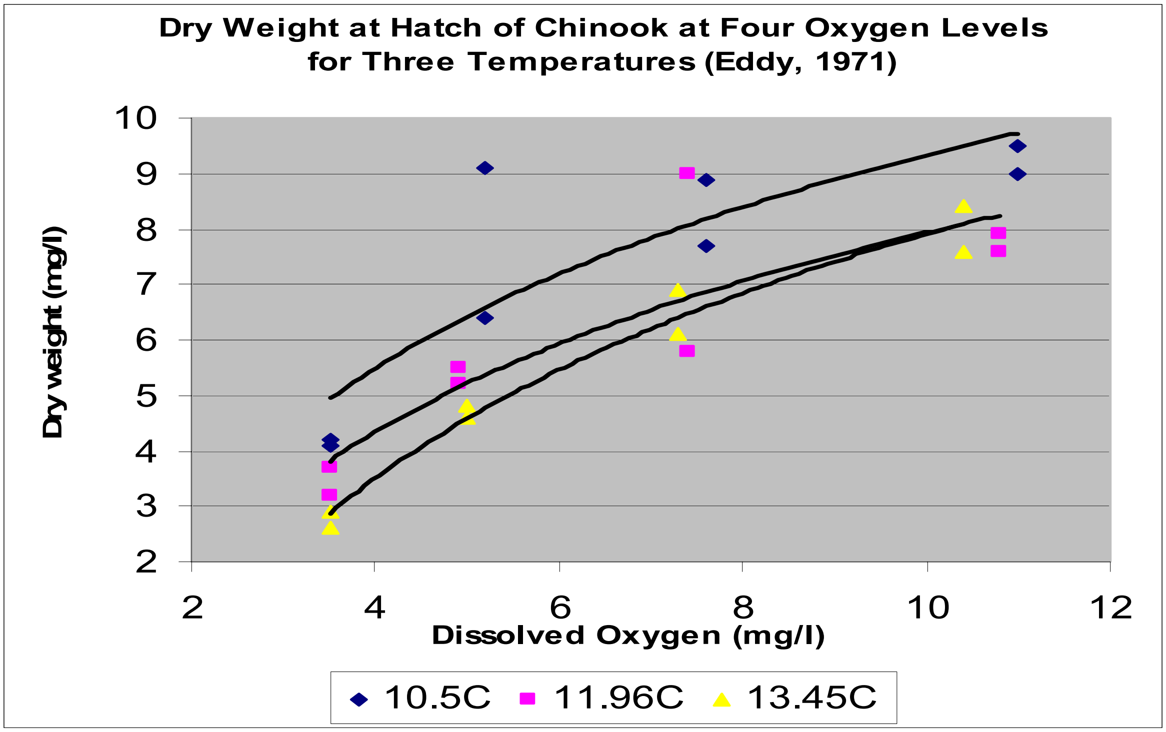

Figure 5. Change in dry weight of chinook salmon at hatching at four oxygen levels for three temperatures (Eddy, 1971)

Shumway et al. (1964) reared coho salmon and steelhead trout from fertilization of the eggs to hatching at about 10°C and at dissolved oxygen concentrations averaging 11.5, 8.0, 5.6, 4.0, 2.5, and 1.6 mg/liter, and at different water velocities ranging from about 3 to 750 cm/hour. The dissolved oxygen concentration of water and the rate at which it flows past developing coho salmon and steelhead embryos were found to markedly influence the size of fry at hatching and the length of time required for them to reach the hatching stage. In both species, the size of newly hatched fry was found to be dependent on the oxygen concentration at all tested concentrations below the air saturation level. The authors found that a reduction in oxygen from 11.2 to 8.6 mg/l resulted in a 5% reduction in the wet weight of coho salmon, and a reduction from 11.2 to 6.5 mg/l resulted in a 26% reduction in wet weight. Deformed fry were found in cylinders having mean oxygen concentration up to 4.1 mg/liter. Even under conditions that are not lethal for embryos, the authors note that a delay of hatching and reduction in size of fry at hatch may result in mortality because emergence from the gravel of small and weak fry or their subsequent success in the natural environment may be impossible.

Figure 6 combines the data from three researchers to get an overall estimate of the effect on the size of newly hatched salmonids (steelhead, coho, and chinook) from varying the mean concentration of oxygen during the incubation period. Using the best fit regression of the data, specific predictions can be made. At a mean incubation concentration of 10.5 mg/l it would be expected that the reduced size of newly hatched alevin would be less than 2 %, at 10 mg/l it would be less than 4% and at 9 mg/l it would be approximately 8%. Mean concentrations of 7 and 6 mg/l would be expected to cause 18 and 25 percent reductions in potential size, respectively.

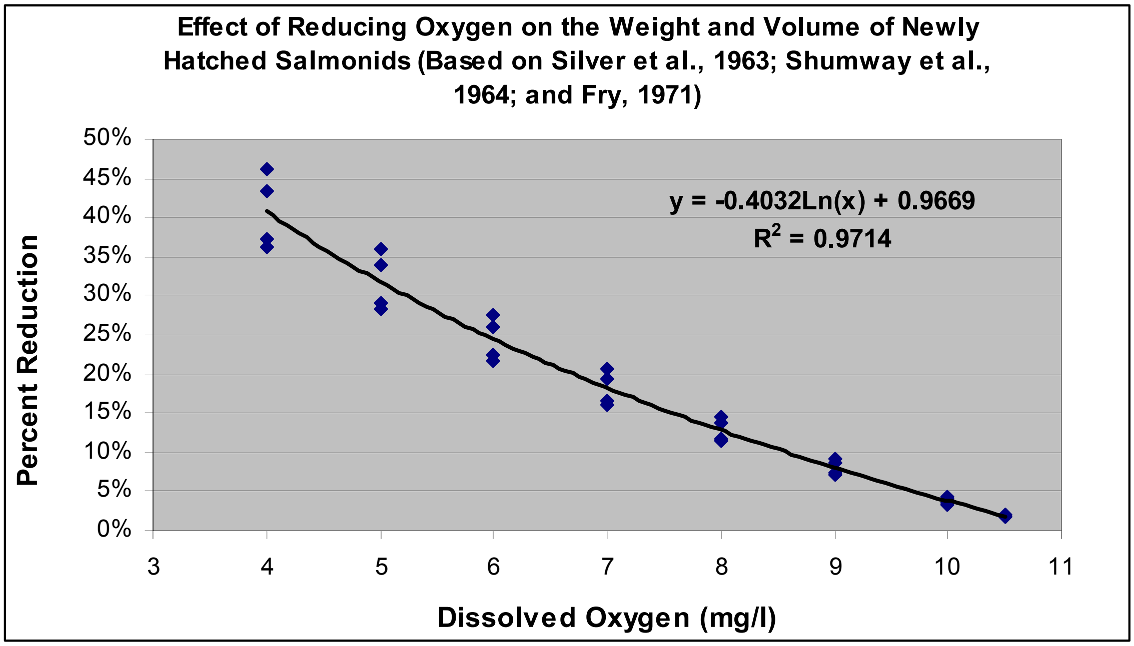

Figure 6. Overall effect on weight and volume of newly hatched salmonids of varying mean oxygen concentrations over the development period. (based on data from Silver, 1963; Shumway, 1964; and Fry, 1971).

Summary of Incubation Growth Rates: Any decrease in the mean oxygen concentration during the incubation period appears to directly reduce the size of newly hatched salmonids. At favorable incubation temperatures the level of this size reduction, however, should remain slight (2%) at mean oxygen concentrations of 10.5 mg/l or more and still remain below 5% at concentrations of 10 mg/l or more. At 9 mg/l, the size of hatched fry would be reduced approximately 8%. Mean concentrations of 7 and 6 mg/l would be expected to cause 18 and 25% reductions in size. While some authors suggested that changes would only be slight at concentrations lower than 6 mg/l, data was not available to support these alternative assessments.

Temperature has a cumulative influence with oxygen on the size of newly hatched fry. As observed from the data of Eddy (1971) in Figure 5, at temperatures above 10.5°C (12-13.5°C) maintaining high oxygen levels may help mitigate the potential effect of higher temperatures.

It is important to keep in mind that the above cited studies were conducted in laboratory tanks, and examined measures of health at the time of hatching. In the natural stream environment, the alevin commonly live in the gravel for an additional 30 days or longer and also must finally work their way up through the gravel to emerge. The alevin must not only be in good enough health to emerge but also to feed and compete once the task of emergence has been completed. The following discussions begin the process of assessing the relative health at emergence with different oxygen concentrations.

Studies of Intragravel Health and Emergence

Oxygen levels are often significantly depressed in the gravels containing incubating embryos and alevin. Several researchers have examined the oxygen levels within the gravel environment associated with promoting healthy emergence rates.

Avoidance Reactions of Alevin in the Gravel

Fast (1987) determined that alevin of four species of salmonids actively avoided intragravel waters having dissolved oxygen in the range of 4.5-7 mg/l, and demonstrated selective preference for waters in the range of 8-10 mg/l.

Fast and Stober (1984) and Stober et al. (1982) are cited by ODEQ (1995) as finding that newly hatched alevins in the gravel were able to detect oxygen gradients and migrate to areas containing more oxygen. Alevins of chum, chinook, coho, and steelhead were tested at mid- and late-alevin development stages. Mid-stage alevins of all species preferred 8 mg/l to 4 mg/l, and always avoided 2 mg/l. Tests performed during late stages generally showed greater movement and avoidance, and all species preferred 10 mg/l to 6 mg/l.

Bishai (1962; as cited in ODEQ, 1995) is noted to have found that avoidance of low oxygen remains marked in 4 week old fry.

Summary of Avoidance Reactions of Alevins: The above works all found a selective preference for oxygen concentrations from 8-10 mg/l in alevin. This preference was strong enough to provoke movement through the gravel medium and suggests the possibility that salmonid alevin recognize some benefit to avoiding intragravel oxygen levels below 8 mg/l.

Controlled Studies of Emergence from Spawning Gravels

Turnpenny and Williams (1980) studied the survival of eyed rainbow trout eggs planted in a river and estimated that the point of 50% mortality was at 6.5 mg/l. They further found that embryo survival and alevin lengths increased with both increases in apparent velocity through the redds and with increasing intragravel oxygen concentrations up to a maximum mean of 7.8 mg/l.

Bams and Lam (1983) found in an experiment conducted in a hatchery channel that depression of intragravel oxygen within the range of a maximum of 9.59 mg/l to a minimum of 6.21 mg/l resulted in reduced growth and development rates of chum alevin at 8.1-7.3°C.

Bailey et al. (1980) found in a laboratory setting that depletion of oxygen around incubating eggs was a likely cause of reduced fry size and early emergence, even while survival to emergence may not be significantly affected. Intragravel concentrations were considered to be stressful below 6 mg/l and limited metabolism.

Summary of Controlled Emergence Studies: The above referenced laboratory and field studies suggest that average intragravel oxygen concentrations of 6-6.5 mg/l and lower can cause significant stress and mortality in developing embryos and alevin. Intragravel concentrations above 7.8 mg/l were cited by one study as the oxygen level above which the size and survival benefits where no longer obvious.

Field Studies of Emergence from Spawning Gravels

Reiser and Bjornn (1979) cite a field study by Philips and Campbell (1961) as demonstrating that an average of 8 mg/l in the intragravel environment was necessary to support high survival of coho and steelhead.

Wells and McNeil (1970) found that survival to emergence was notably greater in streams with average intragravel oxygen concentrations of 7.8 mg/l (77% survival) versus 5.9 and 5.4 mg/l (30% survival).

Coble (1961) showed in a field study that high intragravel oxygen concentrations (average 9.2 mg/l) correlated with greater measured survival rates, that at lower dissolved oxygen levels (6.6-6.4) survival is depressed, and that at these lower dissolved oxygen levels survival is very strongly dependent upon maintaining high flow rates through the gravel.

Koski (1975) in a controlled stream study found that survival to emergence was low in redds with less than 6 mg/l dissolved oxygen, and estimated that a minimum dissolved oxygen threshold for any survival to emergence to occur was about 2.0 mg/l.

Jeric (1996) estimated that survival to emergence of Kokanee in natural redds was zero at 2.2 mg/l. Jeric found that survival to emergence can occur in waters having a range from 1.8-5.2 mg/l (mean of 3.8 mg/l) at temperatures falling to less than 1.7-2.0°C.

Peterson and Quinn (1996) monitored 33 natural egg pockets of chum and found high variability within and between egg pockets and a general trend of declining oxygen over the incubation period that was likely caused by the respiration of the alevins themselves or from the decay of dead embryos.

Phillips and Campbell (1962) found a positive correlation between the survival of coho and steelhead embryos and mean dissolved oxygen concentrations in the gravel beds of two small coastal streams. They concluded that the dissolved oxygen concentration necessary for the embryonic survival of coho and steelhead in coastal stream gravel beds is greater than had been previously suspected. The results of their field experiments indicate that mean oxygen concentrations in the gravel necessary for a high survival of coho and steelhead embryos may exceed 8 mg/liter.

ODEQ (1995) used the raw data collected by Hollender (1981) to show that mean intragravel dissolved oxygen concentrations above 8 mg/l were most consistently associated with high survival rates of brook trout. They were also able to show that survival was consistently poor where concentrations were less than about 6.0 mg/l. Between 6 and 8 mg/l, survival rates were highly variable.

Gangmark and Bakkala (1960; as cited in Raleigh, Miller, and Nelson, 1986) found that survival of chinook salmon embryos in a cold stream (4 to 9ºC) was highest at concentrations of 13 mg/l and lowest at 5 mg/l. The greatest increase in survival occurred between 5 and 7 mg/l. From this the authors concluded that the lower limit of oxygen concentration for survival with short term exposures is greater than 2.5 mg/l at water temperatures less than 7ºC with optimal levels of 8 mg/l or greater at temperatures between 7-10ºC and greater than 12 mg/l at temperatures greater than 10ºC.

Sowden and Power (1985) found that rainbow trout survival in a ground water fed stream was negligible (<1%) until mean oxygen concentrations in redds exceeded 5.2 mg/l. The authors concluded that oxygen concentrations should exceed 8 mg/l, and seepage velocities 100 cm/h, to ensure at least 50% survival during the preemergence period.

Maret et al. (1993) evaluated the survival of eyed brown trout eggs in an Idaho stream and concluded that survival generally increased with mean intragravel dissolved oxygen concentrations above 8.0 mg/l and 70% saturation. Maret et al. (1993) also noted that Hoffman and Scopettone (1984) concluded that high cutthroat trout egg mortality was principally caused by intragravel oxygen concentrations occurring below USEPA's minimum recommended level of 5.0 mg/l.

Summary of Field Studies on Emergence: In the field studies cited above, intragravel oxygen concentrations of 8 mg/l or greater are consistently cited as being associated with, or necessary for, superior health and survival. Significant reductions in survival through emergence and time to first feeding have been commonly noted to occur at average intragravel oxygen concentrations below 6-7.0 mg/l. Negligible survival is noted below 5 mg/l, and the threshold for complete mortality is noted to occur between 2-2.5 mg/l.

In setting water quality criteria, the policy decision needs to be made as to whether or not the criteria will be applied to the water column, to the intragravel environment, or to both. In the following discussion, studies that examined the relationship between oxygen concentrations in the gravels and those occurring concurrently in the overlying waters are summarized. This information can be used to help determine appropriate adjustment factors if the depression of oxygen in the gravel environment is to be considered in setting water quality criteria.

Depression of Inter-gravel Oxygen Concentrations

Several authorities have discussed the relationship between water column dissolved oxygen and the oxygen levels that occur within the gravel redds during incubation. Chambers (1956: as cited in Andrew and Geen, 1960) showed that the amount of dissolved oxygen in water flowing through salmon redds was somewhat less than that in the stream flowing above the redds. They also found that percolation water drawn from the forward slope of the tail spill of a salmon redd, where the eggs were deposited, consistently contained more dissolved oxygen than did samples taken from (1) the identical spot prior to spawning, (2) undisturbed gravel beside the nest, and (3) other parts of the nest.

USEPA (1986) has recommended using the assumption that 3 mg/l of oxygen is lost between the water column and the incubating eggs.

Skaugset (1980; as cited in ODEQ, 1995) found that the average loss of oxygen from surface concentrations to the eggs in redds was 3.3 mg/l, while Hollender (1981) is reported to have found typical losses of 2-3 mg/l. The state of Oregon collected intragravel and surface water oxygen samples from two streams and found that the median oxygen depression was less than 1.0 mg/l, they further reported data collected by Oregon Trout for the Salmonberry River showed depressions typically near 0.5 mg/l (ODEQ, 1995).

Maret et al. (1993) studying a stream heavily impacted by nonpoint sources found losses ranging from 1.6 to 7.2 mg/l.

Summary on Intragravel Oxygen Depression: The studies cited above note that water column dissolved oxygen concentrations may be reduced by anywhere from 0.5 to 7.2 mg/l as it is transmitted to the redds containing developing eggs and larvae. The typical range of the estimate is between 1-3 mg/l, and should be considered more reliable for use in setting water quality criteria.

Effect on Hatch Timing

Eddy (1971) reared chinook salmon from fertilization to several weeks after complete yolk absorption at dissolved oxygen concentrations of 3.5, 5.0, and 7.3 mg/liter and air saturation (10.1-11.0 mg/l) at temperatures of 10.5, 12.0, 13.5, and 15°C. Median hatching time increased with successive lowering of oxygen at all temperatures tested (with no change with a reduction to 7.7 mg/l and 1.5 days with a reduction to 5.2 mg/l at 10.5°C). Figure 7 shows the effect of both temperature and oxygen on hatching rates of chinook salmon. Temperature is clearly the overriding factor in determining hatching rates, and decreasing oxygen levels has a very minor additive effect at oxygen levels above 6 mg/l.

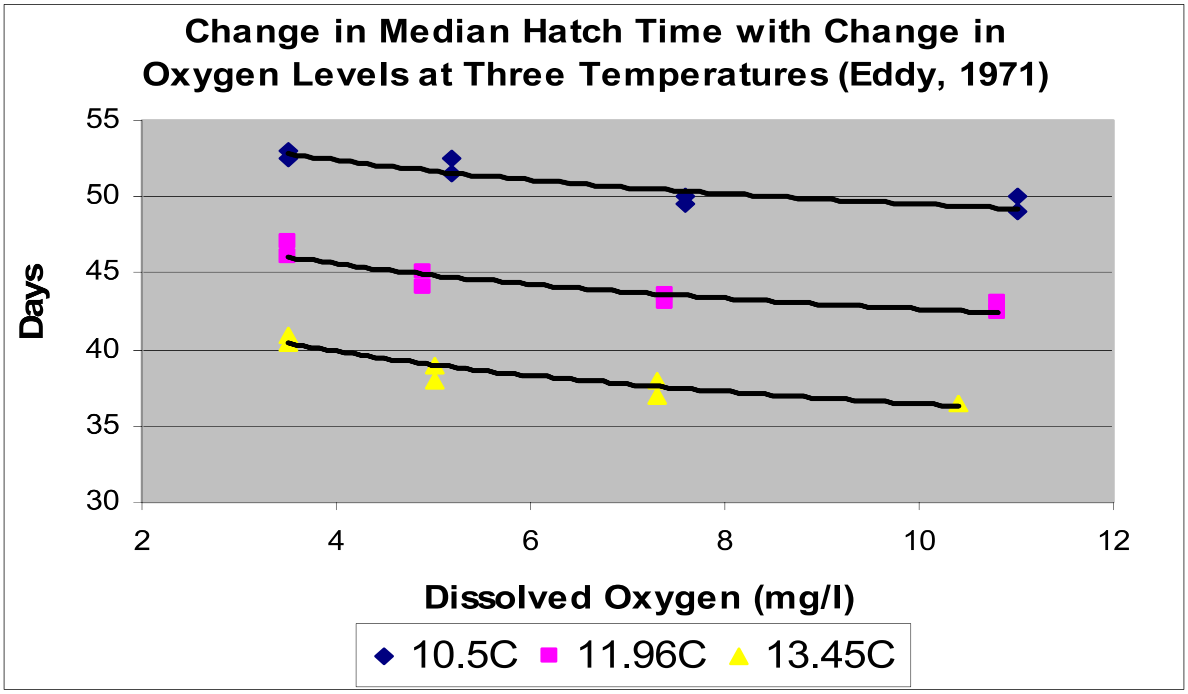

Figure 7. Change in median hatch date with change in oxygen levels in chinook salmon at three temperatures (Eddy, 1971).

Silver et al. (1963) examined the incubation growth of steelhead at 9.5°C under four different flow conditions and six oxygen concentrations (11.2, 7.9, 5.7, 4.2, 2.6, and 1.6 mg/); with no survival at l.6 mg/l. The final hatching date increased by 3 days with a reduction from 11.2 to 4.2 mg/l. In tests with chinook salmon at 11.0-11.4°C and averaged across three different flow conditions (88-1,360 cm/hr) the final hatching dates were increased by 3 days with a reduction from 11.7 to 3.9 mg/l.

Figure 8 combines the data from three authors on the influence of oxygen on the median hatching dates of salmonids. This is done to more dependably clarify the relative effect. Using the regression line of best fit, predictions can be made using the combined strength of all three research efforts and the multiple species tested (Steelhead, Chinook, Coho). At mean oxygen concentrations throughout the development period of 8 mg/l or greater, it should be expected that the change in hatching date would be less than 1 day. At 7 mg/l the development period would be lengthened by just over 1 day, and from 6 to 4 mg/l the development period would extend from 2-7 days.

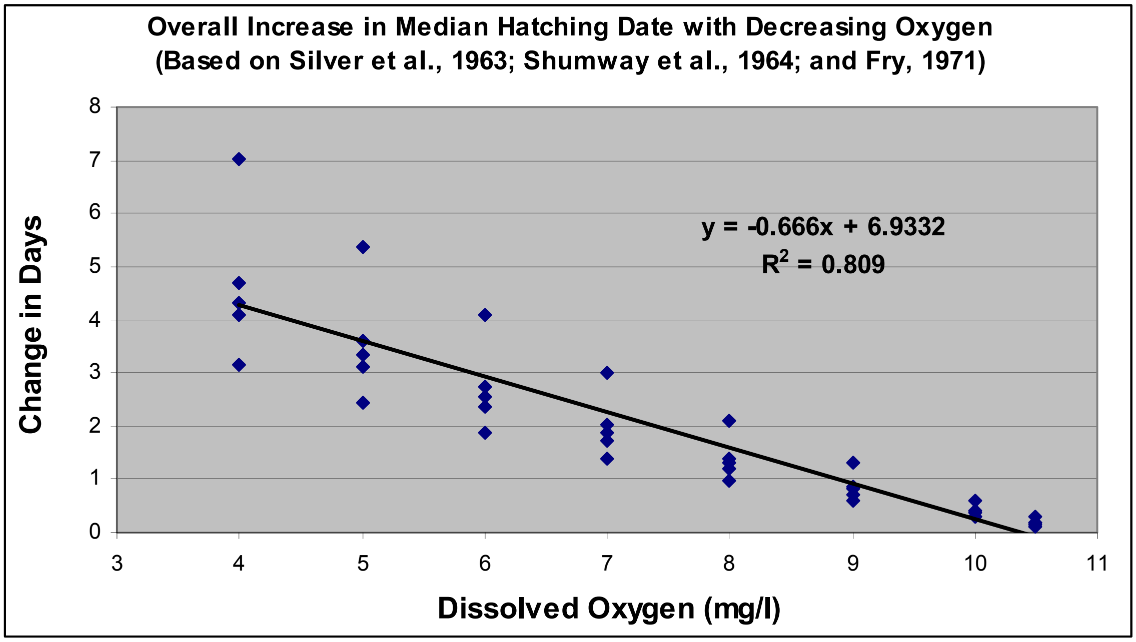

Figure 8. Overall increase in the median hatching date with decreasing oxygen concentrations (Combined data from Silver et al. 1963; Shumway et al., 1964, and Fry, 1971).

Summary on Hatch Timing:

At mean oxygen concentrations throughout the development period of 8 mg/l or greater, it should be expected that the change in hatching date would be less than 1 day. At 7 mg/l the development period would be lengthened by just over 1 day, and from 6 to 4 mg/l the development period would extend from 2-7 days. Thus concentrations above 6-7 mg/l should be considered as having a negligible impact on hatch timing.

Summary of Multiple Lines of Evidence on the Incubation Health of Salmonids

Table 1. Summary table showing the individual lines of evidence produced by the studies examining incubation effects. The estimated level of the effect (as a percent or as a description) is noted to assist in comparing the relative risks of different average dissolved oxygen concentrations. The number appearing at the top of the boxes is the dissolved oxygen concentration, and represents concentrations in mg/l. Concentrations are those developing embryos would be exposed to. In a natural setting, some depression in oxygen levels would occur between the overlying water column and the eggs developing in the spawning gravel (i.e., a 1.0-3.0 mg/l depression is common).

	Higher <----------------- Protection -------------------> Lower			
Laboratory Mortality During Incubation through Hatching	≥9.0 (<1%)	7.0 (1-2%)	6 (2-6%)	4 (7-100%)
Laboratory Studies of Emergence from Gravel (Intragravel O_2)		≥8 (Benefits no longer obvious)		6-6.5 (Stress and high mortality)
Field Studies of Emergence from Gravel (Intragravel O_2)		>8 (High survival)	8 (Sometimes median survival)	6-7 (Significant survival reductions – 50%)
Avoidance Reactions of Alevin in Gravel (Intragravel O_2)			8-10 (Sought out)	4-6 (7) (Avoided)
Growth Reduction During Incubation	10.5 (<2%)	10 (4%)	9.5 (6%)	9 (8%)
Effect on Hatch Timing	>8 (<1 day)	7 (<2 days)	6 (2 days)	

***Note**: Intragravel oxygen concentrations are given in both laboratory and field studies on alevin avoidance and fry emergence. These values should be adjusted upward 1-3 mg/l to get at a comparable water column concentration.*

In the studies examined on incubation effects, virtually all used the overall average of the range of oxygen concentrations that occurred throughout the development period. Fluctuations about this mean occurred both daily and across the study period. In the reported laboratory studies, oxygen levels were characteristically maintained within +/-

1mg/l. The ranges in field testing were of course somewhat greater, but the infrequency of the oxygen analyses makes characterizing these ranges more problematic. None of the authors provided information on the amount of time spent within the lower portion of the reported ranges, and none identified the most characteristic pattern of fluctuations. The results of the above studies can only reasonably be said with confidence to represent the average oxygen concentrations in a system that experiences very little diel fluctuations. No basis is provided to directly estimate the effects of other durations of exposure (e.g., single daily, 7-day average daily, etc.).

Technical Recommendation: The following recommendations are provided to assist in decision-making. Incubation through hatching commonly occurs within 45 days and emergence commonly occurs within another 45 days or so. Since the studies examined health either at hatch or emergence, either a 30-day or 90-day averaging period would be appropriate for expressing the criteria. Since the lower portion of fluctuating diel cycles of oxygen have been shown to be closely related to the overall effects, rather than the daily mean of highly fluctuating environments, the laboratory data may be safely applied as average daily minimum values rather than average daily average values (see discussion in Section 11 below). However, the results could also be applied effectively by using a cautious approximation of the average daily minimums that occurred in the constant exposure studies. These studies generally had fluctuations of at least +/- 0.5-1.0 mg/l or more about the reported mean. By subtracting 0.5-1.0 mg/l from the reported mean concentration, a conservative and thus protective estimate of the associated daily minimum concentrations could be made. For interpreting and applying the results of the field studies, an average oxygen concentration should be used since the studies themselves reported only the overall average concentration occurring across the period of development. Since the fluctuations in these tests are not well documented and since highly fluctuating oxygen levels have been found to negate the benefits of otherwise healthy average conditions, it is recommended that the 0.5-1.0 mg/l adjustment factor be used for these studies as well even though the direct basis is not as well established.

A mean concentration of 9 mg/l is the lowest concentration that has no appreciable impact (<1%) on survival, creates no detectable avoidance (stress) reaction in alevin, is found to support healthy incubation in both field and laboratory research, and has only a minor (8%) expected impact on potential size at hatching. Adjusting the daily average oxygen concentration to obtain an estimate of a protective daily minimum concentration (by subtracting 0.5-1.0 mg/l as discussed above and in Section II) results in an estimate that an average daily minimum oxygen concentration should remain at or above 8-8.5 mg/l in the redds for full protection of salmonid incubation.

The selection of a specific criteria value is made somewhat problematic, however, by the fact that intragravel oxygen concentrations are less than that of the overlying water column. Depressions commonly cited in the literature typically range from about 1-3 mg/l. Using this range, the research conclusions can be adjusted to water column concentrations. This approach results in the recommendation that to fully protect developing salmonids, the average of the daily minimum oxygen concentrations in the water column should remain at or above 9.0-11.5 mg/l. If a lower value is selected because of concern over making this type of categorical adjustment, it may be advisable to include some provision that ensures average minimum intragravel oxygen levels are at least 8-8.5 mg/l if a high degree of protection is intended.

Policy Issues: In addition to selecting the level of support for incubating salmonids, there are other important policy decisions that must be made to translate the research results into water quality criteria.

(1) **Establishing the Criteria Duration**. An important policy decision is whether or not to use the estimate as a mean value to apply to a window of time similar to a typical incubation period, to apply it to the incubation periods specific to individual streams, or to decide to apply it to some shorter time period as a way to simplify monitoring and assessment.

(2) **Establishing Supplemental Duration-Based Criteria**. While studies did not investigate short-term concentrations (e.g., daily or weekly minimums or averages) that would harm incubation, some consideration to establishing such criteria may be warranted. One method would be to use a moderately protective long-term concentration value as a short-term criterion For example, intragravel concentrations below 6-7 mg/l were commonly found to significantly increase stress, mortality, and avoidance in the research. This suggests a basis for not allowing short-term (weekly average for example) exposures to fall this low. Similarly, since concentrations below 5 mg/l are associated with very high and sometimes complete mortality, allowing even a single daily minimum to fall below this level may create an unquantifiable but unacceptable risk.

(3) **Accounting for Depression of Oxygen in the Gravels**. Another important policy decision is how to account for the depression of oxygen that occurs between the water column – where oxygen is typically monitored – and the larvae developing in the spawning gravel. EPA recommends assuming a 3 mg/l depression occurs. This recommendation is supported by the available literature, but depressions in actual streams can vary widely from only a 0.5 mg/l depression to complete entombment. In general, it is believed that the selection should fall within the range of 1-3 mg/l to cover the bulk of the study results cited herein.

(4) **Accounting for Temperature Induced Risks**. When temperatures are above favorable levels for incubation, any reduction in oxygen can cause a notable increase in detrimental effects to embryonic growth and survival. An important policy decision is whether or not to assume temperatures will remain favorable during development, assume they may be slightly warmer and be more protective in the selection of the oxygen criteria, or to establish a narrative standard that changes the oxygen depression allowance for human activities when temperatures are above what is favorable for development (e.g., average 10-10.5°C).

B. Non-Salmonids:

Incubation Studies:

Siefert, Carlson, and Herman (1974) found that smallmouth bass (a non-native species) held at 20°C had a 20% reduction in survival (30% survival) at a mean of 4.4 (4.2-4.8) mg/l compared to the control (40.5% survival) at 8.7 (8.3-8.9) mg/l. Survival of smallmouth bass dropped to zero at 2.2 and 2.5 mg/l, thus a threshold for survival may exist between 2.5 and 4.4 mg/l.

Peterka and Kent (1976) found that smallmouth bass experienced high survival with 8-hour exposure to 2.2 mg/l.

Siefert, Carlson, and Herman (1974) found that mountain whitefish (a native species) survival was similar to controls (82-89% at 12.3 mg/l) at 6.5 mg/l (82-88%), and was only moderately reduced at 4.6 mg/l (66-75%). Survival was nominal or zero at concentrations of 1.7, 2.6, and 3.1 mg/l. They also found that catfish (a non-native species) survival was reduced at all concentrations below 7.3-7.8 mg/l, but only slightly reduced at concentrations of 5.0-5.8 mg/l and statistically significant only below 4.2 mg/l.

Siefert and Spoor (1974) found that white sucker (a non-native species) survival rates were similar to controls (92% at 9.1 mg/l) at 4.9 mg/l (95.5%), and were only slightly reduced at 2.5 mg/l (89.5%). Survival rates were zero at 1.2 mg/l. They also found that the survival rates of walleye (a non-native species) were similar to controls (41.5% at 8.9 mg/l) at 4.8 mg/l (38.5%). Survival dropped to 14.5% at 3.4 mg/l.

Peterka and Kent (1976) studied short-term exposure to incubating northern pike (a non-native species) embryos and found high (93-100%) survival with 8-hour exposure to 4 mg/l. They found that bluegill were even more resistant, maintaining high survival rates with a 6-hour exposure to 1.8 mg/l.

Siefert, Carlson, and Herman (1974) found that white bass (a non-native species) at 16°C only began to experience a clear drop in survival in a duplicate test conducted at a mean of 3.4 mg/l (tests included 9.2, 6.9, 5.0, 3.4, and 1.8 mg/l). No difference in size at hatch was found at any test concentration and survival was 19-25% at 1.8 mg/l compared to the control survival rate of 34-36% at 9.2 mg/l.

Summary of Overall Impact of Oxygen on Non-Salmonid Incubation: As with salmon, char, and trout, oxygen concentrations depressed below saturation levels will tend to exert an influence on both growth rates and size at hatch. However, for the general complex of fishes examined here these effects are more variable and sometimes not found until oxygen levels reach those that are also associated with reduced survival levels. In general, survival rates remained similar to controls (typically at saturation) at concentrations above 6.5-7.0 mg/l. Survival rates were only slightly depressed in the range of 5.5-6.0 mg/l.

The literature search conducted for this paper focused on indigenous species. Little information was found, however, on the oxygen requirements of indigenous species other than salmon, char, and trout except for the mountain whitefish. Since mountain whitefish (a salmonid itself) occur in waters in association with the other salmonids, it will be protected under salmonid-based criteria; however, because of the paucity of data on indigenous non-salmonids it is included here as a supporting surrogate for other untested indigenous species. For similar reasons, the data on non-indigenous species are also being considered in making recommendations for the incubation protection of indigenous non-salmonids. Also considered are the findings of the 1986 USEPA guidance document on freshwater dissolved oxygen criteria. That guidance document reviewed significantly more research on non-indigenous species, particularly warm water species, than was directly examined in this report. It suggested that no production impairment would occur in early life stages of non-salmonid species where the 30-day average dissolved oxygen level is maintained above 6.5 mg/l and only slight production impairment would be expected where the average concentration is maintained above 5.5 mg/l. This recommendation appears reasonably well supported by the studies directly reviewed for this analysis. Since non-salmonid species do not tend to bury their eggs deep in the sediments, no adjustments are necessary to account for oxygen depressions in the gravels as was done previously for the salmonids.

In consideration of all of the above factors, it is concluded that during periods when non-salmonid species are spawning and incubating, average minimum dissolved oxygen levels should be maintained above 6.5-7.0 mg/l to provide for no production impairment. Average concentrations in the range of 5.5-6.0 mg/l would be expected to result in slight impairment of hatching rates.

4. Acute Lethality (Juveniles)

A. Salmon, Char, and Trout:

Lethality from Long-Term Exposure:

Davison et al. (1959) found that juvenile coho could withstand (95-100% survival) dissolved oxygen concentrations from 1.26 to 2.13 mg/l at temperatures ranging from 12 to 23.5°C respectively. They further noted that concentrations near 3 mg/l may sometimes be fatal after moderately prolonged exposure.

Herrman (1958) tested the survival of juvenile coho salmon fed to excess at 20°C over 19-27 day exposure periods. Survival rates were highly variable over the eight individual tests conducted, some of this variability was likely the result of the different temperatures of the tests and may reflect the effect of the minimum values within the range represented by the reported mean test concentrations (fluctuations were as high as 2.5 mg/l). Survival rates were often 100% at mean oxygen rates between 3.1-8.1 mg/l (at 20.3°C), and sometimes 100% at mean concentrations as low as 2.0 mg/l (at 18°C). However, the most consistent occurrence of complete survival appeared to correspond with treatments having lower range values above 3.3 mg/l.

Herrmann et al. (1962) found few exceptions that under otherwise tolerable conditions (20°C for 19-27 days) juvenile coho salmon could survive (typically 100%) for 3 or 4 weeks at oxygen concentrations averaging about 4 mg/l, but that increased mortality can be expected at mean test concentrations of 3 mg/l or lower (LC50 was assumed to be between 2.3-3.1 mg/l at 20°C). **[Note: This finding is used in other parts of this paper to adjust median lethality endpoints to an estimate of the concentration expected to cause no lethality. In the authors' work, a 1.3 mg/l increase in oxygen approximately changed the result from 50% mortality to 100% survival.]**

Baroudy (1993; as cited in Elliott and Baroudy, 1995) found that Arctic char parr better tolerated lower oxygen levels (1.8-2.0 mg/l; 15-17% saturation) at lower (5, 10°C) compared to higher (15, 20°C) acclimation temperatures (2.2-2.4 mg/l; 22-25% saturation).

Warren et al. (1973) found mortality rates of juvenile chinook salmon of 60-80 percent at 3.3 mg/l in 20 day tests at temperatures of 18.6 and 21.7 respectively.

Summary on Long-Term Lethality: Median lethality (50% mortality) of juvenile salmonids would be likely to occur with constant exposure to mean concentrations below 3-3.3 mg/l for periods of 20-30 days. Adding a 1.3 mg/l adjustment to this estimated lethal range would be expected to convert the effects from 50% mortality to no-mortality based in part on the results of Herrmann et al. (1962). Thus, a mean concentration of 4.6 mg/l would seem most likely needed to prevent lethality over a 3-4 week period of time.

Lethality from Short-Term Exposure:

Burdick et al. (1954) found brook and brown trout to be more sensitive to low dissolved oxygen levels than were the rainbow trout stocks tested. Rapid lethality (LC50 in 1-4 hours) ensued in warm waters (20-21°C) at median concentrations as high as 2.6 mg/l for brook trout, 2.51 mg/l for brown trout, and 1.83 and 1.49 mg/l for rainbow trout.

Summary on Short-term Lethality: In warm water, salmonids may require daily minimum oxygen levels to remain above 2.6 mg/l to avoid significant (50%) mortality. To prevent any short-term mortality, daily minimum oxygen levels should be maintained above 3.9 mg/l [a 1.3 mg/l adjustment was made to convert from 50% mortality to no-mortality based in part on the results of Herrmann et al. (1962)].

Field Accounts of Lethality:

Chandrasekaran and Rao (1979) found that rainbow trout could be successfully reared in stagnant ponds in India with a maximum water temperature of 29ºC and the lowest dissolved oxygen of 3.9 mg/l without artificial feed.

Gnaiger (1993) found that complete winter-kill occurred in rainbow trout when oxygen in the water column dropped to 1.92 mg/l.

Holeton (1973) found that even in very cold water (2°C), arctic char may experience lethality at 2.75 mg/l or higher.

Nelson (1986) reported juvenile chinook winter mortalities occurred when oxygen levels were between 2-3 mg/l, but juveniles survived at oxygen levels ranging from 3-7 mg/l.

Bustard (1983; as cited in Raleigh, Miller, and Nelson, 1986) reported juvenile chinook winter mortalities occurred when oxygen levels were between 2-3 mg/l, but juveniles survived at oxygen levels ranging from 3-7 mg/l. The authors concluded that chinook juveniles can survive short term exposures to 3 mg/l oxygen at temperatures <5ºC, but optimal levels are >9 mg/l at <10ºC and 13 mg/l at >10ºC.

Summary on Field Research: Significant mortality has been observed in natural waters with daily fluctuations occurring in the range of 2.5-3.0 mg/l. Adjusting this upward by 1.3 mg/l to convert to levels where little or no mortality would be expected would produce the range of 3.8-4.3 mg/l as an estimate of the daily minimum oxygen reasonably concentrations that would likely not increase mortality rates. This estimate is also consistent with the field study of rainbow trout in India that found daily minima of 3.9 mg/l did not create excess mortality.

Fluctuating Laboratory Tests:

Whitworth (1968) subjected yearling brook trout to diel fluctuations from 10.6-10.7 mg/l to 5.3, 3.6, 3.5, and 2.0 mg/l (at 8.4-11.7°C). He found that most fish were unable to tolerate fluctuations to 2.0 mg/l.

Summary of Fluctuating Tests: Daily minimums as low as 2 mg/l were associated with very high mortality rates even though the daily maximums were approximately 10.5 mg/l. Adding 1.5 mg/l (rather than 1.3 as done previously) to the lower range to try and adjust the high mortality rate (88%) to a level of oxygen that would not be expected to cause any mortality produces the estimate of 3.5 mg/l as a daily minimum. This is confirmed directly through author's research that included a daily minimum of 3.5 mg/l that was not associated with increased mortality.

Summary of Multiple Lines of Evidence on Acute Lethality to Salmonids

Table 2. Summary table showing the individual lines of evidence produced by the studies examined on acute lethality.

Lines of Evidence for Acute Lethality at the Juvenile Life-Stage		
	Threshold of No Lethality (mg/l D.O.)	**Associated Exposure Duration**
Lethality from Long-Term Exposure	4.6	20-30-day Mean Concentrations
Lethality from Short-Term Exposure	3.9	Single Daily Minima
Field Accounts of Lethality	3.8-4.3 (median 4.03)	Single Daily Minima
Fluctuating Laboratory Tests	3.5	Single Daily Minima
Range of Estimates:	***3.5-4.3 (median 3.9)***	***Single Daily Minima***
	4.6	***Weekly or Monthly Ave. Minimum***

Conclusions on Acute Lethality to Salmonids:
Based on the literature cited above, mortality of juvenile salmonids should be prevented by maintaining single daily minimum oxygen concentrations above 3.9 mg/l and by maintaining weekly or monthly average minimum concentrations above 4.6 mg/l. This protection should be expected even at water temperatures approaching the thermal limits of the fish.

While the research examined often did not place the test fish in situations where they needed to exert themselves (resist currents, capture food, avoid predators), it did include some field studies and in the long-term exposure tests would include some of the energy expenditures caused by competition and the digestion of meals. Since the endpoint is mortality, however, it is important to take a cautious approach in recommending criteria values. It is possible, though not directly addressed in the literature, that the increased physical work necessary to live in the natural environment may increase the lethal stress on fish, thus a final decision on setting a water quality criteria should probably error on the cautious side to avoid any direct lethality.

B. Non-Salmonids:

Acute Lethality to Non-Salmonids:

Burdick et al. (1954) found that two populations of smallmouth bass experienced median mortality in approximately 8 hours at median concentrations of 1.17 and 1.03 mg/l at temperatures of 26.7°C, and at concentrations of 0.72 and 0.63 at temperatures of approximately 12°C.

Whitmore et al. (1960) citing unpublished experiments suggest that lethal concentrations for bass in periods less than 24 hours at temperatures near 20°C are below 1 mg/l.

Davison et al. (1959) noted that sculpin (*Cottus perplexus*) at 18-19°C had a median tolerance limit for a 4-day exposure of about 1.46 mg/l.

ODEQ (1995) noted that the endangered shortnose and lost-river suckers in the Klamath Basin in Oregon had initial juvenile mortality during a 96-hour test of 3-4 mg/l. Other authors are noted to have observed acute responses in 2-hour tests at concentrations near 1.0 mg/l.

USEPA (1986) suggested that 3 mg/l would prevent acute mortality in non-salmonids at both juvenile and adult life stages.

Secor and Gunderson (1998) found increased mortality in Atlantic sturgeon at 2-3 mg/l compared to a control at 6-7 mg/l at both 19°C and 26°C. High temperature hypoxia resulted in a very low survival rate (mean of 6.3%), and when sturgeon were denied access to the surface was fully lethal within 30 hours. It is important to note here that sturgeon will occur along with salmonids in Washington's waters and would need to be protected as part of the cold water fish community. They are included here to serve as a surrogate for other untested non-salmonid species.

Conclusions on Acute Lethality to Non-Salmonids: Based on the literature reviewed for this report it appears that acute lethality would be prevented in most introduced warm water fish species where dissolved oxygen concentrations are continuously maintained above 2-2.5 mg/l. Data was not found for any indigenous non-salmonid species. However, using the data for the Atlantic sturgeon (which may be similar to our white sturgeon), the Oregon sucker (which occurs naturally within our region), and the 1986 USEPA recommendations all in combination suggests that lethality may begin at concentrations as high as 3-4 mg/l. This is very similar to the conclusion reached previously for salmonid species. **It is concluded that daily minimum dissolved oxygen levels above 3.5-4 mg/l will generally prevent any acute lethality in juvenile and adult specimens of native and introduced non-salmonid species.**

5. Effect on Juvenile Growth

A. Salmon, Char, and Trout:

Constant Laboratory Exposure Studies:

Hutchins (1973) reported that at 15°C growth of juvenile coho salmon fed to repletion and held at velocities between 1.2 and 3.6 l/sec (lengths per second) at an oxygen level of 3 mg/l for 10 to 12 days was reduced by 20 and 65 percent from that of a control salmon held at respective velocities in air-saturated water (9.5 mg/l). At the intermediate oxygen concentration of 5 mg/l, growth rates of salmon were reportedly reduced by 0 and 15 percent over controls, respectively. The author noted that some increased efficiency in growth may occur at moderate swimming speeds, and this effect may have helped to compensate for the effect of oxygen in the tests.

Herrmann et al. (1962) found that juvenile coho salmon (age class 0) held at 20°C and fed to repletion twice daily experienced declines in growth with reduction of oxygen from a mean of about 8.3 to 6 and 5 mg/l, and declined more sharply with further reduction of oxygen concentration, suggesting further that concentrations near 4 or 5 mg/l can be exceedingly detrimental. The authors estimated a reduction of both percent weight gain and the rate of food consumption by about 11 percent with reduction of oxygen concentration from 8.3 to 5.0 mg/l, and by at least twice as much with reduction of oxygen concentration to 4 mg/l.

Brett and Blackburn (1981) examined the growth rate and food conversion efficiency of young coho and sockeye salmon under full rations at 15°C over 6-8 weeks. In a test series using coho, statistically significant decreases in growth occurred with each successive decrease in oxygen (from 10, to 7, 3, and 2 mg/l) one year but only with a change to 4 mg/l or lower in a subsequent year. In a test series using sockeye, growth rates steadily decreased with each successive decrease in oxygen (15, 10, 7, 5, 4, 3, 2, and 10, 7, 3, 2) but was only statistically significant at 4 mg/l and below. After consulting the literature and considering the results of their own research, Brett and Blackburn concluded that for all species of fish, above a critical level ranging from 4.0 to 4.5 mg/l, growth and conversion efficiency were not limited when tested for relatively short periods (6-8 weeks) under the pristine conditions of laboratory tanks. Although, as noted by the authors the reduction rates were not statistically significant at higher oxygen levels, the data can still be used to describe the general trend in mean growth rates. A reduction from 10 mg/l to 9 mg/l was associated with a 4.6 percent reduction in the growth rate, and reductions to 8 and 7 mg/l would result in reductions in the growth rate of 9.7 and 15.5 percent respectively (Figure 9).

Thatcher (1974) tested the feeding, growth and bioenergetics of juvenile coho salmon during summer, fall and spring at a constant 15°C and at 8, 5, and 3 mg/l. Thatcher concluded that in natural conditions where successful fish must expend energy competing for food, territory, and other required activities, a dissolved oxygen concentration of 5 mg/l may restrict these necessary activities. In those situations, coho living at 5 mg/l dissolved oxygen may not grow nearly as well as fish at higher oxygen levels.

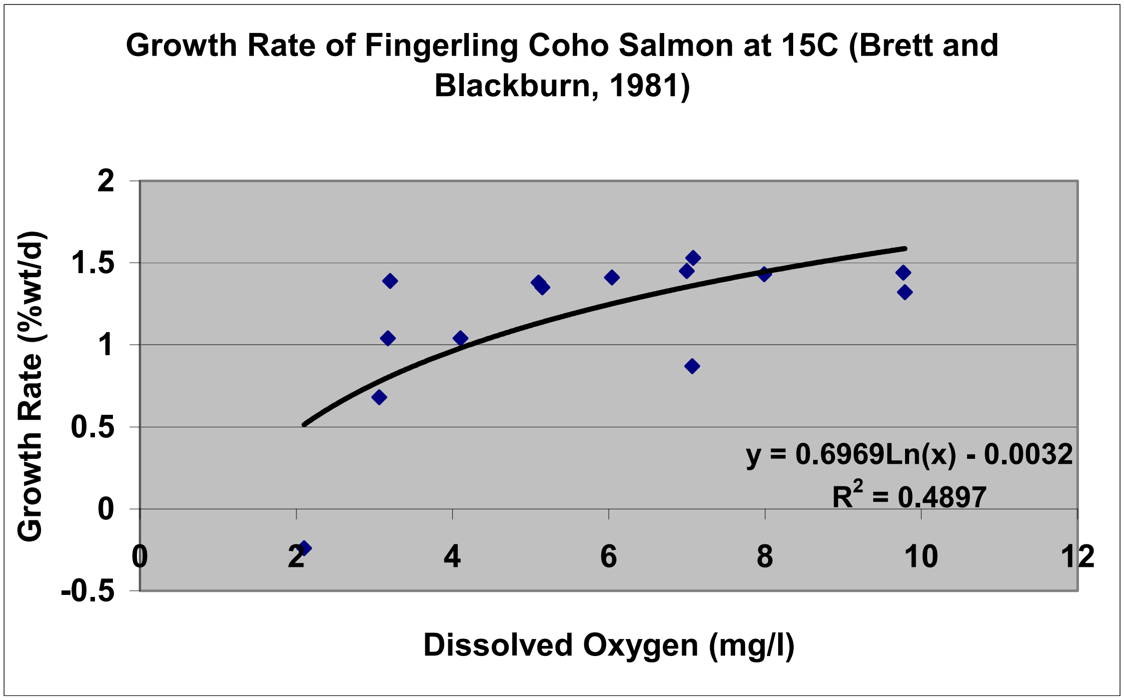

Figure 9. Growth rates of coho salmon in 6-8 week tests at 15°C (data of Brett and Blackburn, 1981).

Pedersen (1987) found that the critical level of oxygen for food consumption in rainbow trout was about 6 mg/l and the critical level for both growth rate and food conversion efficiency was about 7 mg/l for fish fed maximum rations.

Herrman (1958) found that growth, feeding, and food conversion efficiency in juvenile coho salmon generally decreased with decreasing availability of oxygen. Herman, found that at temperatures around 20°C marked effects generally occurred within the range of four to six milligrams per liter with some indication that smaller coho (<2 grams) experienced greater depression of growth at the high end of this range. Using the data of Herrmann (Figure 10), it is estimated that a reduction from 9 mg/l to 8 mg/l would result in a 9.88 percent reduction in growth, and reductions to 7 and 6 mg/l would result in 21 and 34 percent reductions in growth, respectively.

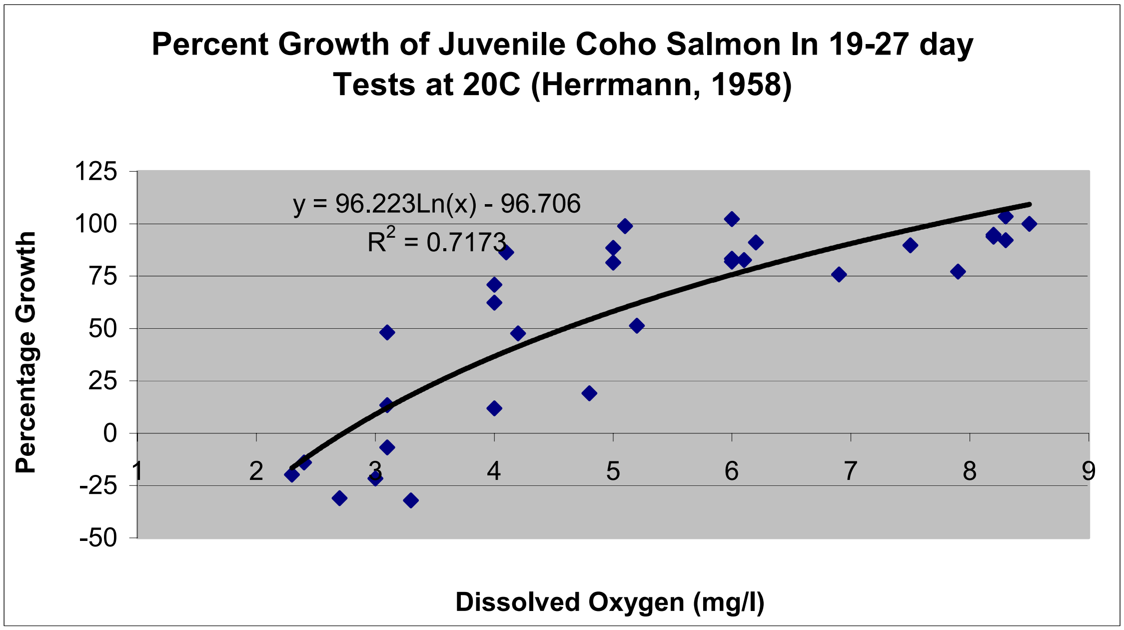

Figure 10. Percentage increase in growth of juvenile coho salmon over 19-27 days at 20°C (Herrmann, 1958).

Keesen et al. (1981) found that when the dissolved oxygen supply (concentration in fresh water) was reduced from 8 mg/l to 4 mg/l, oxygen consumption of trout declined by 17% and growth performance by 34%.

Warren et al. (1973) found that except at relatively low temperatures, any considerable reduction of dissolved oxygen from air-saturation levels usually resulted in some reduction of the food consumption and growth rates of juvenile coho and chinook salmon provided unrestricted food rations. When rations were restricted, the growth of coho salmon was not so affected. Figure 11(a)-(d) demonstrates the general relationship between water temperature and oxygen requirements. Figure 12 uses the data from Warren et al. (1973) to produce an overall estimate of the effect of reducing oxygen on growth rates. Optimal or near optimal (-1.2%) growth occurred at 8 mg/l or more in all tests. Declines to 7 mg/l and 6 mg/l resulted in maximum reductions in growth of 5.3 and 15.3%, respectively.

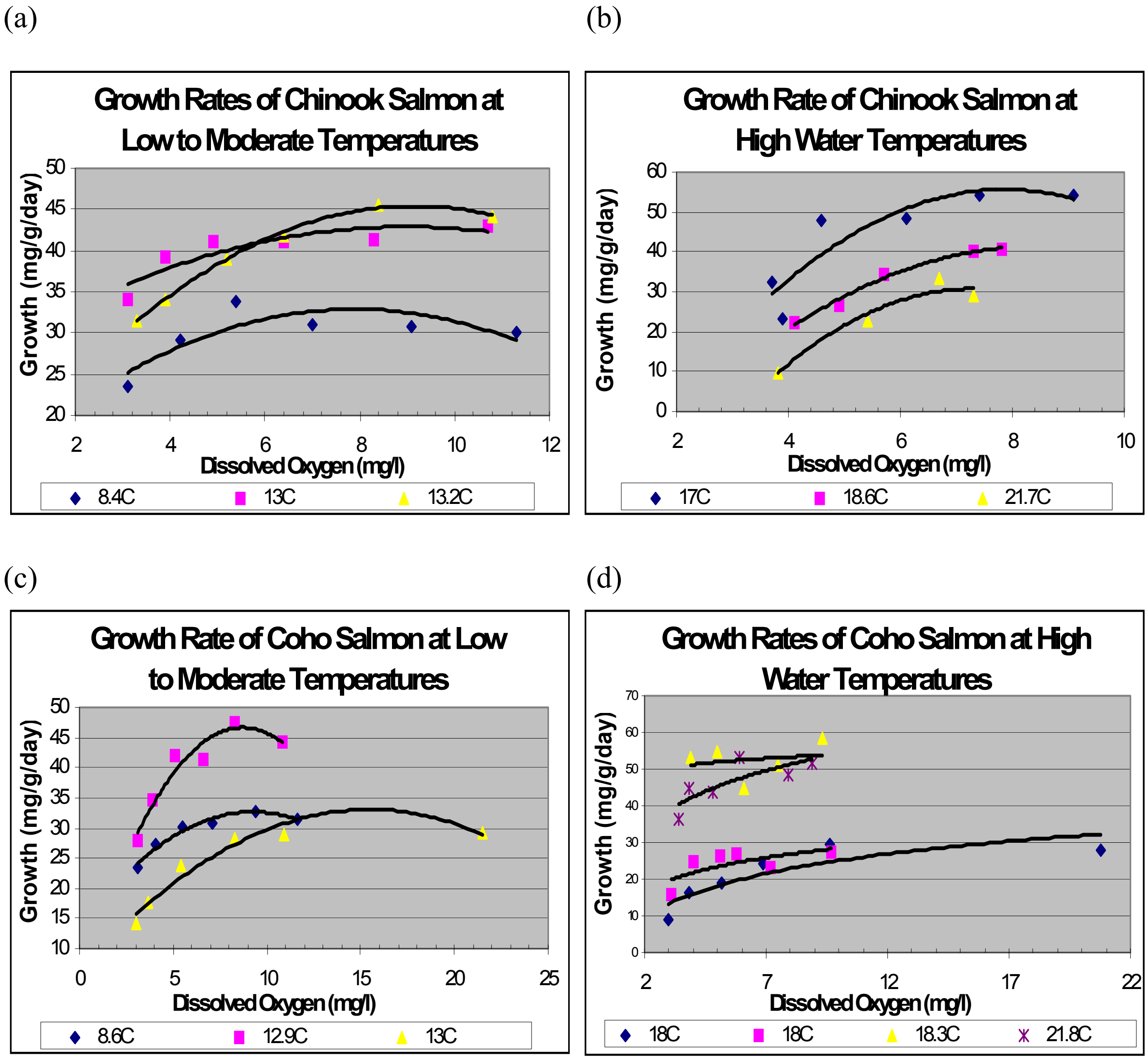

Figure 11(a)-(d). Relationship of dissolved oxygen concentration and temperature on the growth of chinook and coho salmon fed to repletion (Warren et al., 1973).

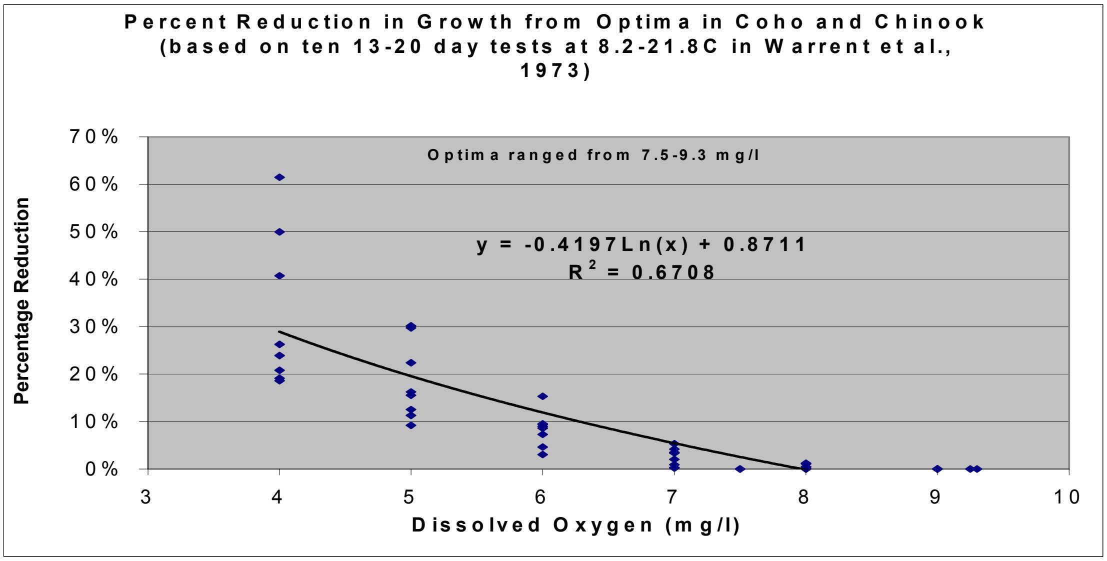

Figure 12. Percent reduction in growth from estimated optimum in coho and chinook salmon in ten tests conducted from 13-20 days at temperature ranging from 8.4-21.8°C (based on Warren et al., 1973). Optimal or near optimal (-1.2%) growth occurred at 8 mg/l or more in all tests. Declines to 7 mg/l and 6 mg/l resulted in maximum reductions in growth of 5.3 and 15.3%, respectively.

Summary of Constant Exposure Studies: The results from constant oxygen exposure testing generally shows the consistent trend of a relatively steady decline in growth as oxygen concentrations decrease from saturation levels. That said, however, it is important to recognize that there was very notable variability in the results. Many authors were unable to find that the decreases in growth rate were statistically significant in the range of 5-8 mg/l. Using the raw data of the authors to try and assess any consistent trend in growth reductions was only slightly more informative. The general pattern was for growth rates to be consistently depressed less than 10% (0-9.8%) at concentrations of 8 mg/l or more, and less than 20% (5.3-21%) at 7 mg/l. Concentrations of 5-6 mg/l had associated reductions ranging from 0-34% but in general were less than 22%.

Fluctuating Oxygen Tests:

Fisher (1963) conducted laboratory experiments to determine the influence of constant and widely fluctuating diurnal fluctuations of nonlethal levels of dissolved oxygen on the growth, food consumption, and food conversion efficiency of under-yearling coho salmon at a constant 18°C for 18 to 21 days. Fisher found that fish kept on an unrestricted diet and exposed to constant oxygen concentrations from 3 to 29.9 mg/l in one set of tests and from 2.5 to 35.5 mg/l in a second set of tests experienced a marked decrease in growth at oxygen concentrations less than the air-saturation level (9.5 mg/l). Based on a graphic plot of the data conducted by Fisher, the percent gains in wet and dry weight increase markedly up to approximately 8 mg/l beyond which the percent gains began to decline becoming generally negative above approximately 10 mg/l. However, when the data points are examined independently, concentrations about twice the air-saturation value show a slightly favorable influence on growth. The differences in growth rates observed at different oxygen concentrations were associated with corresponding differences of food consumption rates. Food conversion efficiencies of fish held at different constant oxygen concentrations were not markedly different, there having been no appreciable impairment of the efficiency at concentrations as low as 3.8 mg/l. Fisher compared the dry weight gains of coho salmon subjected to fluctuating dissolved oxygen concentrations (equal periods of non-lethal low and high oxygen concentrations) with the gains estimated at constant oxygen concentrations corresponding to the means for the fluctuating tests. He found that fluctuating tests (with equal periods of the day at each extreme) from 3-9.5 (median 6.25) mg/l and 3-18.0 (median 10.5) mg/l had growth rates corresponding to constant exposure tests conducted at 3.4 and 3.8 mg/l, respectively. Fluctuating tests from 2.3-9.6 (median 5.95) mg/l and 4.9-35.5 (median 20.1) mg/l had corresponding growth rates of constant tests conducted at 4.8 and 6.8 mg/l, respectively. The growth rates of fish kept for 21 days on equal, restricted rations at various constant oxygen concentrations ranging from about 3 to 18.1 mg/l did not differ greatly; with only the growth of the fish exposed to the lowest tested dissolved oxygen level showing considerable impairment, ascribable to impaired digestive or assimilatory efficiency. The gross food conversion efficiencies of all the fish in this experiment proved markedly greater than those of the fish that had been fed unrestricted rations under the same conditions, although the growth rates were much less than those fish fed unrestricted rations. Using the data of Fisher for all constant oxygen tests in below 18 mg/l, the trend of declining growth with reduced oxygen can be estimated. A reduction from 10 mg/l to 9 mg/ resulted in a 4% reduction in wet weight, and reductions to 8, 7, and 6 mg/l resulted in reductions in growth of 8.6, 13.8, and 19.8 percent, respectively (Figure 13).

Whitworth (1968) subjected yearling brook trout to diel fluctuations from 10.6-10.7 mg/l to 5.3, 3.6, 3.5, and 2.0 mg/l at 18°C. He found that each level of fluctuation significantly depressed growth of yearling brook trout in comparison to a constant control held at average constant levels of 10.6-11 mg/l and that most fish were unable to tolerate fluctuations to 2.0 mg/l. In fact, all of the fish experiencing the fluctuations lost weight over the 60-70 day test period. This may be at least partly attributed, however, to the fact that Whitworth held the fish at a temperature above optimal for growth (Hicks, 2002) and fed them less than satiation rations. But, since the temperature is one that is rather common in Washington’s mainstem rivers, and maximal feeding would not be experienced in nature, these are also important factors in determining the relative risks of allowing oxygen to fluctuate to levels that have been shown to be lower then optimal in laboratory studies.

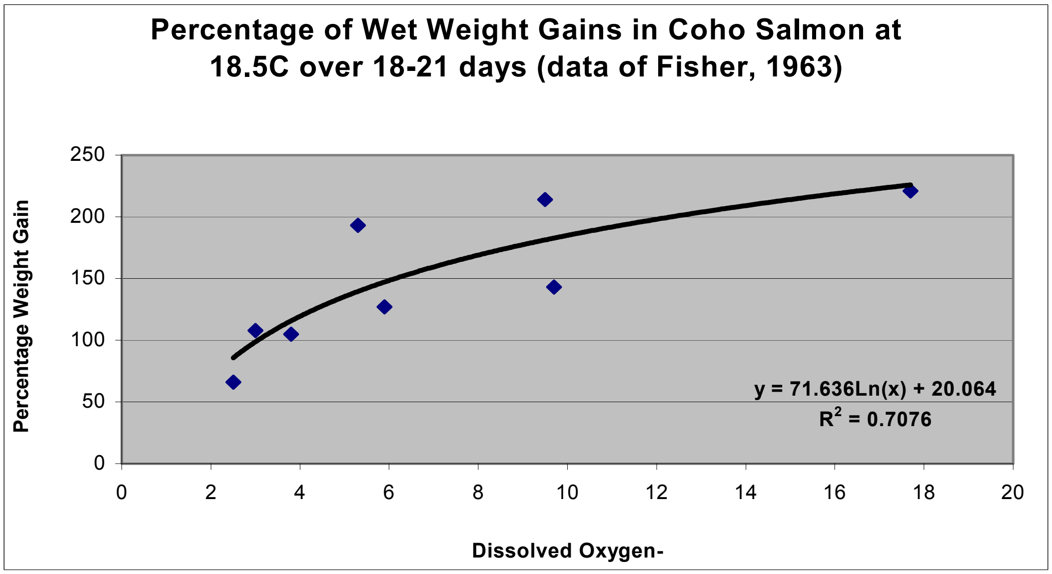

Figure 13. The percentage of wet weight gains with increasing oxygen concentrations at 18.5°C over 18-21 days (data of Fisher, 1963).

Summary on Fluctuating Concentration Testing: Whitworth found that at high temperature and low feeding, that fluctuations from high (10.6-10.7 mg/l) to low oxygen (5.3-3.5 mg/l) resulted in a loss of growth in brook trout. Fisher found that a reduction from 10 mg/l to 9 mg/ resulted in a 4% reduction in wet weight of coho salmon, and reductions to 8, 7, and 6 mg/l resulted in reductions in growth of 8.6, 13.8, and 19.8 percent, respectively.

Artificial Stream Experiments:

Warren et al. (1973) subjected juvenile chinook salmon to testing in nine replicate laboratory stream flumes receiving filtered river water. Tests varied in length from 10-27 days. Fish had to feed on the macroinvertebrates that had colonized the flumes prior to the start of testing. Both the availability of insects for food, and the growth of the chinook were examined. Where food availability was low, food availability rather than dissolved oxygen was the apparent cause of reduced growth (growth was often negative even at the highest concentrations); but where food availability was higher there was a fairly strong dependence on dissolved oxygen concentrations at all levels tested (3-10 mg/l at average temperatures of 9-14.3°C). The authors concluded that their work showed that under some conditions of food availability and temperature, any appreciable reduction in dissolved oxygen concentrations below the air saturation level is likely to reduce salmonid growth rates. Using the data from the experiments that the authors noted as having sufficient food resources to support growth, overall predictions on changes to growth rates can be made (Figure 14). A reduction from 10 mg/l to 9 mg/l would result in a 1.3% reduction in growth; reductions to 8, 7, and 6 mg/l would reduce growth by approximately 3.2, 6.2 and 10.7%, respectively. At 5 mg/l growth reductions would be expected to be over 17%.

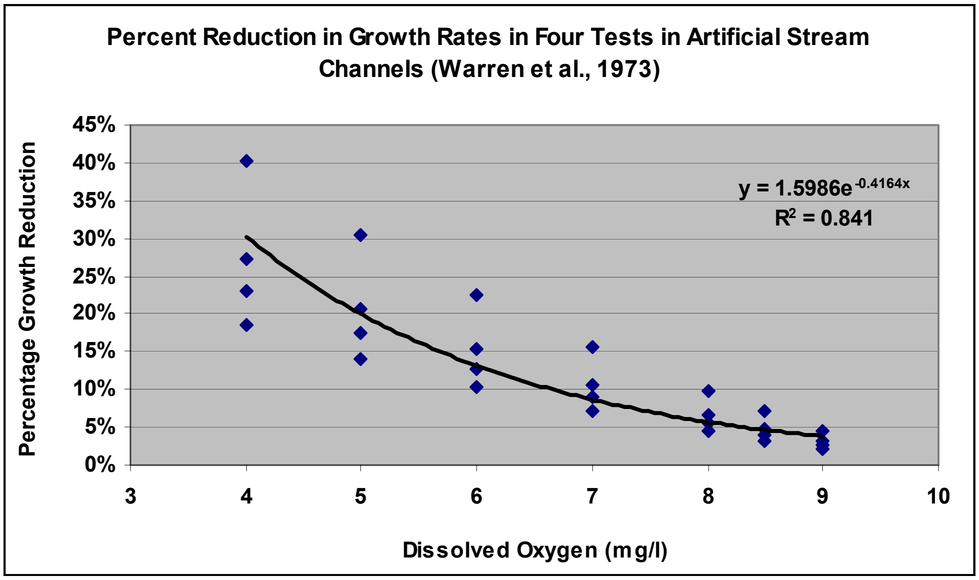

Figure 14. Percentage change in growth rates over a range of DO concentrations of juvenile chinook salmon. Composite of data from four experiments conducted in artificial stream channels over 10-20 days at average temperatures from 9.5-14.3°C. Tests included are those the authors noted as having sufficient benthic and drift food organisms in the channels (from Warren et al., 1973).

Field Studies of Growth:

Chandrasekaran and Rao (1979) found that rainbow trout reared in stagnant ponds in India grew reasonably well on natural foods (in comparison to hatchery fish) even though water temperatures reached a maximum of 29°C and dissolved oxygen a minimum of 3.9 mg/l. They found the dissolved oxygen content rarely reached 6 mg/l, and it was around 4.5 mg/l during most of the months. The lowest oxygen level of 4.0 mg/l and 3.9 mg/l were often met in the months of April and May respectively, and the fishes in general were healthy.

Young (1987) subjected rainbow trout fingerlings to dissolved oxygen regimes of 7-8.8 (7.9), 5.3-7.2 (6.3), and 3.5-6.0 (4.7) mg/l and compared their growth to control fish exposed to 11.5-13.0 (12.3) mg/l. This test was conducted for an 80-day period over the winter in outdoor channels. Growth rates at 7.9 mg/l were considered comparable to the control and were only slightly depressed in the test having an average of 6.3 mg/l. Growth was substantially reduced (15.3%) in the test having a mean of 4.7 mg/l.

Summary of Field Growth Tests: Good growth was found in rainbow trout during in a rearing pond study in India where oxygen concentrations ranged between 4-6 mg/l, and growth rates similar to controls was found in a 80-day winter test at 7.9 mg/l, with reductions considered to be only slight at an average of 6.3 mg/l, and greater (15.3%) at 4.7 mg/l.

Hatchery Water Reuse Studies:

Larmoyeux and Piper (1973) tested the effect of water reuse in hatcheries and the influence of ammonia and dissolved oxygen on the health of rainbow trout. The authors found that fish length was significantly reduced when oxygen was less than 5.0 mg/l and ammonia greater than 0.5 mg/l. They cite unpublished studies that found that growth was not affected when trout were maintained for 6 weeks in an environment with an oxygen level in excess of 7 mg/l and an ammonia level of 0.8 to 1.0 mg/l, suggesting that low oxygen stress affects growth more than ammonia levels encountered in their experiment.

Morrison and Piper (1986) found that in water reuse tests that growth rates of brown trout fingerlings began to decline when dissolved oxygen averaged 4.8 mg/l and total ammonia averaged 0.6 mg/l.

MacConnell (1989) found that in water reuse tests, the growth of lake trout began to decline when the dissolved oxygen level averaged 3.5 mg/l and ammonia 0.75 mg/l.

Summary of Water Reuse Studies: Mean concentrations of 3.5-5.0 mg/l in association with moderate ammonia concentrations significantly reduced growth; however, at oxygen levels of 7 mg/l even higher ammonia concentrations could be tolerated without significantly impacting growth.

Miscellaneous Observations:

Weithman and Haas (1984) investigated a popular put-grow-and-take fishery for rainbow trout and found that fishing success declined each fall when oxygen-depleted waters enter the lake. A decrease of 1 mg/liter dissolved oxygen, between 6.0 and 2.4 mg/liter, measurably reduced catch rates.

Brett and Groves (1979) suggested that the limiting effects of reduced oxygen concentration probably impose some increased maintenance ration through increased ventilation.

Summary of Multiple Lines of Evidence on the Effect of Dissolved Oxygen on Salmonid Juvenile Growth

Table 3. Lines of Evidence for Growth Effects in Juvenile Salmonids

Summary table showing the individual lines of evidence produced by the studies examined on growth effects on juveniles. The estimated level of the effect (as a % or as a description) is noted to assist in comparing the relative risks of different average dissolved oxygen concentrations. The number appearing at the top of the boxes is the dissolved oxygen concentration, and represents concentrations in mg/l.

Lines of Evidence for Juvenile Growth Effects				
	Higher <---------------------Protection---------------------------> Lower			
Constant Laboratory Tests	Unknown	**8-10** (<10%)	**7** (<20%)	**5-6** (<22%)
Fluctuating Laboratory Tests	**9** (5%)	**8** (9%)	**7** (14%)	**6** (20%)
Artificial Streams	**9** (1.3%)	**8** (3.23%)	**7** (6.18%)	**6** (10.66%)
Field Studies (Data from winter)	**7.9** (same as controls)	Unknown	**6.3** (slightly depressed)	**4.7** (15.3%)
Water Reuse Studies (with ammonia)			**>7** (no significant effect)	**3.5-5** (Significant effect)

Conclusions on the Overall Impact of Oxygen on Salmonid Growth:
Growth rates in salmonids are influenced by temperature, food availability, and dissolved oxygen. When food availability is high, particularly at warmer temperatures, any depression in oxygen from air saturation rates can be expected to reduce the potential growth rates of fish. When food availability is low, particularly at cool temperatures, fish growth may become independent of dissolved oxygen at concentrations of oxygen well below saturation levels. Since fish rely on the summer growth period to sustain them through the winter, taking full advantage of periods of food availability may be biologically important. However, a wide variety of control stream and laboratory studies were examined and cited above, and the general trend is for growth rates even in highly fed salmonids in warm waters to commonly be indistinguishable from controls at concentrations above 8 mg/l (Figure 11). The studies reviewed for this section were generally of about 20 days or more in duration, and thus, the results would well represent either a weekly average or monthly average oxygen concentration.

The USEPA (1986) guidance document on dissolved oxygen concluded that salmonids would suffer no production impairment at dissolved oxygen concentrations in excess of 8 mg/l and suffer only slight impairment at levels of 6 mg/l. These USEPA recommendations are reasonably well supported by the research directly reviewed in this analysis. It is also reasonably clear, however, that growth and survival will have the greatest chance of being optimized in waters fully saturated with oxygen (even though the growth rates may often be practically indistinguishable at concentrations above 8 mg/l). It is possible that fish escaping predation and feeding in the currents of our rivers may expend greater energy reserves than those in the tests.

Technical Recommendations: In consideration of all the above factors and the strength of the supporting literature, a monthly (or weekly) average concentration of 9.0 mg/l would be the lowest that would confidently have a negligible effect (5% or less) on growth rates. A 9.0 mg/l concentration representing the mean concentration reported for the research results can be adjusted (discussed previously and in Section 11) to approximate associated daily minimum concentrations (by subtracting 0.5-1.0 mg/l). **This results in the recommendation that to support healthy growth rates in salmonids, monthly average daily minimum oxygen concentrations should be at or above 8-8.5 mg/l.** It is important to note that the data also supports the assertion that minor and infrequent (once per week) depressions of oxygen into the range of 5-6 mg/l are highly unlikely to cause measurable reductions in overall growth. So using an average minimum value rather than a single daily minimum to express this growth criteria is a reasonable and safe approach.

Policy Issues: When selecting or reviewing criteria, it is important to keep in mind the averaging period. A lower criterion (7 mg/l) used with a shorter averaging period (1-day or 1-week) would be similar in protection than a slightly higher criterion (7.5 mg/l) applied as a longer-term average (30-day). Similarly, selecting a higher criterion (9 mg/l) but applying it as a long-term average (90-day) would be similar in protection to a lower criterion applied as a shorter-term average (30-day). However, the relative benefit of applying a higher value (9 mg/l) to a longer-term average (90-day) would be increased if that value is accompanied by a protective short-term limit as well (7 mg/l as a single-day minimum).

B. Non-salmonids:

Studies on Juvenile Growth:

Stewart et al. (1967) and Stewart (1962) found at 26°C the gross food conversion efficiency of largemouth bass was considerably reduced only at concentrations below 4 mg/l in 15 day tests providing an unrestricted diet. However, they found that growth rates and food consumption rates of the bass increased markedly with increased constant oxygen concentrations up to saturation (approximately 8.2 mg/l); above which growth rates began to decline. In three out of four tests an increase from 5.1-5.8 mg/l to 8.0-8.2 mg/l resulted in a marked improvement in growth. In the work of Stewart (1962) concentrations of oxygen significantly greater than saturation appeared to be unfavorable to growth.

Bouck and Ball (1965) found that a diurnal oxygen pulse of 3 mg/l for 8 hours per day produced a significant stress pattern in the serum protein fractions of bluegills and largemouth bass, and suggested that the minimum oxygen level (for eight hours) that will not adversely effect bluegills and largemouth bass is well above the generally proposed 3 mg/l. Raible (1975; as cited in ODEQ, 1995) found that channel catfish at 27°C (saturation 8.07 mg/l) experienced weight gains as much as 50 percent higher at 6.8 mg/l than at 3 mg/l when fed at repletion. Mortality was high at 2.5 mg/l.

Andrews et al. (1973; as cited in ODEQ, 1995) found that catfish at 26.6°C experienced reduced growth at 4.9 mg/l under replete feeding. When feeding rates were reduced to demand, growth reduction was noted only under the lower concentration studied of 3.0 mg/l.

Secor and Gunderson (1998) found that the growth rates of Atlantic sturgeon were 2.9 times less at 3 mg/l than at 7 mg/l. They also noted that the sturgeon continued to feed and allocate some energy to growth even at combinations of temperature and oxygen that were severely lethal.

Cech, Mitchell, and Wragg (1984) found that the growth rates of both white sturgeon and striped bass were reduced at a median oxygen concentration of approximately 4 mg/l.

Carlson, Blocher, and Herman (1980) tested the growth (weight) of juvenile catfish exposed for 69 days at 25°C to 10 mean dissolved oxygen levels from 7.7 to 2.0 mg/l and found that growth generally began declining at average dissolved oxygen levels of below 5 mg/l.

Bejda, Phelan, and Studholme (1992) found that growth rates (length and weight) of young-of-the-year winter flounder were significantly reduced at either constant 2.2 mg/l or at diurnal fluctuations from 2.5-6.4 mg/l. Growth rates of fish exposed to a constant 6.7 mg/l were over twice those of fish held under low oxygen conditions. Under fluctuating conditions, fish grew at intermediate rates. An important aspect to this study was that following these exposures, all fish were subsequently held at 7.2 mg/l for five weeks. While growth rates increased rapidly after moving the fish to more oxygenated waters, the authors estimated the smaller flounder reared at 2 mg/l would require over two months to catch up to the size of the fish reared at the higher oxygen level. Thus the effects of impaired growth can be far lasting.

Conclusions on Growth Effects to Juvenile Non-Salmonids: Similar to salmonids, the growth of non-salmonids may benefit from oxygen levels approaching or exceeding full saturation. Oxygen levels in the range of 6.7 to 8.2 mg/l have been shown to produce significantly better growth than levels at or below 5 mg/l. It must be pointed out that tests showing greater growth at 8 mg/l using warm water species were conducted at very hot (26°C) constant temperatures, thus the reader should not assume that warm water fish necessarily have the same oxygen requirements as the cold water salmonids. It can be said, however, that in very warm waters non-salmonid growth will benefit from oxygen concentrations at saturation (water would be unable to hold more than about 8.3 mg/l in saturation at 26°C). Also similar to salmonids, the literature becomes very consistent in finding significant effects below 5 mg/l. USEPA (1986) suggests based on their review of the literature that no production impairment will occur to non-salmonids at concentrations of 6 mg/l and above and that only slight production impairment will occur at concentrations as low as 5 mg/l. Considering that several authors reviewed herein noted marked decreases in growth at concentrations above 6.0 mg/l, strict acceptance of the USEPA conclusions for non-salmonids is not recommended.

Technical Recommendation:

Based on the literature reviewed, and in recognition that the studies examined did not include any of our state's indigenous non-salmonid freshwater species, a cautious approach to estimating a healthy growth condition for non-salmonids may be warranted. Full support for the juvenile growth of non-salmonid species should occur when average oxygen concentrations exceed 7-8 mg/l. To prevent short-term harm, the daily minimum should not fall below 5-6 mg/l. Since test conditions varied typically by +/- 0.5-1.0 mg/l about the reported mean, adusting the effect range downward by 0.5-1.0 mg/l provides a safe approximation of daily minima that can be related to the research (see Section 11 for more discussion). **Thus to fully protect non-salmonid growth it is recommended that the 30-day average of the daily minimum oxygen concentrations not fall below 6.0-7.5 mg/l.**

6. Avoidance Reactions

A. Salmon, Char, and Trout:

Spoor (1990) found that brook trout fingerlings avoided concentrations below 4 mg/l and showed a preference for oxygen concentrations 5 mg/l or higher (up to 8.9 mg/l was available).

Whitmore et al.(1960) found that juvenile chinook salmon showed marked avoidance of oxygen concentrations near 1.5, 3.0 and 4.5 mg/l in summer at high temperatures. At summer temperatures, juvenile coho salmon showed some avoidance of all the reduced oxygen concentrations, including 6 mg/l, but their behavior was more erratic than that of the chinook.

Hampton and Ney (1993) found that brown and rainbow trout in a large reservoir were confined to areas outside their preferred temperature range (14-18°C) when dissolved oxygen concentrations were less than 5 mg/l. This restriction of location due to oxygen depletion also resulted in reduced food consumption as the trout were isolated from their primary forage, alewife.

Matthews and Berg (1997) cited studies showing that fish will generally avoid oxygen concentrations below 5 mg/l and will move to find higher oxygen concentrations if available (cites Reynolds & Thompson, 1974; Kramer, 1987; Spoor, 1990). However, they noted finding a population of rainbow trout congregating in cooler but hypoxic pool bottoms fed by groundwater seeps to avoid lethal temperatures (27.9-28.9°C) occurring in the overlying waters. Fish were found in pools with dissolved oxygen ranging from less than 1 to 5 mg/l over a 24 hour period, while the surface oxygen ranged from 4.1 to 10.0 mg/l.

Hallock et al. (1970) note that starting in 1961, salmon runs of the San Joaquin River suffered a disastrous collapse, probably due to water conditions in the San Joaquin part of the Delta. An annually recurring oxygen block caused by pollution in the south-eastern part of the Delta, plus reversal of direction of flow in all three major north-south channels of the San Joaquin (southern) part of the Delta, were believed responsible for the collapse. Salmon avoided water with less than 5 mg/l dissolved oxygen by staying farther downstream until the oxygen block cleared.

Fish and Wagner (1950; as cited in Andrew and Geen, 1960) reported that pollution of the Willamette River in Oregon in 1949 was of sufficient magnitude to overload the lower reaches during periods of low flows and high temperatures. During July, August, and September, the dissolved oxygen level was less than 5 mg/l. The authors stated: “the lowest reach of the river is degraded to the point where oxygen deficiency precludes any movement of migratory fishes through the affected areas.” The blockage of the river caused by low oxygen levels was said to have destroyed a significant run of fall chinook in the Willamette River.

Conclusions on Avoidance by Juvenile Salmonids: Numerous authors have demonstrated that fish will actively avoid dissolved oxygen concentrations above the levels that would cause acute lethality, and that chronically low oxygen levels will determine the presence and distribution of fish species in natural waters. In general, avoidance reactions in salmonids have been noted in both field and laboratory studies to occur consistently at concentrations of 5.0 mg/l and lower. There is some indication, however, that avoidance reactions may sometimes be triggered at concentrations as high as 6.0 mg/l in salmon. **Oxygen levels below 5.0-6.0 mg/l should be considered a potential barrier to the movement and habitat selection of salmonids.** It is not clear from the research whether or not the fish will avoid waters with average oxygen concentrations below 5-6 mg/l, or would respond even if only the daily minimums fell below this range. It seems warranted to assume that anytime the oxygen concentrations fall below 5-6 mg/l fish will begin to avoid that portion of the waterbody. Thus, treating the values as single daily minimums may be most appropriate to ensure full protection.

B. Non-Salmonids:

Smale and Rabeni (1995) found Missouri stream fish assemblages were influenced by dissolved oxygen minimum values up to approximately 4-5 mg/l.

Coble (1982) conducted field studies on walleyes, and yellow perch, and 13 species of centrarchids and found that average July and August dissolved oxygen levels above 5 mg/L were associated with a greater abundance of sport fish.

Whitmore et al. (1960) found that largemouth bass and bluegill markedly avoided concentrations near 1.5 mg/l, but showed little or no avoidance of the higher concentrations, only the bass showed any avoidance of concentrations near 4.5 mg/l. Avoidance reactions of sticklebacks, minnows, and trout to concentrations as high as 3.2 to 5.5 mg/l, at temperatures of 13 to 24ºC, were reported from the literature.

Conclusions on Avoidance by Juvenile Non-Salmonids: No literature was found that directly addresses avoidance reactions by non-salmonid species clearly indigenous to the state of Washington. Further, the work referenced by Whitmore et al. (1960) included trout so it should be considered with caution. **Based on the literature reviewed for this paper, however, dissolved oxygen levels below 5.0-5.5 mg/l should be considered a barrier to the movement and habitat selection of non-salmonid species.**

7. Predation Effect

Numerous authors have demonstrated that predators will venture into hypoxic zones within waterbodies to feed on species that are moribund or slowly recovering from hypoxia, even where these zones would otherwise prove lethal to the predator if exposure was prolonged (Luecke and Teuscher, 1994; Rahel and Nutzman, 1994; and Pihl et al., 1992). The ability to exploit these weakened prey may affect the ecosystem as a whole and disrupt the distribution of energy throughout the aquatic system. Thus concentrations of oxygen that would significantly impair the motility of an organism could indirectly result in greater mortality rates through increased predation.

8. Swimming Speed

Swimming performance has been reported in the literature in relation to sustained, prolonged, and burst activity levels. Each reflects not only the constraints imposed by time, but also on the biochemical processes which supply the fuel for their application (Brett, 1964; and Beamish, 1978). Sustained swimming performance is applied to those speeds that can be maintained for long periods (greater than 200 min) without resulting in muscular fatigue. Prolonged swimming speed is of shorter duration (20 sec-200min) and ends in fatigue. The highest speeds of which fish are capable are organized under the category of burst swimming. Beamish (1978) suggests that burst speed depending as it does on anaerobic energy sources may be expected to be largely independent of ambient oxygen except that between swimming events the accumulated metabolic debt must be repaid before the next burst of swimming can realize its full potential. These distinctions are very important to interpreting the effect of reduced dissolved oxygen on swimming speeds in laboratory tests. This is because as the fish progress from prolonged to burst speeds, they change towards being less dependent upon ambient oxygen concentrations. The remainder of this section summarizes the studies reviewed that determined levels of oxygen that impede sustained swimming performance.

A. Salmon, Char, and Trout:

Dahlberg et al. (1968) found that for juvenile coho salmon, at temperatures near 20°C and carbon dioxide concentrations near 2 mg/liter, any considerable reduction of the oxygen concentration from about 9 mg/liter, the air-saturation level, resulted in some reduction of the final swimming speed. In evaluating the data of Dahlberg et al. (1968), the State of Oregon (ODEQ, 1995) calculated that reduction to 7 mg/l from saturation (9.1 mg/l) would not likely result in a significant (>5%) reduction in maximum swimming speeds.

Davis et al. (1963) found that the sustained swimming speeds of juvenile coho and chinook salmon were dependent on the dissolved oxygen concentration at any tried concentration below the air-saturation level at temperatures from 10-20°C. Reduction of oxygen concentration from air saturation levels (typically 10-10.8 mg/l) to 7, 6, 5, 4, and 3 mg/l usually resulted in a reduction of the maximum sustained swimming speed of coho salmon by about 5, 8, 13, 20, and 30 percent, respectively. The corresponding estimated percent reduction for chinook salmon were somewhat greater, averaging approximately 10, 14, 20, 27, and 38 percent, respectively.

Brett (1964) found a logarithmic increase in oxygen demand in 14-18 month old sockeye salmon with an increase in swimming speed at test temperatures from 5 to 20°C. The greatest scope for activity occurred at 15°C, whereas above 15°C active metabolism was limited, apparently by oxygen availability. Thus any reduction in saturation could be expected to further reduce maximum activity above this temperature.

Katz et al. (1959) found that in water at 20°C with a mean dissolved oxygen concentration of 3.0 milligrams per liter or greater, juvenile chinook salmon were typically capable of swimming for at least one day against a current of 0.8 feet per second. In all tests at mean oxygen concentrations less than 2.84 milligrams per liter, some fish were unable to swim for the one-day period. In experiments at mean dissolved oxygen concentrations above 2.96 milligrams per liter, all juvenile coho salmon were able to swim against a current of 0.8 foot per second for two days. At oxygen levels between 2.0 and 2.7 milligrams per liter, some of the juvenile coho were able to swim for two days. Katz (1958; as cited in ODEQ, 1995) is reported to have found that salmonids are capable of maintaining low swimming speeds (2-4 cm/sec) for extended periods at dissolved oxygen concentrations below 4 mg/l.

Graham (1949) and Davis et al. (1963) are cited by Reiser and Bjornn (1979) as demonstrating that swimming performance in salmonids is sharply decreased at 6.5-7.0 mg/l at a wide range of temperatures.

Conclusions on Swimming Performance Effects on Juvenile Salmonids: Swimming performance is dependent upon temperature and dissolved oxygen. At optimal temperatures, dissolved oxygen depressions will have less of an effect on the maximum sustained swimming speed than at temperatures either above or below their optimum temperature. In either case, however, any decrease in oxygen level below saturation values will reduce the maximum swimming speed in fish. Given that swimming speed is related to the ability of fish to avoid predation and the ability to hold position or migrate through river currents, decreases in maximum swimming speed should be minimized.

An absolute oxygen concentration above 8-9 mg/l would be the lowest oxygen concentration that should be assumed to fully protect the swimming performance of salmonids. Based on the literature, a drop in oxygen from high saturation concentrations (greater than 10 mg/l) to 7 mg/l would be expected to only result in undetectable to modest (5-10%) changes in maximum swimming speed, but below 7 mg/l the impact to swimming speed may become significant. Based on a projection of the data produced by Davis et al. (1975) using coho and chinook salmon the following effect levels would be expected.

- At 9.0 mg/l maximum sustained swimming speed would be reduced less than 2%.
- At 8 mg/l minor decreases in swimming speed (from 3-7%), should be expected.
- At 7 mg/l swimming performance would likely be reduced by 5-10%.

It is important to recognize that reducing the fitness in fish that have long or difficult migrations, and reducing a fish’s ability to repeatedly escape predation may produce lethal consequences to the fish. It is also important to acknowledge, however, that no clear empirical evidence exists that suggests a moderate (5-10%) reduction in the maximum sustained swimming speeds will translate into reduced fitness in the field.

Taken together the data reviewed for this paper suggests that the swimming fitness of salmonids is maximized when oxygen levels are maintained above 8.0-9.0 mg/l (most appropriately expressed as a daily minimum since the effect is essentially instantaneous). If a longer term average exposure metric (7-30 days or more) is used to express such a criteria, it may be prudent to also include a single daily minimum value that is also in the range of what would provide good support (7 mg/l).

B. Non-Salmonids:

Katz et al. (1959) found that largemouth bass during September were able to swim against a current of 0.8 feet per second for one day at 25°C in water having a mean dissolved oxygen content of 2.0 milligrams per liter. In early December, at temperatures from 15.5 to 17° C, the bass could swim against the 0.8 foot per second current when the water was nearly saturated with dissolved oxygen but they were unable to do so by the time the oxygen was reduced to 5.0 milligrams per liter.

Dahlberg et al. (1968) found that the final swimming speed of juvenile largemouth bass, was reduced markedly at oxygen concentrations below 5 or 6 mg/liter in tests at 25°C. At levels above 6 mg/liter, the final swimming speed was virtually independent of the oxygen concentration.

Conclusions on Swimming Performance Effects on Juvenile Non-Salmonids: Very scant information was reviewed on the effect on the swimming performance of non-salmonids, and no study examined any non-salmonid species native to Washington. The two studies reviewed are in conflict to some degree with one another; although; in general they share the opinion that lowering ambient concentrations from saturation to 5-6 mg/l can be detrimental to swimming speed of largemouth bass. **Until further information suggesting otherwise is presented, it should be assumed that oxygen concentrations below 6-6.5 mg/l are detrimental to the swimming performance of non-salmonids (most appropriately expressed as a daily minimum since the effect is essentially instantaneous)**. If a longer term average expsoure metric (7-30 days or more) is used to express such a criteria, it may be prudent to also include a single daily minimum value that is also in the range of what would likely provide good support (5.5 mg/l).

9. Macroinvertebrates Species

Information on the oxygen requirements of non-fish species is generally more limited than that for fish. However, while the information on amphibians is too scarce to come to any conclusions, information on the requirements of macroinvertebrates is both informative and sufficient to warrant making water quality recommendations.

Short-term (24-96 hours) Lethality:

Sprague (1963) determined the 24hr LC50 values for four crustaceans at 20°C. They were 0.03 mg/l for *Asellus intermidius,* 0.07 mg/l for *Hyalella azteca* 2.2 mg/l for *Gammarus pseudolimnaeus*, and 4.3 mg/l for *Gammarus fasciatus* (*G. pseudolimnaeus* is not known to be present in Washington).

Nebecker (1972) determined the dissolved oxygen requirements for survival and adult emergence for 9 species of aquatic insects. The mayflies *Ephemerella subvaria* and *Baetisca laurentina* had the highest and third highest 96-hr LC50 at 3.9 and 3.5 mg/l respectively at 18°C, with the stone fly *Acroneuria lycorias* having the second highest LC50 at 3.6 mg/l.

USEPA (1973) examined the effect of low dissolved oxygen concentrations on twenty species of aquatic insects (Diptera, Ephemeroptera, Plecoptera, and Tricoptera) and a scud (Amphipoda). They found the mayfly, *Ephemerella doddsi* (now *Drunella*), was the most sensitive with a 96-hour TLm of 5.2 mg/l. The five tested plecoptera had 96-hr LC50 values ranging from 1.6-3.9 mg/l, the four emphemeroptera ranged from 1.8-5.2 mg/l, the 6 trichoptera ranged from 1.7-<4.0 mg/l, the diptera was 3.2 mg/l, and the amphipoda was <3.0 mg/l.

Daphnia magna proved very resistant to low oxygen with Homer and Waller (1983) finding only a slight reduction in survival (from 90 to 85%) at 1.8 mg/l. They noted that while growth was affected at all lowerings of oxygen below 7.6 mg/l it was only significant below 3.7 mg/l.

Jacob, Walther, and Klenke (1984) provided lethal oxygen concentrations and their temperature dependence for 22 species of aquatic insects. The LC50 values for the ephemeroptera *Baetis alpinus* and *Epeorus sylvicola* were 82.5% and 80.2% of saturation at 15°C (approximately 8.1-8.4 mg/l; this estimate was made assuming the work was conducted at 500 feet altitude); with the LC50 for *Eperorus sylvicola* increasing to 96.5% saturation at 20°C (approximately 8.7 mg/l). The trichoptera *Silo pallipes* had an LC50 of 79.3% saturation at 15°C (Note that *E. sylvicola* and *S. pallipe*s are not known to be present in Washington although the genus *Epeonus* is common).

Eriksen (1986; as cited in ODEQ, 1995) found the damselfly *Lestes disjunctus* to have a critical oxygen level of 2.5-5.5 mg/l depending upon temperature.

Summary of Short-term Lethality Testing: Three groupings of sensitivity seem to best describe the species tested. The highest is the "high altitude" ephemeroptera at 8.1-8.4 mg/l, the next highest are the other "headwater" mayflies and damselflies at 5.2-5.5 mg/l, and finally the remainder of the sensitive species at 3.5-4.3 mg/l. Since these tests measured the point of 50% mortality the results should be adjusted upwards to try and eliminate the lethal effect. Adding 1.3 mg/l to the LC50 should transform results to non-lethal concentrations (based on Herrman et al., 1962). The result of this exercise is the production of three ambient water concentrations expected to avoid lethality:

- **High altitude streams: 9.4-9.7 mg/l;**
- **Mid-elevation streams: 6.5-6.8 mg/l;**
- **Other waters: 4.8-5.6 mg/l**

In the one 24-hour test, median lethality was found in a crustacean at 4.3 mg/l. Finding this level of sensitivity in the 24-hour test suggests that it would not be unreasonable to apply the results from all the short-term tests as single daily average oxygen concentrations, although, they are more appropriately viewed as 4-day averages.

Long-term (30-111days) Lethality:

Nebecker (1972) determined the dissolved oxygen requirements for survival and adult emergence for 9 species of aquatic insects, including mayflies, stoneflies, caddisflies, and midges. All species tested were less tolerant of low oxygen concentrations for 30 days than for 96 hours. In the 30-day LC50 tests at 18.5°C, of four Washington species tested, three had LC50 values between 4.4 and 5.0 mg/l with the mayfly *Baetisca laurentina* being highest. Nebeker (1972) suggested that based on his work, the 96-hour test commonly used does not reflect the true effect of oxygen concentrations on aquatic insects.

Nebeker's conclusion was also shared by USEPA (1973) where it was found that while 50% of *Acroneuria pacifica* (now *Hesperoperla*) survived an oxygen concentration of 1.6 mg/l for 4 days, the minimal oxygen level for 50% survival at 111 days was 5.8 mg/l.

USEPA (1973) reported long-term dissolved oxygen bioassay data from the University of Montana. For the longer-term exposures, the LC50 values generally increased such that three tested plecoptera had 40-50% survival from 4.4-5.8 mg/l, one tested emphemeroptera had 30% survival at 4.6 mg/l, two trichoptera had 30-50% survival at 3.2-4.8 mg/l, and an amphipoda had 50% survival at 2.8 mg/l. Similarly, USEPA (1973) reported the results from long-term testing done at the University of Utah. In these tests, plecoptera survivals were very poor (10-30%) at concentrations below 3.4 mg/l, emphemeroptera survivals ranged from very poor (10%) for *Baetis bicaudatus* at 3.8 mg/l to moderate (50%) at 3.3-3.8 mg/l for three other tested species. Tricoptera survivals ranged from good (80%) for *Brachycentrus occidentalis* at 2.6 mg/l to fair (40-60%) for *Parapsyche elsis* at 4.8 and 5.2 mg/l respectively. Diptera survivals ranged from good (70-90%) at 1.7-2.4 mg/l to fair (40%) at 3.4 mg/l; and survival of two odonata species were moderate (50%) at 1.4-3.0 mg/l.

Summary of Long-Term Lethality Testing: As noted by some of the authors, preventing lethality with long-term exposure requires that oxygen levels be maintained at higher levels than that needed to prevent short-term lethality. The overall differences in the upper ranges produced, however, are very minimal.

Striking a parallel between the recommendations made for short-term tests (discussed previously) is not completely possible. This is because long-term testing was not conducted for the most sensitive group of headwater species used in the short-term tests. However, two groupings can be generally identified in association with the general habitat descriptions of "mid-elevation streams" and "other waters".

The sensitive "mid-elevation" species seem to be best described by having median lethality at oxygen concentrations of 5.2-5.8 mg/l, and the "other" more sensitive grouping of species seems best described by the concentrations of 4.4-4.8 mg/l. Adding 1.3 mg/l to the LC50 concentrations should transform results into an estimate of a non-lethal level. The result of this exercise is the production of two ambient water concentrations expected to avoid lethality:

- **Mid-elevation streams: 6.5-7.1 mg/l;**
- **Other waters: 5.7-6.1 mg/l**

Given that the long-term tests cited above were of durations between 30-111 days, it would be reasonable to apply these concentrations as monthly average values or possibly as as seasonal (90-day) average values.

Summary of Lethal Effects to MacroInvertebrates: Table 6 summarizes the research results discussed above on the concentrations of oxygen that caused lethality in macroinvertebrate species. Lethality is affected by temperature as well as oxygen concentration such that the point of 50% mortality (LC50) will typically be higher at higher test temperatures. Much of the research reported above tested oxygen effects in water with a temperature between 15-20°C. This range fits well within the state's allowable temperature criteria limits and makes the research results more pertinent. The research consistently indicated that a wide variety of aquatic macroinvertebrates have lethal oxygen concentrations well above those of fish species (discussed earlier).

To prevent direct lethality, dissolved oxygen levels may need to remain above the values provided in Table 4 below. Since the upper ends of the range were established using individual species, rather than representing different test results using the same species (thus is not based on variable test results for the same species), care should be exercised in selecting values from the lower portions of these ranges. The one exception is for the upper end of the range for high altitude streams, which was set using two species that are not resident to the state but which were included to represent other potentially sensitive but untested resident headwater species. The lower end of the range was set using results from a species resident to Washington.

Table 4. Oxygen concentrations that will prevent lethality in sensitive macroinvertebrates. General habitat associations are provided to assist with interpretation and application.

Technical Recommendations for Preventing Lethality to Macroinvertebrates		
Habitat Type	**24 hour average** (mg/l)	**30-day or seasonal average** (mg/l)
High altitude streams	9.4-9.7 (median 9.55)	N/A
Mid-elevation streams	6.5-6.8 (median 6.65)	6.5-7.1 (median 6.8)
Other waters	4.8-5.6 (median 5.2)	5.7-6.1 (median 5.9)

The values in Table 4 above can be safely translated from constant laboratory mean concentrations to associated daily minimum values by subtracting 0.5-1.0 mg/l – which is a conservative estimate of the typical fluctuations in those laboratory tests. Table 5 below shows the results of making such adjustments to the median values shown in Table 4.

Table 5. Daily minimum oxygen concentrations that will prevent lethality in sensitive macroinvertebrates. Based upon making a 0.5-1.0 mg/l downward adjustment from the median estimates of constant laboratory test concentrations from Table 4.

Technical Recommendations for Daily Minimum Concentrations (Based on Table 5)		
Habitat Type	**1-Day Minimum** (mg/l)	**30-90-Day Average Minimum** (mg/l)
High altitude streams	8.55-9.05 (median 8.8)	N/A
Mid-elevation streams	5.65-6.05 (median 5.9)	5.80-6.30 (median 6.05)
Other waters	4.20-4.70 (median 4.45)	4.90-5.40 (median 5.15)

Table 6. Summary of the results of testing to determine concentrations of dissolved oxygen that are lethal to macroinvertebrate species.

Summary Table of Results from Macroinvertebrate Lethality Testing			
Mean Dissolved Oxygen (mg/l)	**Type of Organism**	**Test Duration**	**Effect Level**
Short-term testing			
8.1, 8.4, 8.7 (estimated from saturation value)	3 ephemeroptera	96 hr	LC50
2.5-5.5 (at multiple temperatures)	1 damselfly	96 hr	LC50
5.2	1 mayfly	96-hr	LC50
1.8-5.2	4 emphemeroptera	96 hr	LC50
0.3-4.3	4 crustacean	24 hr	LC50
3.5,3.6, 3.9	2 mayfly, 1 stonefly	96-hr	LC50
1.6-3.9	5 plecoptera	96 hr	LC50
1.7-<4.0	6 trichoptera	96 hr	LC50
3.2	1 diptera	96 hr	LC50
<3.0 mg/l	1 amphipoda	96 hr	LC50
Long-term testing			
5.8	Hesperoperla	111-d	LC50
4.4-5.8	3 plecoptera	≥30-d	LC50-60
4.8-5.2	2 tricoptera	≥30-d	LC40-60
4.4-5.0	4 species	30-d	LC50
3.2-4.8	2 trichoptera	≥30-d	LC50-70
3.2-4.8	2 trichoptera	≥30-d	LC50-70
4.6	1 emphemeroptera	≥30-d	LC70
3.3-3.8	4 emphemeroptera	≥30-d	LC50-90
3.4	plecoptera	≥30-d	LC70-90
3.4	1diptera	≥30-d	LC60
1.4-3.0	2 odonata	≥30-d	LC50
2.8	1 amphipoda	≥30-d	LC50
2.6	1 tricoptera	≥30-d	LC20
1.7-2.4	diptera	≥30-d	LC10-30

Non-Lethal Effects:

When Nebeker (1972) tested emergence at 18.5°C, he found significant depressions in the rate of emergence (20-40%) occurring when dissolved oxygen levels were lowered from 9.0 to 7.6 mg/l for the mayflies *Ephemera simulans* and *Leptophlebia nebulosa*, or when lowered from 7.0 to 6.0 mg/l for *Baetisca laurentina.*

Nebeker et al. (1996) exposed embryos, larval stages (instars I-V), pupal stages, and pharate adults of the caddisfly *Clistoronia magnifica* to a range of dissolved oxygen concentrations (0.9-8.3 mg/l) for 4-88 days in the laboratory. At concentrations below 4.6 mg/l, egg hatch, larval development, molting success, time of molting, pupation, and adult emergence were delayed.

Kolar and Rahel (1993) studied the behavior of benthic invertebrates in hypoxic environments and found that in the absence of predators the insects would move above the benthic refuge to areas with higher oxygen, but with fish present they would reduce their activity and remain until hypoxia reached critical levels where they would then move up and be preyed upon. A reduction from 4.5 mg/L to 2.5 mg/l resulted in the mayfly, amphipod, and caddisfly beginning to move up from the benthic cover in the absence of fish, but such movements did not typically begin until about 1.7 mg/l in the presence of fish.

Homer and Waller (1983) noted that while growth of *Daphnia magna* was affected at all lowerings of oxygen below 7.6 mg/l it was only significant below 3.7 mg/l.

Costa (1967; as cited in Davis, 1975) found *Gammarus pulex* exhibits a slowly developing avoidance reaction to oxygen concentrations up to 7 mg/l.

Moshiri et al. (1970: as cited by Davis 1975) found that at 20°C oxygen utilization was elevated below 5.7 mg/l and ventilation depressed below 3.6 mg/l in the crayfish *Pacifastacus leniusculus*.

Gaufin and Gaufin (1961; as cited in ODEQ, 1995) were reported to have found ventilation movements (considered a sign of increasing oxygen stress) in two stone fly species *Acroneuria pacifica* and *Pteronarcys californica* starting at 8.6 mg/l (60-50°F), 7.6 mg/l (50-55°F), and 4.5 mg/l (46°F).

Summary of Non-Lethal Effects to MacroInvertebrates: Oxygen stress as measured through increased ventilation movements may begin in some species at oxygen concentrations as high as 8.6 mg/l, emergence of adults impeded at concentrations of 7.6 mg/l, avoidance movements can begin below 7 mg/l , and below 4.6 mg/l the progression of critical life-stages is slowed. Together these factors suggest that oxygen concentrations below 8-8.5 mg/l may interfere with sensitive macroinvertebrate species.

The most serious of the non-lethal effects described above is the interference with adult emergence. Reducing average oxygen levels to 7.6 mg/l in two mayfly species and to 6 mg/l in one other mayfly species depressed emergence rates. The increased ventilation movements at oxygen levels from 7.6-8.0 mg/l seems to support the hypothesis that the stressful emergence stage creates a metabolic oxygen demand that cannot be fully satisfied in some species at concentrations below 8.0 mg/l

Dissolved oxygen concentrations above 8-8.5 mg/l appear necessary to avoid creating oxygen stress and to avoid interfering with the emergence of sensitive mayfly species. These species would generally be found in mid to upper reaches of watersheds. The one test using a less sensitive mayfly species may be used as a reasonable estimate for the emergence requirements in the lower reaches of watersheds. That test suggested that oxygen should be maintained above 6.5 mg/l. Based on this assumption, mean ambient water concentrations expected to support adult emergence and minimize respiratory stress are:

- **Mid-elevation streams: 8.0-8.5 mg/l (midpoint 8.25)**
- **Other waters: 6.5-7.0 mg/l (midpoint 6.75)**

Mayflies often produce multiple broods per year, development is faster in the warmer periods of the year, emergence often occurs throughout broad seasons, and the sensitive stage of emergence generally passes quite rapidly (Edmunds and Waltz, 1996; Jensen, 1966; and Hafele and Hinton, 1996). Daily minimum oxygen levels are likely to be an important influence on the emergence success of individual broods, yet isolated or infrequent daily minimum values are unlikely to have any discernable effect on the overall population. It is unknown whether or not insects exert some behavioral control over the time of emergence in response to less than optimal environmental conditions thus further mitigating to some extent the potential effects of infrequent sub-optimal oxygen conditions. However, it is also unknown whether or not the average oxygen conditions occurring in the days just prior to emergence are just as important as the concentration at the time of emergence.

It is generally recommended that the above estimates be viewed as daily average concentrations occurring during the emergence period, as that best reflects the data reported in the research. Since fluctuations of 0.5-1.0 mgl/l were common in such tests, adjusting the mean laboratory concentrations downward by 0.5-1.0 mg/l would provide a safe basis for estimating associated daily minimum values. Taking this approach, it is recommended that 1-7 day average daily minimum concentrations not fall below the values presented in table 7 below:

Table 7. Daily minimum oxygen concentrations that will prevent detrimental non-lethal effects in sensitive macroinvertebrates. Based upon making a 0.5-1.0 mg/l downward adjustment from the median estimates of constant laboratory test concentrations.

Habitat Type	**1-7-Day Average Daily Minimums** (mg/l)
Mid-elevation streams	7.25-7.75 (median 7.5)
Other waters	5.75-6.25 (median 6.0)

Conclusion on Oxygen Concentrations Protective of Macroinvertebrates:

As a category, macroinvertebrates include the most sensitive as well as the most tolerant aquatic species to depressions in dissolved oxygen. This makes establishing simple standards for their protection challenging. Full protection of aquatic macroinvertebrates is most likely to occur in waters with daily minimum oxygen concentrations above 8.5-9.0 mg/l. Applying this standard statewide, however, may result in a many of the state's waters being judged against standards they are not physically capable of complying with to protect species that would not naturally be found in those types of waters. For this reason, technical recommendations are made according to broad habitat types. Table 8 summarizes the conclusions noted above for both lethal and sublethal effects to sensitive macroinvertebrate species.

Table 8. Summary table of oxygen concentrations that will fully protect sensitive macroinvertebrates. General habitat associations are provided to assist with interpretation and application. Oxygen concentrations shown in mg/l.

Technical Recommendations for Protecting Macroinvertebrates						
Habitat Type	**Prevent Lethality – Short-Term Exposure**		**Prevent Lethality – Long-Term Exposure**		**Adult emergence – and other Non-Lethal Effects**	
	1-Day Minimum	**24 hr Average.**	**30-90-Day Min. (Ave)**	**30-90 day Average**	**1- to 7-Day Minimum**	**24 hr Average**
High altitude streams	8.55-9.05 (med. 8.8)	9.40-9.70 (med. 9.55)	N/A	N/A	N/A	N/A
Mid-elevation streams	5.65-6.05 (med.5.9)	6.50-6.80 (med. 6.65)	5.80-6.30 (med. 6.05)	6.50-7.10 (med. 6.8)	7.25-7.75 (med. 7.50)	8-8.5 (med. 8.25)
Other waters	4.40-4.70 (med. 4.45)	4.80-5.60 (med. 5.20)	4.90-5.40 (med. 5.15)	5.70-6.10 (med. 5.90)	5.75-6.25 (med. 6.00)	6.5-7.0 (med. 6.75)

Technical Recommendations: To be confident that all stream macroinvertebrates will be fully protected, headwater streams would need to be protected with a 1-day minimum of 8.5-9.0 mg/l, and mid-elevation waters (e.g., salmonid spawning streams) with 1-day minimums of 7.5-8.0 mg/l . Insects associated with non salmonid waters, or waters used only for salmonid rearing – which would be comprised of lower elevation mainstem waters – would need to be protected with a 1-day minimum of 5.5-6.0 mg/l.

Since mountainous headwater streams characteristically do not have problems with human-caused oxygen depletion, focusing only on the requirements of mid-elevation streams may also be reasonably (yet unquantifiable) protective. To have a reasonable probability of being protective, however, such an alternative should be set at a 1-day minimum of 7.5-8.0 mg/l.

Policy Decisions: Several important policy decisions must be made when translating the technical findings into water quality criteria.

1. **Protection of the most Sensitive Species**. An important policy decision is whether to select the upper end of the most sensitive species tested, or use a value that

represents the lethality of a group of sensitive species in general. Since the lethality patterns of several species tended to produce the very small concentration ranges shown, only rounding the upper end estimates to whole or half numbers may be most advisable to ensure full protection. This issue is more pronounced, however, when determining whether to set a criteria based upon the data for the headwater species *Baetis alpinus*. The concentration is an estimate from a single study, yet it produces an LC50 value well above (2..3 mg/l higher) the next most sensitive species (which is of the same genus).

2. **Establishing the Criteria Duration**. The estimates are very similar for a 24-hour average and a 30-day average concentration, so having both metrics may be unnecessary if a single day exposure is chosen as a metric. Similarly, the selection of a daily minimum metric to represent an average-based research value adds a precautionary element that would help offset selecting a number from the lower end of an estimated range.

3. **Setting multiple criteria based on general habitat descriptions**. It is important to point out that the distinctions made above for “high altitude”, “mid-elevation”, and “other waters” are generalized relationships. They reflect only the general patterns of where these species would be commonly expected to be found (pers. comm. Plotnikoff, 2000). It is being suggested here in an attempt to place the results in a habitat context and provide a means for policy makers to potentially set different levels of criteria across the landscape – to avoid applying criteria necessary to protect the most sensitive headwater species statewide. An important policy decision is whether to apply these multiple levels of protection, or to assign protective criteria more uniformly across the state.

4. **Should emergence be protected fully at all times.** An important policy decision is whether to provide full protection at every hour of every day for adult emergence. It is unknown if species will be able to control the time of day for emergence such that even during the worst of days emergence will be sufficiently protected.

10. Synergistic Effects

Downing (1954) studying the effects of cyanide, and Hicks and DeWitt (1971) examining the effect of kraft mill effluent, all found that survival times were directly linked to oxygen levels. As the oxygen levels declined from saturation there was a steady decline in the median survival times for the test fish (coho salmon and rainbow trout).

Birtwell et al. (1983) examined the impact of discharging secondary effluent to a marine intertidal area in British Columbia. They determined that low levels of dissolved oxygen were a contributing factor in the mortality of caged juvenile chinook salmon up to 4.4 km away from the outfall. Dissolved oxygen concentration ranges that existed at sites when 50% mortality of insitu bioassays occurred in less than 26 hours ranged from a high of 3.4-

7.4 (5.4) mg/l and a low of 0.1-8.1 (4.2) mg/l. Mortality of greater than 50% occurred in less than 96 hours in tests with mean oxygen levels of 7.1 (3.0-10) and 8.0 (6.7-10.4).

Numerous authors have tested the effect of lowering oxygen on increasing the toxicity or reducing the resistance time to ammonia. Downing and Merkens (1955) found that survival times of rainbow trout in concentrations of un-ionized ammonia in the range of 0.86 – 1.96 mg/l of nitrogen increased as the concentration of dissolved oxygen was raised from 1.5 to 8.5 mg/l. They found the effect of oxygen in increasing survival time was greater in the lower concentrations of un-ionized ammonia.

Thurston, Phillips, Russo, and Hinkins (1981) conducted fifteen 96-hr flow-through tests over the dissolved oxygen range 2.6 to 8.6 mg/L. They concluded that any reduction in dissolved oxygen below the highest tested concentration (8.6 mg/l), reduced the tolerance of rainbow trout fingerlings to acutely toxic concentrations of ammonia; the estimated tolerance at 5.0 mg/l dissolved oxygen was 30% less than that at 8.5 mg/l dissolved oxygen.

Jensen (1981) found a synergistic effect of combining high ammonia levels and low dissolved oxygen concentrations. Alevin mortality rates were less than 1.9% at 10 μg/l of NH3 and 3.4 mg/l oxygen, and also at 191 μg/l NH3 and 10.9 mg/l oxygen; however, at 191 μg/l NH3 and 3.4 mg/l oxygen the mortality rate increased dramatically to 38.1%. At 100 μg/l NH3 and 3.0 mg/l oxygen, mortality rates further increased to 54.7%. The combination of high ammonia and low oxygen also resulted in delayed time to hatch and reduced growth rates.

Larmoyeux and Piper (1973) tested the effect of water reuse in hatcheries and the influence of ammonia and dissolved oxygen on the health of rainbow trout. The authors found that fish length was significantly reduced when oxygen was less than 5.0 mg/l and ammonia greater than 0.5 mg/l. In addition to reduced growth rates, the authors noted damage to the gill tissue and occasional pathology in the kidney and liver tissue at oxygen levels below 5.0 mg/l and ammonia greater than 0.5 mg/l. Waistbrot et al. (1990; as cited in ODEQ, 1995) found increased toxicity of ammonia to juvenile tiger shrimp (*Penaeus semisulcatus*) at dissolved oxygen levels below 3.7 mg/l (55% saturation). At 27% saturation, the ammonia toxicity (96-hour LC50) was doubled. In addition, the time of exposure to ammonia required for a given lethal effect decreased with reduced oxygen concentrations.

Conclusion on Synergistic Effects with Dissolved Oxygen: It is clear that maintaining high (>8.5 mg/l) oxygen levels provides added protection from the effects of several very common pollutants, and that low oxygen in combination with wastewater can significantly increase detrimental effects.

In establishing numeric criteria for various pollutants, neither the state nor the USEPA incorporated considerations of how the effects of these pollutants may be aggravated by generally poor water quality (warm and low in oxygen). It would have been more appropriate for the toxic substance criteria to have been established with estimates on the safety within a typical range of temperature and oxygen levels, rather than generally assuming that each would be optimized. It is difficult to incorporate these concerns in reverse, such that we ask the question what is a likely concentration of a toxic pollutant (e.g., ammonia or cyanide) when setting oxygen or temperature standards.

Policy Issue:

While information is not sufficient to suggest dissolved oxygen criteria on the basis of the likely concentrations of the myriad of other pollutants in the state's waters, we can be reasonably certain that the risks of unintended consequences to the biota increase as either temperature increases or dissolved oxygen decreases. In setting oxygen standards, the state needs to be careful to avoid establishing oxygen limits too close to critical threshold levels since most of the state's major waterways receive substantial discharges of toxic pollutants.

11. General Discussion on Fluctuating Versus Constant Oxygen Regimes

Most researchers examining the effects of dissolved oxygen have attempted to hold the concentration of oxygen in their tests at constant concentrations. In natural waters, however, oxygen concentrations vary significantly during and between days. It is necessary to understand how the results of these constant exposure tests pertain to setting criteria for natural waterways. Fortunately, enough researchers have made comparisons between constant and fluctuating oxygen environments to help clarify this issue.

Brett (1979) used the work of Stewart et al. (1967), Whitworth (1968), and Fisher (1963) to conclude that exposure to subcritical levels of oxygen for only a portion of the day (e.g., 8-12 hours) is sufficient to depress the growth rate to that comparable with the constant low oxygen level. He further concluded that concentrations of oxygen significantly above air-saturation do not confer any substantial benefit compensating for the periods of low concentration.

Fisher (1963) conducted two sets of tests to compare fluctuating and constant dissolved oxygen levels on the growth of under-yearling coho salmon. Fisher found in the first set of tests that the dry weight gains were much less than the gains that could have been expected at constant oxygen concentrations near the arithmetic or geometric means of the fluctuating concentrations tested. In the second set of tests, however, the dry weight gains were either equal or slightly less than what would have been expected had the fish been exposed to constant oxygen concentrations equal to the respective geometric means of the fluctuating concentrations. The growth rates in the fluctuating tests were approximated that which would be expected at concentrations between the 5th and 35th percentile of the fluctuating oxygen range; rather than the 50th (the mean).

Stewart (1962) examined the growth rates of bass at 26°C subjected alternatively to low and higher oxygen levels for either equal or unequal portions of each 24-hr day (using a square wave versus sinusoidal pattern). Both when fluctuations were relatively small (as low as 2-4 mg/l) and when they were very large (as high as 15 mg/l) the level of growth observed was typically far less than what would be expected in constant exposure tests at oxygen levels equal to the means of the fluctuating tests. In the work of Stewart (1962), concentrations of oxygen greater than saturation appeared to be unfavorable to growth; particularly at the higher concentrations tested. In the test at the highest fluctuation (3.8-24.1 mg/l cycle), growth rates were less than what would have been expected in a constant test conducted at the lowest concentration. In all others, however, the growth rates appear to congregate between approximately the 10th and 25th percentile area of the fluctuating oxygen range. Doudoroff and Warren (1962) note from the work of Stewart (1962) that bass exposed to concentrations near 2.0 mg/l for less than one-third of each 24-hour day and to concentrations near 8.1 mg/l for the remainder of the day showed a dry weight gain that would have also occurred at a constant oxygen concentration of about 3.0 mg/l. They further noted that coho salmon exposed alternately to concentrations of 3 and 9.5 mg/l or 3 and 18 mg/l for equal periods each day showed weight gains in 18 days approximately equal to the estimated weight gains that would have occurred at constant oxygen concentrations near 3.5 mg/l. The authors opined that it was evident that, even in the absence of lethal concentrations, mean oxygen levels in eutrophic waters with wide diurnal fluctuations of dissolved oxygen content are virtually meaningless and can be misleading; and growth rates of fish subjected to fluctuating concentrations may be largely dependent on the dissolved oxygen minima occurring at night or early in the morning. Stewart, Shumway, and Doudoroff (1967) concluded that exceedingly high concentrations far above air saturation levels occurring during the daylight hours not only do not compensate for the occurrence of low concentrations at night and early in the morning, but also may do additional harm. The authors cite Tarzwell and Gaufin (1953) in support for their premise that average dissolved oxygen concentrations are by themselves of little value as indices of the suitability of dissolved oxygen conditions in aquatic environments. They argue that minimum and maximum levels must be considered in evaluating fish habitat.

Whitworth (1968) subjected yearling brook trout to diel fluctuations from 10.6-10.7 mg/l to 5.3, 3.6, 3.5, and 2.0 mg/l at 18°C. He found that each level of fluctuation significantly depressed growth of yearling brook trout in comparison to a constant control held at average constant levels of 10.6-11 mg/l, and that most fish were unable to tolerate fluctuations to 2.0 mg/l. In fact, all of the fish experiencing the fluctuations lost weight over the 60-70 day test period. This may be at least partly attributed, however, to the fact that Whitworth held the fish at a temperature above optimal for growth (Hicks, 2002) and fed them less than satiation rations.

Bouck and Ball (1965) found that a diurnal oxygen pulse of 3 mg/l for 8 hours per day for 9 days was sufficient to produced a significant stress pattern in bluegills and largemouth bass, though it did not have a measurable effect on yellow bullheads.

Bejda, Phelan, and Studholme (1992) found that growth rates (length and weight) of young-of-the-year winter flounder were significantly reduced at either constant 2.2 mg/l or at diurnal fluctuations from 2.5-6.4 mg/l.

Conclusion on Fluctuating Oxygen Effects and Implications for Establishing Water Quality Criteria:

Numerous authors have found that the growth rates of fish in highly fluctuating oxygen environments are less than that which would occur at constant concentrations equal to the mean of those fluctuating test conditions (Brett, 1979; Stewart et al., 1967; Whitworth, 1968; Fisher 1963; Stewart, 1962; and Doudoroff and Warren, 1962). Other authors have found that the stress caused by low daily minimum oxygen levels may be the cause for reduced growth in fluctuating tests (Bejda, Phelan, and Studholme, 1992; and Bouck and Ball, 1965). Typically, the growth rates in fluctuating tests have been found to be equivalent to those that would have occured at constant concentrations equal to the 5th - 35th percentiles of the fluctuating range, rather than the 50th (the mean of the fluctuating range).

This characteristic was also noted by USEPA (1986) when making national criteria recommendations for dissolved oxygen. As stated by USEPA, "In considering daily or longer-term cyclic exposures to low dissolved oxygen concentrations, the minimum values may be more important than the mean levels." And as noted by Stewart et al. (1967), "average dissolved oxygen concentrations are by themselves of little value as indices of the suitability of dissolved oxygen conditions in aquatic environments" - arguing that minimum and maximum levels must be considered in evaluating fish habitat.

If criteria are established using the reported mean oxygen concentrations from research that held oxygen levels relatively constant, then the natural fluctuations that occur in the field will cause less than expected protection. If the means are applied as daily minima, however, then the criteria would be slightly more protective than intended. USEPA (1986) recommends that "If only a minimum or a mean can be given as a general criterion, the minimum must be chosen because averages are too independent of the extremes."

Another option, however, is to set the criteria as daily minimums in recognition of the variability that occurred in the constant exposure tests. While these tests tried to hold oxygen concentrations constant, fluctuations of +/- 0.5-1.0 mg/l were characteristic. Subtracting 0.5-1.0 mg/l from the mean of the constant test results (reported as mean concentrations) would be a reasonable way to set a daily minimum value that will provide the level of protection represented by the test mean. For example, if a constant exposure test mean of 9.0 mg/l was found to produce near optimal growth, lowering the test mean by 0.5-1.0 mg/l (producing the range of 8.0-8.5 mg/l) would create an estimate of an average daily minimum concentration that would also have near optimal growth. This approach is the one used in the analysis of this paper to set technical recommendations. It is believed to be a sound way to minimize any excess stringency without jeopardizing the intended level of protection.

12. Establishing a Duration of Exposure

Once the metric (average as a daily minimum) is chosen, there is still a need to determine the averaging period. This should be done in consideration of the test durations and conclusions themselves. Where the testing was based on a long-term exposure, the criteria can be effectively applied as a long term average as well. Where the testing showed detrimental effects (such as acute lethality) in a shorter period of time, then the criteria duration should take that into account. If a long term averaging period is used, then it becomes advisable to also set a short-term concentration criteria (i.e., establishing two metrics) to guard against short-term lethality and periods of significant stress that would negate the benefits of an otherwise health longer-term average condition.

In balance it seems most favorable to establish oxygen criteria that combine a criterion for a healthy long-term (30-90 days) average condition with an additional criterion that will protect against harmful short-term (1-7 day) effects. However, it would be just as effective for protecting the resource to establish a short-term averaging period (1-day) that is set using effect-concentrations from longer term exposure studies.

13. Summary of Fully Protective Oxygen Levels

A consistent theme among authors whose research was examined for this paper is the belief that any depression of oxygen from saturation will produce some reduction in the performance of fish, whether salmonids or non-salmonids. That said, however, most authors go on to note that statistically significant changes to growth, swimming speed, etc. do not occur until oxygen levels are depressed to levels that are sometimes well below the saturation value. While it may be “safe” to set oxygen criteria at levels where adverse effects are not discernable in the research, doing so does result in increased risks to the health of fish and other aquatic life. Although this paper recommends oxygen concentrations that if applied as intended will not adversely effect Washington’s indigenous aquatic life, the direct dependence of biological processes on available oxygen concentrations suggests caution should be exercised when allowing even moderate reductions in of oxygen.

Tables 9 and 10, below, summarizes the technical conclusions made in the body of this paper for levels of oxygen that fully protect aquatic communities. In this context, full protection implies that impacts to critical life-stages and process will not reach levels that have a reasonable possibility of impairing the potential health of individuals or populations.

Table 7. A summary of the technical recommendations for oxygen concentrations for individual life-stages and activities of salmonid species expected to confidently provide for full protection (approximately less than 1% lethality, 5% reduction in growth, and 7% reduction in swimming speed). Other possibly acceptable alternatives for criteria are contained in the text of the analysis document.

Life-Stage or Activity	Oxygen Concentration (mg/l)	Intended Application Conditions
Incubation through Emergence	≥**9.0-11.5** (30 to *90-DADMin*) **and** No measurable change when waters are above 11°C (weekly average) during incubation.	• Applies throughout the period from spawning through emergence. • Assumes 1-3 mg/l will be lost between the water column and the incubating eggs.
Growth of Juvenile Fish	≥ **8.0-8.5** (*30-DADMin*) **and** ≥**5.0-6.0** (*1-DMin*)	• In areas and at times where incubation is not occurring.
Swimming Performance	≥ **8.0-9.0** (*1-DMin*)	• Year-round in all salmonid waters.
Avoidance	≥ **5.0-6.0** (*1-DMin*)	• Year-round in all salmonid waters.
Acute Lethality	≥ **3.9** (*1-DMin*) ≥**4.6** (*7 to 30-DADMin*)	• Year-round in all salmonid waters.
Macro-invertebrates (*stream insects*)	≥ **8.5-9.0** (*1-DMin or1-DAve*)	➢ Mountainous Headwater Streams
	≥ **7.5-8.0** (*1-DMin or1-DAve*)	➢ Mid-Elevation Spawning Streams ➢
	≥ **5.5-6.0** (*1-DMin or1-DAve*)	➢ Low-Elevation Streams, Lakes, and Non-Salmonid Water
Synergistic Effect Protection	≥ **8.5** (***1-DAve***)	• Year-round in all salmonid waters to minimize synergistic effect with toxic substances.

Table 8. A summary of the technical recommendations for oxygen concentrations for individual life-stages and activities of non-salmonid species expected to confidently provide for full protection. Other possibly acceptable alternatives for criteria are contained in the text of the analysis document.

Life-Stage or Activity	Oxygen Concentration (mg/l)	Intended Application Conditions
Incubation through Emergence	≥ **6.5-7.0** (30 to 60-*DADMin*) **and** ≥ **5.5-6.0** (*1-DMin*)	- Throughout the period of incubation.
Growth of Juvenile Fish	≥ **6.0-7.5** (*30-DADMin*) **and** ≥ **5.0-6.0** (*1-DMin*)	- Year-round in non-salmonid waters.
Swimming Performance	≥ **6.0-6.5** (*1-DMin*)	- Year-round in non-salmonid waters.
Avoidance	≥ **5.0-5.5** (*1-DMin*)	- Year-round in non-salmonid waters.
Acute Lethality	≥ **3.5-4.0** (*1-DAve*)	- Year-round in non-salmonid waters.
Macro-invertebrates (*stream insects*)	≥ **5.5-6.0** (*1-DMin*)	- Year round. Assumes sensitive mayfly species are absent.
Synergistic Effect Protection	≥ **8.5** (*1-DAve*)	- Year-round in non-salmonid waters to minimize synergistic effect with toxic substances.

Abbreviations:
1-DMin = annual lowest single daily minimum oxygen concentration.
1-DAve = annual lowest single daily average concentration.
90-DADMin = lowest 90-day average of daily minimum concentrations during incubation period.

Cited References

Alabaster, J. S., and R. Lloyd. 1980. Dissolved oxygen. In: Water quality criteria for freshwater fish. Edited by J. S. Alabaster and R. Lloyd. Butterworths, London. Pp. 127-142.

Alderdice, D. F., W. P. Wickett, and J. R. Brett. 1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. J. Fish. Res. Bd. Canada 15:2:229-249.

American Public Health Association. 1989. Standard methods for the examination of water and wastewater, 17th edition. Lenore S. Clesceri et al. Editors. Published jointly by the American Public Health Association, American Water Works Association, and Water Pollution Control Federation. Baltimore, Maryland.

Atlas, M. 1938. The rate of oxygen consumption of frogs during embryonic development and growth. Physiological Zoology. XI:3:278-291.

Bailey, J. E. et al. 1980. Effects of seeding density of pink salmon, *Oncorhynchus gorbuscha*, eggs on water chemistry, fry characteristics, and fry survival in gravel incubators. U.S. Department of Commerce, National Marine Fisheries Service. Fisheries Bulletin.78:3:649-658.

Bams, R. A., and C. N. H. Lam. 1983. Influence of deteriorating water quality on growth and development of chum salmon (*Oncorhynchus keta*) larvae in a Japanese-style keeper channel. Can. J. Fish. Aquat. Sci. 40:2098-2104.

Bejda, A. J., B. A. Phelan, and A. L. Studholme. 1992. The effect of dissolved oxygen on the growth of young-of-the-year winter flounder, *Pseudopleuronectes americanus*. Environmental Biology of Fishes. 34:321-327.

Beamish, F. W. H. 1978. Swimming Capacity. In: Fish Physiology, Volume 7, W. S. Hoar, and D. J. Randall (eds.) Academic Press, New York. Pp. 101-187.

Birtwell, I. K., et al. 1983. Studies on the impact of municipal sewage discharged onto an intertidal area within the Fraser River Estuary, British Columbia. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1170.

Bjornn, T. C. 1969. Embryo survival and emergence studies. Federal Aid in Fish and Wildlife Restoration. Job. Compl. Rept., Proj. F-49-R-7. Idaho Fish and Game Dept. Boise, ID. 11p.

Bjornn, T. C. 1969. Survival to emergence of trout and salmon fry in various gravel-sand mixtures. In: Proceedings, Forum on the Relation between Logging and Salmon, pp. 80-

88. Juneau, AK: American Institute of Fishery Research Biologists, and Alaska Department of Fish and Game.

Bouck, G. R. and R. C. Ball. 1965. Influence of a diurnal oxygen pulse on fish serum proteins. Trans. Amer. Fish. Soc. 94:363-370.

Brett, J. R. 1979. Environmental Factors and growth. In: Fish Physiology, Volume 8, W. S. Hoar, D. J. Randall, and J. R. Brett (eds.) Academic Press, New York. Pp. 559-675.

Brett, J. R., and T. D. D. Groves. 1979. Physiological energetics. In: Fish Physiology, Volume 8, W. S. Hoar, D. J. Randall, and J. R. Brett (eds.) Academic Press, New York. Pp. 279-352.

Brett, J. R. 1964. The respiratory metabolism and swimming performance of young sockeye salmon. J. Fish. Res. Bd. Canada 21:5:1183-1226.

Brett, J. R., and J. M. Blackburn. 1981. Oxygen requirements for growth of young coho (*Oncorhynchus kisutch*) and sockeye (*O. nerka*) salmon at 15°C. Can. J. Fish. Aquat. Sci. 38:399-404.

Burdick, G. E., et al. 1954. Lethal oxygen concentrations for trout and smallmouth bass. New York Fish and Game Journal 1:1:84-97.

Carlson, A. R., J. Blocher, and L. J. Herman. 1980. Growth and survival of channel catfish and yellow perch exposed to lowered constant diurnally fluctuating dissolved oxygen concentrations. Prog. Fish-Cult. 42:73-78.

Carlson, A. R., R. E. Siefert, and L. J. Herman. 1974. Effects of lowered dissolved oxygen concentrations on channel catfish (Ictalurus punctatus). Trans. Amer. Fish. Soc. 103:623-626.

Cederholm, C. J., and E. O. Salo. 1979. The effects of logging road landslide on the salmon and trout spawning gravels of Stequaleho Creek and the Clearwater River basin, Jefferson County, Washington, 1972-1978. University of Washington Fisheries Research Institute, College of Fisheries, Seattle, Washington. FRI-UW-7915. 99pp.

Cederholm, C. J., L. M. Reid, and E. O. Salo. 1980. Cumulative effects of logging road sediment on salmonid populations in the Clearwater river, Jefferson County, Washington. University of Washington Fisheries Research Institute, College of Fisheries, Seattle, Washington. Fisheries Contribution No. 543.

Chandrasekaran, G., and B. S. Rao. 1979. On the growth and survival of rainbow trout reared in stagnant pond at higher water temperature and low dissolved oxygen. Matsya 5:35-37.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Trans. Amer. Fish. Soc. 117:1-21.

Chech, J. J. Jr., S. J. Mitchell, and T. E. Wragg. 1984. Comparative growth of juvenile white sturgeon and striped bass: Effects of temperature and hypoxia. Estuaries 7:1:12-18.

Coble, D. W. 1982. Fish populations in relation to dissolved oxygen in the Wisconsin River. Trans. Amer. Fish. Soc. 111:612-623.

Coble, D. W. 1961. Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout. Trans. Amer. Fish. Soc. 90:4:469-474.

Dahlberg, M. L., D.L. Shumway, and P. Doudoroff. 1968. Influence of dissolved oxygen and carbon dioxide on swimming performance of largemouth bass and coho salmon. J. Fish. Res. Board Canada, 25:1:49-70.

Davis, G. E., J. Foster, C. E. Warren, and P. Doudoroff. 1963. The influence of oxygen concentration on the swimming performance of juvenile Pacific salmon at various temperatures. Trans. Amer. Fish. Soc., 92:111-124.

Davis, J. C. 1975a. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32:2295-2332.

Davis, J. C. 1975b. Waterborne dissolved oxygen requirements and criteria with particular emphasis on the Canadian environment. Publication No. NRCC 14100. National Research Council of Canada, NRC Associate Committee on Scientific Criteria for Environmental Quality Report No. 13. Department of Environment. West Vancouver, B.C.

Davison, R. C., W. P. Breese, C. E. Warren, and P. Doudoroff. 1959. Experiments on the dissolved oxygen requirements of cold-water fishes. Sewage and Industrial Wastes. 31:950-966.

Doudoroff, P. and D. L. Shumway. 1970. Dissolved oxygen requirements of Freshwater fishes. Food and Agriculture Organization of the United Nations. FAO Fisheries Technical Paper No. 86:291 p.

Doudoroff, P. and D. L. Shumway. 1967. Dissolved oxygen criteria for the protection of fish. American Fisheries Society Special Publication No. 4. Pp 13-19.

Doudoroff, P. and C. E. Warren. 1962. Dissolved oxygen requirements of fishes. Biological problems in water pollution. Third Seminar, 1962. PHS Publ. No. 999-WP-25. 1965. Pp. 145-155.

Downing, K. M. 1954. The influence of dissolved oxygen concentration on the toxicity of potassium cyanide to rainbow trout. The Journal of Experimental Biology 31:161-164.

Downing, K. M. and J. C. Merkens. 1955. The influence of dissolved-oxygen concentration on the toxicity of un-ionized ammonia to rainbow trout (*Salmo gairdnerii* Richardson). Ann. Appl. Biol. 43:2:243-246.

Eddy, R. M. 1972. The influence of dissolved oxygen concentration and temperature on the survival and growth of chinook salmon embryos and fry. Master of Science Thesis. Oregon State University. Corvallis, Oregon. 45 p.

Edmunds, G. F. Jr., and R. D. Waltz. 1996. Ephemeroptera. Chapter 11. In: An Introduction to the Aquatic Insects of North America. Third Edition. R. W. Merrit and K. W. Cummins editors.

Everest, F. H., et al. 1987. Fine sediment and salmonid production: A paradox. Chapter 4 of Streamside Management: Forestry and Fishery Interactions (Salo, E. O., and Cundy, T. W., eds.), pp. 98-142. University of Washington Institute of Forest Resources Contribution No. 57. Seattle, Washington.

Fast, D. E. 1987. The behavior of salmonid alevins in response to changes in dissolved oxygen, velocity and light during incubation. Doctorate dissertation. University of Washington.

Fast, D. E. et al. 1981. Survival and movement of chinook and coho salmon alevins in hypoxic environments. In proceedings of the salmon and trout migratory behavior symposium. School of fisheries, University of Washington. E.L . Brannon and E.O. Salo, editors. Pages 51-60.

Feder, M. E. 1982. Effect of Developmental Stage and Body Size on Oxygen Consumption of Anuran Larvae: A Reappraisal. Journal of Experimental Zoology. 220:33-42.

Fisher, R. J. 1963. Influence of oxygen concentration and of its diurnal fluctuations on the growth of juvenile coho salmon. Master of Science Thesis. Oregon State University. Corvallis, Oregon. 48 p.

Fry, F. E. J. 1957. The aquatic respiration of fish. In: The physiology of fishes, M. E. Brown, Ed., Volume 1. Metabolism. Academic Press, Inc., New York. Pp 1-63.

Fry, F. E. J. 1947. Effects of the environment on animal activity. Univ. Toronto Studies, Biol. Ser. No. 55 (Pub. Ontario Fish. Res. Lab. No. 68), 62 pp.

Fuss, H. J., and C. Johnson. 1982. Quality of chum salmon fry improved by incubation over artificial substrates. Prog. Fish-Cult. 44:4:170-172.

Garside, E. T. 1966. Effects of oxygen in relation to temperature on the development of embryos of brook trout and rainbow trout. J. Fish. Res. Bd. Canada 23:8:1121-1134.

Gaufin, A. R. 1973. Water quality requirements of aquatic insects. Environmental Protection Agency, Ecological Research Series EPA-660/3-73-004.

Gnaiger, E. 1993. Adaptations to winter hypoxia in a shallow alpine lake. Ecophysiological energetics of *Cyclops abyssorum* and rainbow trout. Verh. Dtsch. Zool. Ges. 86:2:43-65.

Hafele, R. and S. Hinton. 1996. Guide to Pacific Northwest Aquatic Invertebrates. Aquatic Biology Series: Book 1. Published by Oregon Trout, Portland, Oregon 97204.

Hall, J. D., and R.L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. pp. 355-375. In: Symposium on salmon and trout in streams, T. G. Northcote, Ed., Univ. of Brit. Columb. H. R. MacMillan Lectures in Fisheries.

Hampton, T. M., and J. J. Ney. 1993. Effects of summer habitat limitation on trout in Lake Moomaw, Virginia. Virginia Journal of Science 44:2:147

Hausle, D. A., and D. W. Coble. 1976. Influence of sand in redds on survival and emergence of brook trout. Trans. Amer. Fish. Soc. 105:1:57-63.

Hayes, F. R., J. R. Wilmot, and D. A. Livingstone. 1951. The oxygen consumption of the salmon egg in relation to development and activity. The Journal of Experimental Zoology 116:3:377-395.

Herrmann, R. B. 1958. Growth of juvenile coho salmon at various concentrations of dissolved oxygen. Master of Science Thesis. Oregon State University. Corvallis, Oregon.

Herrmann, R. B., C. E. Warren, and P. Doudoroff. 1962. Influence of Oxygen Concentration on the Growth of Juvenile Coho Salmon. Technical Paper No. 1389, Oregon Agricultural Experiment Station.

Hicks, M. P. 2002. Draft Discussion Paper and Literature Summary Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards, Temperature Criteria, Part II. October, 2002. Washington State Department of Ecology, Olympia, Washington.

Hicks, D. B., and J. W. DeWitt. 1971. Effects of dissolved oxygen on kraft pulp mill effluent toxicity. Water Research 5:693-701.

Holeton, G. F. 1973. Respiration of arctic char (*Salvelinus alpinus*) from a high arctic lake. J. Fish. Res. Board Canada 30:717-723.

Holeton, G. F. 1971. Respiratory and circulatory responses of rainbow trout larvae to carbon monoxide and to hypoxia. J. Exp. Biol. 55:683-694.

Hollender, B. A. 1981. Embryo survival, substrate composition, and dissolved oxygen in redds of wild brook trout. Master of Science Thesis. University of Wisconsin. Stevens Point, Wisconsin.

Homer, D. H., and W. T. Waller. 1983. Chronic effects of reduced dissolved oxygen on *Daphnia Magna*. Water, Air, and Soil Pollution, 20:23-28.

Hutchins, F. E. 1974. Influence of dissolved oxygen concentration and swimming velocity on food consumption and growth of juvenile coho salmon. Master of Science Thesis. Oregon State University. Corvallis, Oregon.

Irving, L., E. C. Black, and V. Stafford. 1941. The influence of temperature upon the combination of oxygen with the blood of trout. Biol. Bull. 80:1-17.

Itazawa, Y. 1970. Characteristics of respiration of fish considered from the arterio-venous difference of oxygen content. Bulletin of the Japanese Society of Scientific Fisheries 36:6:571-577.

Jacob, U., H. Walther, and R. Klenke. 1984. Aquatic Insect Larvae as Indicators of Limiting Minimal Contents of Dissolved Oxygen – Part II. Aquatic Insects 6:3:185-190.

Jensen, J. O. T. 1981. Some spawning and incubation conditions that affect salmonid gamete viability and embryo development. In Proceedings: Salmonid Broodstock Maturation May 20-22, 1980 and March 11, 1981. Washington Sea Grant Publication. University of Washington, Seattle. Terry Nosho, Editor. Pages 50-53.

Jensen, S. L. 1966. The mayflies of Idaho (Emphemeroptera). Department of Zoology and Entomology, University of Utah. Master of Science. August, 1996

Jeric, R. J. 1996. Physical factors influencing survival to emergence and time of emergence of shoreslope-spawned kokanee salmon in flaming gorge reservoir, Utah-Wyoming. Master of Science. Utah State University.

Jones, D. R. 1971. The effect of hypoxia and anemia on the swimming performance of rainbow trout (*Salmo gairdneri*). J. Exp. Biol. 55:541-551.

Kamler, E., and T. Kato. 1983. Efficiency of yolk utilization by *Salmo Gairdneri* in relation to incubation temperature and egg size. Pol. Arch. Hydrobiol. 30:3:271-306.

Katz, M., A. Pritchard, and C. E. Warren. 1959. Ability of some salmonids and a centrarchid to swim in water of reduced oxygen content. Trans. Amer. Fish. Soc., 88:88-95.

Keesen, H. W., et al. 1981. Oxygen assessment in trout production with regard to special environmental conditions. Archiv Feur Fishchereiwissenschaft. 31:3:115-121.

Kolar, C. S., F. J. Rahel. 1993. Interaction of a biotic factor (predator presence) and an abiotic factor (low oxygen) as an influence on benthic invertebrate communities. Oecologia 95:210-219.

Koski, K.V. 1975. The survival and fitness of two stocks of chum salmon (*Oncorhynchus keta*) from egg deposition to emergence in a controlled-stream environment at big beef creek. Doctoral dissertation. University of Washington. Seattle, Washington.

Kramer, D. L. 1987. Dissolved oxygen and fish behavior. Environmental Biology of Fishes 18:2:81-92.

Kutty, M. N. 1968. Respiratory quotients in goldfish and rainbow trout. J. Fish. Res. Bd. Canada 25:8:1689-1728.

Larmoyeux, J. D., and R. G. Piper. 1973. Effects of water reuse on rainbow trout in hatcheries. Prog. Fish-Cult. 35:2-8.

Layher, W. G., and O. E. Maughan. 1985. Relations between Habitat Variables and Channel Catfish Populations in Prairie Streams. Transactions of the American Fisheries Society 114:771-781.

Luecke, C., and D. Teuscher. 1994. Habitat selection by lacustrine rainbow trout within gradients of temperature, oxygen, and food availability. In Theory and Application of Fish Feeding Ecology, Volume 18. D. J. Strouder, K.L. Fresh, and R. J. Feller, eds. Columbia University Press, South Carolina. Pp. 133-150.

MacConnell, E. 1989. Effects of water reuse on lake trout. Prog. Fish-Cult. 51:1:33-37.
Maret, T. R., T. A. Burton, G. W. Harvey, and W. H. Clark. 1993. Field testing of new monitoring protocols to assess brown trout spawning habitat in an Idaho stream. North Amer. Journal of Fish. Mngmt. 13:567-580.

Mason, J. C. 1969. Hypoxial stress prior to emergence and competition among coho salmon fry. J. Fish. Res. Bd. Canada 26:63-91.

Matthews, K. R., and N. H. Berg. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. Journal of Fish Biology 50:50-67.

McNeil, W. J. 1964. Redd superimposition and egg capacity of pink salmon spawning beds. J. Fish. Res. Bd. Canada 21:6:1385-1396.

Morrison, J. K., and R. G. Piper. 1986. Effect of reused water on brown trout. Prog. Fish-Cult. 48:2:139-141.

Moss, D. D., and D. C. Scott. 1961. Dissolved-oxygen requirements of three species of fish. Trans. Amer. Fish. Soc., 90:377-393.

Nebeker, A. V. 1972. Effect of low oxygen concentration on survival and emergence of aquatic insects. Trans. Amer. Fish. Soc. 4:675-679.

Nebeker, A. V., S. T. Onjukka, D. G. Stevens, and G. A. Chapman. 1996. Effect of Low Dissolved Oxygen on Aquatic Life Stages of the Caddisfly *Clistoronia magnifica* (Limnephilidae). Archives of Environmental Contamination and Toxicology. 31:453-458.

Oregon Department of Environmental Quality. 1995. Water quality standards review 1992-1994: Final issue papers. Department of Environmental Quality, Standards and Assessment Section. Portland, Oregon 97204.

Pauley, G. B., B. M. Bortz, and M. F. Shepard. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest) – steelhead trout. U. S. Fish Wildl. Serv. Biol. Rep. 82(11.62). U.S. Army Corps of Engineers, TR EL-82-4. 24pp.

Pedersen, C. L. 1987. Energy budgets for juvenile rainbow trout at various oxygen concentrations. Aquaculture 62:3-4/289-298.

Peterka, J. J., and J. S. Kent. 1976. Dissolved oxygen, temperature, survival of young at fish spawning sites. Environmental Research Laboratory. Duluth, Minnesota. EPA-600/3-76-113

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.

Phillips, R. W., R. L. Lantz, E. W. Claire, and J. R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Trans. Am. Fish. Soc. 104:461-466.

Phillips, R. W., and H. J. Campbell. 1962. The embryonic survival of coho salmon and steelhead trout as influenced by some environmental conditions in gravel beds. 14th Annual Report of the Pacific Marine Fisheries Commission for the year 1961. Pacific Marine Fish. Comm., Portland, Oregon, pp. 60-73.

Pihl, L., S. P. Baden, R. J. Diaz, and L. C. Schaffner. 1992. Hypoxia-induced structural changes in the diet of bottom-feeding fish and crustacea. Marine Biology 112:349-361.

Plotnikoff, R. 2000. Aquatic Biologist. Washington State Department of Ecology. Personal Communication.

Rahel, F. J., and J. W. Nutzman. 1994. Foraging in a lethal environment: fish predation in hypoxic waters of a stratified lake. Ecology 75:5:1246-1253.

Randall, D. J., G. F. Holeton, and E. D. Stevens. 1967. The exchange of oxygen and carbon dioxide across the gills of rainbow trout. Journal of Exp. Biol. 6:339-348.

Randall, D. J. and J. C. Smith. 1967. The regulation of cardiac activity in fish in a hypoxic environment. Physiol. Zool. 40:2:104-113.

Redding, J. M., and C. B. Schreck. 1979. Possible adaptive significance of certain enzyme polymorphisms in steelhead trout (Salmo gairdneri). J. Fish. Res. Board Canada. 36:544-551.

Reiser, D. W., and T. C. Bjornn. 1979. Influence of forest management on anadromous fish habitat in western north America: habitat requirements of anadromous salmonids. U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station. General Technical Report PNW-96.

Rombough, P. J. 1988. Growth, aerobic metabolism, and dissolved oxygen requirements of embryos and alevins of steelhead, Salmo gairdneri. Can. J. Zool. 66:651-660.

Scrivener, J. C. and M. J. Brownlee. 1989. Effects of forest harvesting on spawning gravel and incubation survival of chum (Oncorhychus keta) and coho salmon (O. kisutch) in Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 46:681-696.

Secor, D. H., and T. E. Gunderson. 1998. Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon Acipenser oxyrinchus. U.S. Department of Commerce, National Marine Fisheries Service. Fisheries Bulletin 96:3:603-613.

Servizi, J. A., D. W. Martens, and R. W. Gordon. 1971. Toxicity and oxygen demand of decaying bark. Journal of the Water Pollution Control Federation 43:278-292.

Shumway, D. L., C. E. Warren, and P. Doudoroff. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. Technical Paper No. 1741, Oregon Agricultural Experiment Station.

Siefert, R. E., A. R. Carlson, and L. J. Herman. 1974. Effects of reduced oxygen concentrations on the early life stages of mountain whitefish, smallmouth bass, and white bass. Prog. Fish-Cult., 36:186-190.

Siefert, R. E., and W. A. Spoor. 1974. Effects of reduced oxygen on embryos and larvae of the white sucker, coho salmon, brook trout, and walleye. In: J. H. S. Blaxter, ed. The early life history of fish. The proceedings of an international symposium, Oban, Scotland, May 17-23, 1973. Springer-Verlag, Berlin. Pp. 487-495.

Silver, S. J., C. E. Warren, and P. Doudoroff. 1963. Dissolved Oxygen Requirements of Developing Steelhead Trout and Chinook Salmon Embryos at Different Water Velocities. Transactions of the American Fisheries Society. 92:4:327-343.

Smale, M. A., and C. F. Rabeni. 1995. Influences of hypoxia and hypothermia on fish species composition in headwater streams. Transactions of the American Fisheries Society 124:711-725.

Sowden, T. K., and G. Power. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning sites. Trans. Amer. Fish. Soc. 114:804-814.

Sprague, J. B. 1963. Resistance of four freshwater crustaceans to lethal high temperature and low oxygen. J. Fish. Res. Board Canada, 20:2:387-415.

Spoor, W. A. 1990. Distribution of fingerling brook trout, *Salvelinus fontinalis* (Mitchill), in dissolved oxygen concentration gradients. J. Fish Biol. 36:363-373.

Sterling, G. L. 1992. Fry emergence survival of rainbow trout, *Oncorhynchus mykiss* (Walbaum), following timber harvest in two foothill streams of west-central Alberta. Master of Science. Department of Forest Science. University of Alberta, Canada.

Stewart, N. E., D. L. Shumway, and P. Doudoroff. 1967. Influence of oxygen concentration on the growth of juvenile largemouth bass. J. Fish. Res. Bd. Canada 24:3:475:494.
Stewart, N. E. 1962. The influence of oxygen concentration on the growth of juvenile largemouth bass. Master of Science Thesis. Oregon State University. Corvallis, Oregon.

Tagart, J. V. 1983. Coho salmon survival from egg deposition to fry emergence. In Proceedings of the Olympic Wild Fish Conference, March 23-25. Dr. J. M. Walton, Fisheries Technology Program. Peninsula College. Port Angeles, WA 98362. Pages 173-181.

Thatcher, T. O. 1974. Some effects of dissolved oxygen concentration on feeding, growth and bioenergetics of juvenile coho salmon. Doctorate dissertation. Oregon State University.

Thurston, R. V., G. R. Phillips, and R. C. Russo. 1981. Increased toxicity of ammonia to rainbow trout (Salm*o gairdneri*) resulting from reduced concentrations of dissolved oxygen. Canadian Journal of Fisheries and Aquatic Sciences. 38:8:983-988.

Turnpenny, A. W. H., and R. Williams. 1980. Effects of sedimentation on the gravels of an industrial river system. J. Fish. Biol. 17:681-693.

United States Environmental Protection Agency. 1986. Ambient Water Quality Criteria for Dissolved Oxygen. EPA 440/5-86-003. Office of Water. April, 1986.

U.S. Environmental Protection Agency. 1973. Water Quality Requirements of Aquatic Insects. Written by Arden R. Gaufin. EPA-660/3-73-004, September, 1973. Washington, D.C.

Waller, U. H., Rosenthal, and E. A. Black. 1997. The respiration of young coho Oncorhynchus kisutch at gradually declining oxygen levels and during recovery from oxygen deprivation. J. Appl. Ichthyol. 13:73-78.

Warren, C. E., P. Doudoroff, and D. L. Shumway. 1973. Development of dissolved oxygen criteria for freshwater fish. Terminal report from Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon to United States Environmental Protection Agency, Washington D.C. EPA-R3-73-019 February 1973.

Washington Department of Fish and Wildlife. 1992. Washington State salmon and steelhead stock inventory. Appendix one: Puget Sound, Hood Canal, and Strait of Juan de Fuca Stocks; Appendix two: Coastal Stocks; and Appendix three: Columbia River Stocks. Washington Department of Fish and Wildlife. June, 1993. Olympia, Washington.

Washington Department of Fish and Wildlife. 1997. State of Washington Wild Salmonid Policy. Environmental Impact Statement. Washington Department of Fish and Wildlife. Olympia, Washington.

Weithman, A. S., and M. A. Hass. 1984. Effects of dissolved-oxygen depletion on the rainbow trout fishery in Lake Taneycomo, Missouri. Trans. Amer. Fish. Soc., 113:109-124.

Wells, R. A., and W. J. McNeil. 1970. Effect of quality of the spawning bed on growth and development of pink salmon embryos and alevins. U. S. Fish and Wildlife Service Special Scientific Report – Fisheries No. 616. 6 pp.

Whitmore, C. M., C. E. Warren, and P. Doudoroff. 1960. Avoidance Reactions of Salmonid and Cetrarchid Fishes to Low Oxygen Concentrations. Technical Paper No. 1205, Oregon Agricultural Experiment Station.

Whitworth, W. R. 1968. Effects of diurnal fluctuations of dissolved oxygen on the growth of brook trout. J. Fish. Res. Board Can. 25:579-584.

Wickett, W. P., 1954. The Oxygen Supply to Salmon Eggs in Spawning Beds. J. Fish. Res. Bd. Canada. 11:6:933-953.

Witzel, L. D, and H. R. MacCrimmon. 1983. Embryo survival and alevin emergence of brook charr, Salvelinus fontinalis, and brown trout, Salmo trutta, relative to redd gravel composition. Can. J. Zool. 61:1783-1792.

Witzel, L. D, and H. R. MacCrimmon. 1981. Role of gravel substrate on ova survival and alevin emergence of rainbow trout, *Salmo gairdneri*. Can. J. Zool. 59:629-636.

Young, R. C. 1987. Response of rainbow trout to variable dissolved oxygen regimes. Technical Report. Tennessee Valley Authority. TVA/ONRED/AWR 87/40 July, 1987.

Appendix A: The General Physiology of Oxygen Use in Fish

This section discusses the general physiology of oxygen uptake and use in aquatic species. It is included to set the stage for better understanding the results and implications of the research that will be cited and summarized later in this paper. It also provides the reader with a general background on this important aspect of fish biology. It is particularly hoped this review will help the reader understand the adaptive mechanisms, and the costs of adapting, to low dissolved oxygen levels. Readers seeking a more thorough understanding of fish physiology should directly review the works cited herein; particularly those of Fry, Brett, and Davis.

1. Extracting Oxygen from the Water Environment

In the water environment, the availability of oxygen is often naturally limited by location, depth, and season. Because oxygen is a critical resource that is often in short supply, fish have evolved very efficient physiological systems for obtaining and using oxygen to meet their metabolic demands. Atmospheric oxygen enters the water primarily by the slow process of diffusion at the water's surface, and then is transported vertically throughout the water column with the mixing action associated with currents and turbulence. Fry (1957) notes that where water circulation is poor, the water column becomes stratified, or at great depths the water generally becomes increasingly lacking in available oxygen. As living organisms exert a demand for oxygen the supplies can become exhausted if not adequately replenished from surface waters.

Climate and geography can both profoundly affect the ability of water to hold dissolved oxygen in saturation and directly influence the availability of oxygen to fish and other aquatic species. The saturation value of dissolved oxygen is a function of salinity, temperature, and barometric pressure, with altitude an important constant affecting barometric pressure. In freshwaters, it is important to consider how both temperature and altitude combine to limit the available oxygen. Figure 1 below demonstrates how altitude and temperature affects the dissolved oxygen saturation potential. In examining this relationship, it is important to recognize that localized weather patterns will affect barometric pressure and may greatly influence the actual saturation potential on any given day. It is also important to recognize that in the turbulent stream environment waters normally exceed their theoretic saturation potential. So, even though a beaker of water held at 4,000 feet altitude at 11°C cannot hold 9 mg/l or more of oxygen in saturation, a stream at 4,000 feet altitude can regularly be expected to have oxygen levels in the range of 11-12 mg/l during the late fall through early spring period.

In juvenile and adult fish, water is pumped, and flows through differential pressure, through the gill membranes where the oxygen is transferred through diffusion to the bloodstream. When fish are active, further irrigation of the gills occurs as a by-product of forward movement. Fish in the early embryonic state conduct their early respiration over the general body surface. As they develop, a vascular network typically envelops the yolk and greatly extends the respiratory surface. Still later the median fin folds and the pectoral fins provide a further extension (Fry, 1957).

The gills of fish are highly efficient in oxygenating the blood. Randall, Holeton, and Stevens (1967) found the removal efficiency of oxygen from the water was 11-30%, and that the effectiveness of oxygen uptake by the blood approaches 100%. Itazawa (1970) concurred that fish were very efficient in their use of oxygen, and further estimated that the utilization of blood transported to the tissues by the arterial blood reached high levels (60-80%) in contrast to mammals (24-34%). While Van Dam (1938) and Hazelhoff (1938) are cited by Fry (1957) as supporting the utilization estimate of Itazawa under ordinary circumstances, Van Dam found the percentage fell appreciably at higher ventilation volumes (down to 50% in *Salmo*). Randall, Holeton, and Stevens (1967) noted that while hypoxia resulted in a marked decrease in the effectiveness of oxygen uptake by the blood, it has little effect, however, on oxygen removal from the water. While it is clear that fish are very efficient in extracting and using oxygen, Itazawa suggested that this highly efficient utilization was an indication that there is “little room to spare for activity or resistance to lack of oxygen”. Much of the literature examined in this paper appears to support Itazawa’s assertion as minor changes in oxygen result in measurable declines in physiological performance.

2. Respiration and Metabolic Demand in Fish

Respiration in fish is controlled by the respiratory center and modified by local reflexes that keep the mechanism functioning smoothly (Fry, 1957). Fish may respond to decreasing oxygen concentrations (Randall and Smith, 1967; Fry, 1957) and increasing carbon dioxide levels (Fry, 1967) by increasing breathing rate and amplitude and, hence, ventilation volume (Holeton and Randall, 1967, and Garey, 1967; as cited in Davis 1975). Heart rate may decrease rapidly as the partial pressure of oxygen falls. Synchronicity between heartbeat and breathing movements develop simultaneously, and is believed to assist in maximizing efficiency of oxygen uptake. As the gill transfer factor (a measure of the ability of the gills to transfer oxygen per unit gradient) increases, gill water flow goes up, and venous oxygen tension drops. All these factors operate to maintain oxygen uptake in the face of reduced oxygen availability. Fry (1957) notes that because of the density and viscosity of the respiratory medium together with the low concentration of oxygen in it, the cost of respiration is high. Van Dam (1938; as cited in Fry, 1957) found a 70% increase in the resting metabolism when the ventilation volume increased four-fold in rainbow trout exposed to water low in oxygen.

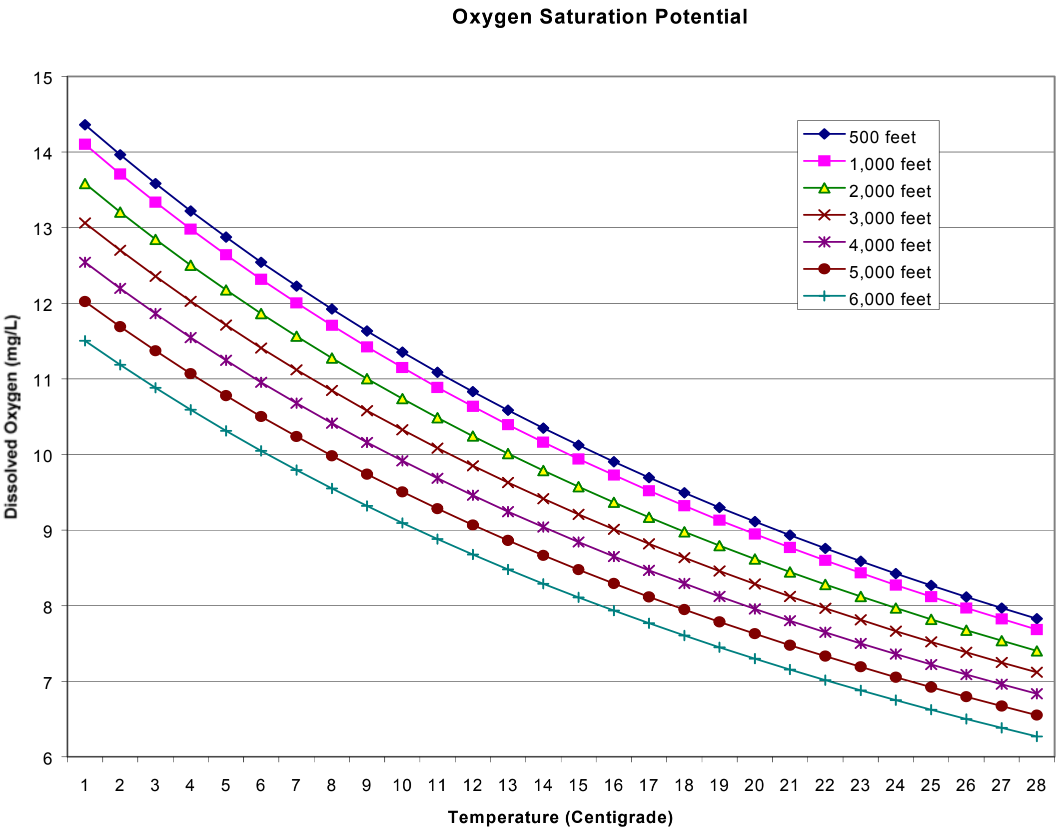

Figure II-A-1. Influence of altitude and temperature on the potential saturation of dissolved oxygen in freshwaters. Based on equations presented in American Public Works Association (1989), assuming zero chlorinity.

As temperature and salinity increase, oxygen content decreases owing to reduced solubility. Thus, a fish breathing warm water must pump more water over the gills than in cold water to deliver a given volume of oxygen per unit time because of the reduced oxygen content of inspired water. Davis (1975) suggests this is necessary even though the oxygen tension gradient between blood and water is little changed at high temperatures (oxygen partial pressure drops only slightly owing to increased molecular activity). He suggests further that severe respiratory problems can result from a combination of high temperature and reduced oxygen tension because both availability and the gradient for oxygen diffusion are reduced. Adding to this phenomenon is the fact that higher temperatures increase the metabolic demand for oxygen.

The point at which the available oxygen level coincides with the oxygen needed for bare maintenance of bodily functions is termed the incipient lethal tension or incipient lethal level. Below this point, the organism may resist for a time but eventually dies. The point at which the metabolic rate ceases to be dependent on available oxygen is termed the incipient limiting tension and has also been referred to as the critical oxygen tension or critical oxygen level (Prosser and Brown, 1962: as cited by Davis, 1975; and Fry, 1957).

Use of regulatory or compensatory mechanisms requires an energy expenditure and consequently reduces energy reserves for swimming, feeding, growth, avoiding predators, and other activities.

Fry (1957) suggests the major factor in producing the phenomenon of respiratory dependence is the limitation imposed by the maximum amount of water that can be presented to the gills by the ventilatory apparatus. It does not appear to be the affinity of the hemoglobin for oxygen, since the decrease in uptake sets in at a level well above the oxygen pressure that permits the hemoglobin to be saturated. If the standard (basal) rate of oxygen consumption is considered in relation to the oxygen content, there should be an extended range where the respiratory rate is independent of the oxygen concentration. The first change to be expected below this level is an increase in oxygen consumption. This increase in metabolic rate reflects the increase in cost of ventilation (Fry cites Van Dam, 1938) since the response of the fish is to pump more water in order to provide a sufficient oxygen supply to satisfy its resting metabolic rate. Any reduction of the oxygen content below the level where the active metabolic rate begins to be restricted is probably unfavorable to the species concerned. From the ecological point of view this “incipient limiting level” (the critical level under conditions of activity) can be taken as the point where the oxygen content begins to be unsuitable. The limiting effect of the oxygen supply may have special significance in the case of embryos, at least of oviparous species. During the early stages, the oxygen requirement of the growing embryo may overpass the extension of the respiratory surface, which at this stage is the vascular surface of the yolk sac. Thus, even at air saturation there may be a reduction in the rate of oxygen uptake before this stage is completed and growth may be temporarily slowed down. At later stages the restriction may be brought about by the limiting surface of the egg capsule. Hayes et al. (1951; as cited in Fry, 1957) showed how the capsule may restrict the passage of oxygen. The larvae freed of their egg capsule took up oxygen at the maximum rate displayed by the encapsulated larvae at a much lower partial pressure. Lindroth (1942; as cited in Fry, 1957) recognized this restriction and pointed out that the most dangerous time for developing eggs as far as lack of oxygen is concerned comes just prior to hatching. Fry opined, however, that the energy required for the activity of development, just like the energy required for physical activity, can apparently be limited without damage to the organism. Thus restriction of the oxygen supply for the developing egg, at least when this restriction concerns only the upper region of respiratory dependence, may do no more than slow down the development of the organism. In such a case, oxygen is operating as a limiting factor. Though it is clear from the evidence presented in the literature that reduced embryonic growth is a common consequence.

3. Resting Versus Active Metabolism

Fry (1957) suggests that while the resting metabolism of fishes is adequately handled by their respiratory system often down to a concentration of ambient oxygen of the order of 1 mg/l, the active metabolism of fish is much more dependent on the oxygen content of the water. The activity of which the fish is capable is correlated with the difference between the standard and active rates of metabolism. Thus any partial pressure of oxygen, which reduces the active rate of metabolism, reduces the activity of the fish and places the species in question at a disadvantage. At a certain low partial pressure of oxygen the active metabolic rate of a fish is reduced down to the bare maintenance requirements and the organism is no longer able to perform external work. Below this level a further reduction in the partial pressure of oxygen quickly leads to death. The rate of standard metabolism increases continuously with increasing temperature up to the lethal temperature in animals. The active rate of metabolism may, however, level off or even decline at a temperature well below the upper lethal limit. The effect of a given reduction in the oxygen content of the water will differ at different temperatures. The general effect will be that a given reduction in dissolved oxygen will restrict activity most severely at the highest temperature and that the optimum temperature, when conditioned by a reduced oxygen content, will be lower than the unconditioned optimum (Fry, 1957).

Moss and Scott (1961 as cited in Doudoroff and Warren, 1962) found that with little exception, the critical dissolved-oxygen levels in all tests with each of three species tested (bluegill, largemouth bass, and catfish) showed a progressive increase with increasing temperatures from 25 to 30 to 35°C. They further found that resting largemouth bass, *Micropterus salmoides*, bluegill, *Lepomis macrochirus*, and channel catfish, *Ictalurus punctatus*, held at 25, 30, or 35ºC in a respirometer in which the oxygen concentration was gradually reduced usually showed no marked reduction of oxygen consumption rates until a lethal oxygen concentration was reached and the fish were about to die. With both bluegills and largemouth bass the relative metabolic rate decreased with increasing size up to weights between 10 and 15 grams; beyond this point there was no measurable drop in metabolic rate over the size range tested.

Job (1955; as cited in Fry, 1957) showed a complete reversal in the relation of the scope for activity with temperature in brook trout over the size range of 5-1000 g. The smallest fish showed an increasing scope (oxygen consumption increased with increasing temperature) from 5°C up to 20°C, while the largest fish showed a decreasing scope (oxygen consumption decreased with increasing temperature). This change was believed brought about by a relatively greater reduction in the active rate in larger fish as the temperature increased (at this point we are referring to the active rate; the standard rate of oxygen consumption relative to size is considered to be essentially independent of temperature). Doudoroff and Shumway (1970) after surveying the literature concluded that young fish tend to be less resistant to a reduction of oxygen concentration than older and larger individuals. Based on the work cited above by Moss and Scott, however, this relationship may be more or less dependent upon the specific species.

Food consumption has a direct relationship to the dissolved oxygen requirements of fish. Brett (1979) noted that at the time of feeding and for some hours thereafter the metabolic rate of fish is elevated, and that large rations may increase the demand for oxygen to levels as high as the active metabolic rate (Brett cites Paloheimo and Cickie, 1966). A reduction in feeding level will reduce an organism's dissolved oxygen requirements. Brett and Groves (1979) studied the bioenergetics of fish by examining the rates of energy expenditure, the losses and gains, and the efficiencies of energy transformation, as functional relations of the whole organism. Upstream migration of spawning adult salmon was found to be the most costly *sustained* energy expenditure of all the activities recorded. They suggested, however, that the heat increment from metabolic processing in combination with the activity accompanying feeding raises the daily metabolic rate of fish that are feeding heavily by a factor of approximately 4 times the standard rate. They further opined that while growth has the lowest immediate priority to a species, in the long run growth and reproduction will dictate the species' survival. The need to collect and convert enough food to meet the growth requirements was noted as being almost always pressing in nature. They suggest that in almost all cases recorded, the higher the ration the greater the growth rate. Only carp, *Cyprinus carpio*, has been shown to experience some rate reduction at maximum ration (Huisman, 1974, 1976). Fry (1957) noted that the metabolic rate of fish in relation to size gives a straight line when the logarithm of the rate of respiration is plotted against the logarithm of the body weight – oxygen consumption increasing with increasing weight – and that standard metabolism decreases markedly with starvation. Feeding tends to restore the metabolism to the prestarvation rate.

4. Acclimation and Adaptation

Doudoroff and Shumway (1970) surveyed the literature and concluded that resistance to reduced oxygen can be increased in fish subjected for some time to nonlethal levels. Acclimation can be nearly complete in about ten days or sooner, but may be much slower or not occur at very low temperatures and under other unfavorable circumstances. After complete acclimation of fish to the lowest tolerable levels of oxygen, their tolerance thresholds can be about half the threshold levels evaluated after acclimation to air-saturation levels of oxygen. In difference to the opinion of Doudoroff and Shumway, the research reviewed directly for this paper did not provide evidence that effect-concentrations substantially change with acclimation.

Fish are able to slightly increase their resistance to otherwise lethal dissolved oxygen levels through gradual or prior acclimation. Moss and Scott (1961) found that the minimal dissolved oxygen levels for which fish survived in acclimation tests was lower than that survived in shock tests at any given temperature. In shock tests, the minimum dissolved oxygen survived by bluegills was 0.75 mg/l at 25°C, 1.00 mg/l at 30°C, and 1.23 mg/l at 35°C (slightly higher values were obtained for the largemouth bass at all three temperatures and for the channel catfish at 25°C and 30°C). In the acclimation tests, however, the critical oxygen values obtained for bluegills were 0.70 mg/l at 25°C and 0.80 mg/l at 30°C.

Redding and Schreck (1979) acclimated two replicate groups of winter steelhead to 7.5 and 4.0 mg/l oxygen at 12°C. The challenge condition of 1.5 mg/l oxygen was reached within 270 min and sustained for the duration of the experiment. All fish that were acclimated at 7.5 mg/l oxygen died within 675 min. About 10% of the fish that were acclimated at 4.0 mg/l oxygen survived until the experiment was terminated after 2880 min.

In addition to the ability of fish to acclimate, stocks of fish species that have evolved in waters more limited in dissolved oxygen may have developed some increased tolerances. In the work by Redding and Schreck (1979), the differential survival and growth performances during the period between the eyed-egg stage and emergence in winter steelhead trout (*Oncorhynchus* *mykiss*) fry was examined. The authors suggested that stocks of steelhead trout in the Pacific Northwest exhibit a conspicuous dichotomy in the frequencies of alleles that code for polymorphisms of lactate dehydrogenase (LDH) and isocitrate dehydrogenase (IDH). LDH regulates the balance between aerobic respiration and anaerobic glycolysis. The authors hypothesized that in juvenile steelhead trout, isozyme phenotypes of LDH, IDH, and several other enzyme systems possess different tolerances to acute high temperature and low dissolved oxygen challenges. They found the relative mortality of the phenotypes between eyed-egg stage and emergence was unaffected by different subgravel conditions of temperature and dissolved oxygen. Differential tolerance to acute challenges of high temperature and low dissolved oxygen was observed between phenotypes of isocitrate dehydrogenase (IDH) enzyme and LDH in juvenile trout. In their research, Redding and Schreck (1979) acclimated winter steelhead to either 12°C and 8.0 mg/l dissolved oxygen or 18°C and 4.0 mg/l dissolved oxygen. The fish were subjected to rapidly increasing temperature (2-3°C/h) and decreasing dissolved oxygen (2.5-3.5 mg/l/h). All fish died within 225 min, and before the target conditions of 26.5°C, 1.5 mg/l oxygen were reached. For fish acclimated at 18°C, 4.0 mg/l oxygen, the BB phenotype of LDH was significantly more tolerant than B'B'. Although they suggest their results do not support the notion that variants of LDH are associated with differential tolerance, it does suggest that tolerance to high temperature or low dissolved oxygen is at least partially heritable. Interior stocks from the Snake and Deschutes River systems tended to have higher frequencies of the A1 and A3 alleles of IDH than coastal stocks of steelhead trout (cites Oregon Cooperative Fishery Research Unit unpublished data). Their experiments suggest that the isozyme phenotypes of the A1 and A3 alleles may possess a greater tolerance to high temperature than those of the A alle. Water temperature in the Snake River may rise as high as 25°C in the summer (cites Beiningen and Ebel, 1971), a value that approaches the upper thermal tolerance limit of steelhead trout. In contrast, a typical coastal stream in Oregon may have summer thermal maximums of only 15°C (cites Moring, 1975). It is interesting to note that differences in weight, length, and condition factors between LDH phenotypes that were apparent at emergence were not observed 9 months after fertilization in a sample of siblings from the same experimental population that were reared in incubation trays and circular tanks at 12°C, 9-10 mg/l oxygen.

In the above cited works, the general conclusion is that both acclimation and adaptation may increase the resistance capacity and lower the lethal levels in fish. The documentation and the levels of observed benefit are not sufficient, however, to provide a basis for establishing watershed-specific dissolved oxygen criteria. Nor is the information sufficient to document that a biologically relevant buffer of protection exists in natural waters subject to periodic decreases to below levels found lethal in laboratory tests.

Part III

Ambient Dissolved Oxygen Concentrations Found in Washington's Streams and Rivers

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Introduction

As described in Part II of this discussion document, salmonids require more dissolved oxygen during spawning and incubation than during rearing. Spawning and incubation usually occur in the fall, winter, and spring. One of the main options when establishing dissolved oxygen criteria is whether to apply two seasonal criteria (one during rearing and a colder one during spawning/incubation) or a year-round criterion that is more reflective of rearing and relies on natural seasonal patterns to protect spawning and incubation.

In other words, can a year-round criterion be developed that will protect rearing and spawning/incubation? This section describes the physical characteristics of rivers in Washington in order to help answer that question.

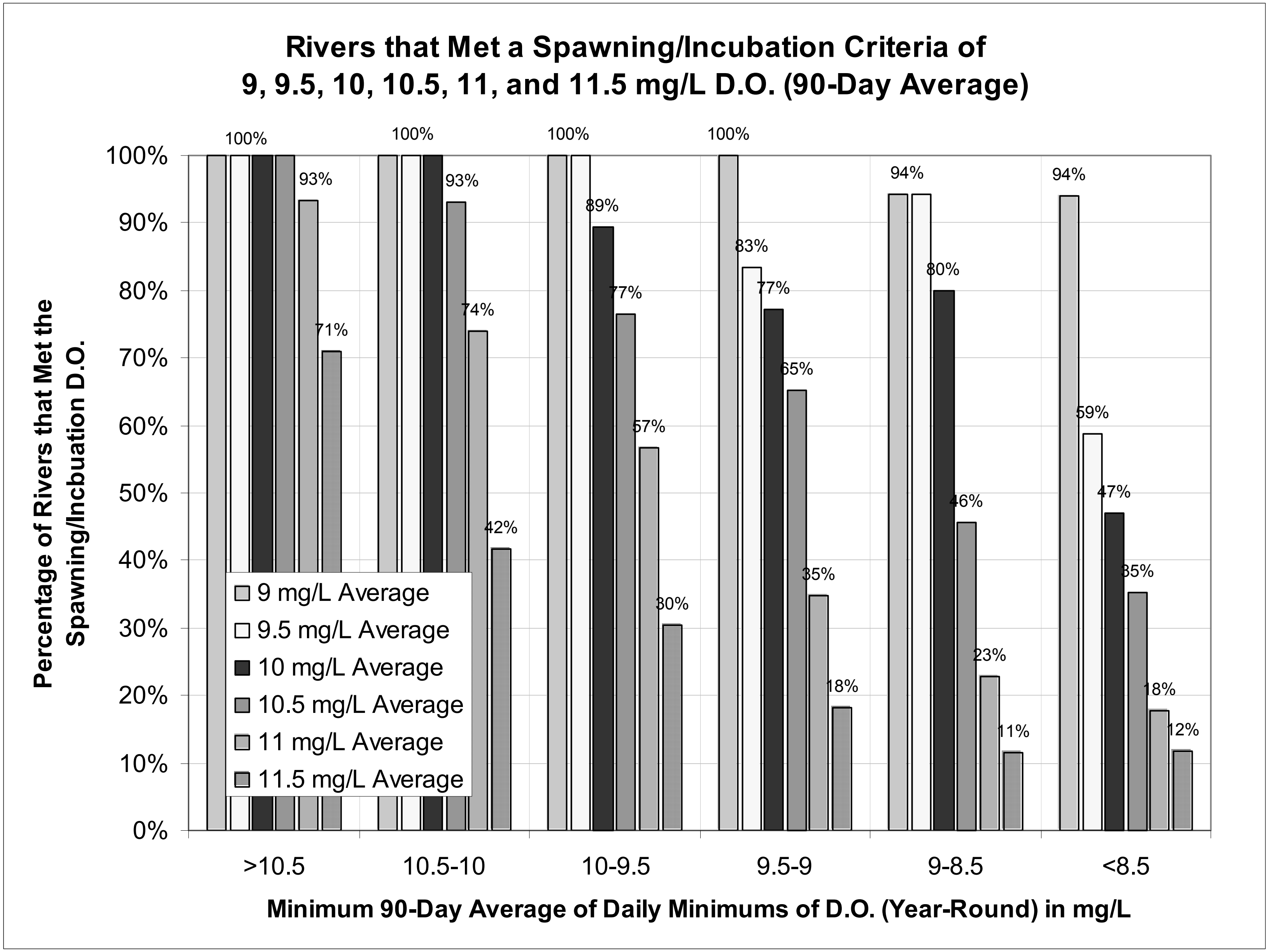
Comparison of Dissolved Oxygen Levels Year-Round and Dissolved Oxygen Levels during Spawning and Incubation

The crux of whether or not to apply separate spawning/incubation criteria comes from a comparison of year-round dissolved oxygen levels with the dissolved oxygen levels occurring during spawning/incubation. Before a year-round criterion can be used, the question must be asked "Will a year-round criterion protect spawning and incubation when it occurs?"

In order to answer this question, Ecology evaluated monthly grab samples from its ambient monitoring program at 84 sites. Data from 1977-2001 was analyzed, providing a sample size of 1,332 river-years. (It is important to note that grab samples tend to over-estimates the daily minimum dissolved oxygen levels. The lowest oxygen levels usually occur very early in the morning, before sampling crews arrive. The intermittent sampling – one day a month – also tends to miss the worse days most years.) While the ambient monitoring program collects data from a variety of rivers across the entire state, Ecology made no attempt to determine if this data set was representative with respect to the year the monitoring occurred, elevation, geography, river temperature, river size, river type, or any other factor. Although the sites do not proportionately represent water bodies in Washington, they do provide a broad sample of water body types.

Ecology used the WDFW Salmonid Stock Inventory (SaSI) to identify dates when spawning occurred in individual waterbodies.

The following chart shows how rivers with different minimum 90-day averages of the daily minimums (90-DAMin) increased their dissolved oxygen by the time spawning began. Part II of this document showed that dissolved oxygen levels during spawning/incubation should be greater than 9.0-11.5 mg/L as a 90-DAMin – with the highest probability of protection occurring at concentrations above 10.5 mg/l.


Rivers that Met a Spawning/Incubation Criteria of
9, 9.5, 10, 10.5, 11, and 11.5 mg/L D.O. (90-Day Average)
Percentage of Rivers that Met the Spawning/Incbuation D.O.
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
>10.5
10.5-10
10-9.5
9.5-9
9-8.5
<8.5
Minimum 90-Day Average of Daily Minimums of D.O. (Year-Round) in mg/L
9 mg/L Average
9.5 mg/L Average
10 mg/L Average
10.5 mg/L Average
11 mg/L Average
11.5 mg/L Average
100%
93%
71%
100%
93%
74%
42%
100%
89%
77%
57%
30%
100%
83%
77%
65%
35%
18%
94%
80%
46%
23%
11%
94%
59%
47%
35%
18%
12%

Minimum 90-DAMin of Dissolved Oxygen in mg/L (Year-Round)	Number of River-Years
>10.5	342
10.5-10	218
10-9.5	141
9.5-9	66
9-8.5	35
<8.5	17

Looking at the rivers with a minimum 90-DAMin D.O. of 9.5-10 mg/L, one can see that 30% of those rivers had 11.5 mg/L D.O. (90-DAMin) or more by the time spawning occurred, 57% had 11 mg/L or more D.O., 77% had 10.5 mg/L or more D.O., 89% had 10 mg/L or more D.O., and all of the rivers had 9.5 mg/L or more D.O.. As the year-round dissolved oxygen levels increased, a higher percentage of rivers reached dissolved oxygen levels of 9-11.5 mg/L (90-DAMin) during spawning/incubation. As the year-round dissolved oxygen levels decreased, a lower percentage of rivers reached dissolved oxygen levels of 9-11.5 mg/L (90-DAMin) during spawning/incubation.

These data show that a year-round criterion of 9.5 mg/L (90-DAMin) would have protected spawning/incubation in many, but not all rivers. Before drawing conclusions about the protectiveness of a year-round criterion, two additional factors should be taken into account. These factors are inter-annual variability (how the minimum dissolved oxygen level in a water body varies from year to year) and spatial variability (how the dissolved oxygen level in a water body varies as it flows downstream).

Inter-Annual Variability

An important issue to address when setting dissolved oxygen criteria is how minimum dissolved oxygen levels fluctuate from year to year, also known as inter-annual variability. Unfortunately, there is very little continuous dissolved oxygen data over a long period of time (i.e. ten or more years). It is not known how much of the inter-annual variability is due to natural conditions (i.e. climate and rainfall) and how much is due to human activity (i.e. discharges of organic material which lowers dissolved oxygen). Dissolved oxygen levels are also greatly influenced by river temperatures, so inter-annual variability in river temperatures will cause inter-annual variability in dissolved oxygen levels.

When deciding if a year-round criterion is protective enough, it is important to keep inter-annual variability in mind. While a water body might have a low probability of protecting spawning/incubation during some years (especially very warm years), during other years (especially cold years) it would be have a much higher probability of protecting spawning/incubation.

Spatial Variability

In general, dissolved oxygen levels decrease as a river flows downstream. The dissolved oxygen criteria apply throughout the entire length of the river, including the furthest downstream point. This means that in order to meet the dissolved oxygen criteria at the furthest downstream point, upstream areas will often have to have more dissolved oxygen than the criteria. How much dissolved oxygen changes in a river as it flows downstream – spatial variability – is quite different for each water body and depends on the characteristics of the individual water body.

When deciding if a year-round criterion is protective enough, it is important to keep spatial variability in mind. While a water body might have a low probability of protecting spawning/incubation at the lowest downstream point, it would have a higher probability of protecting spawning/incubation further upstream.