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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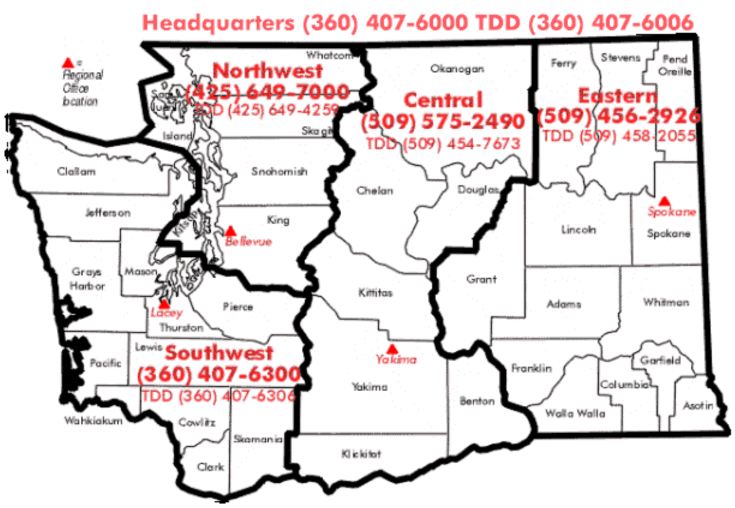

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Abstract

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.

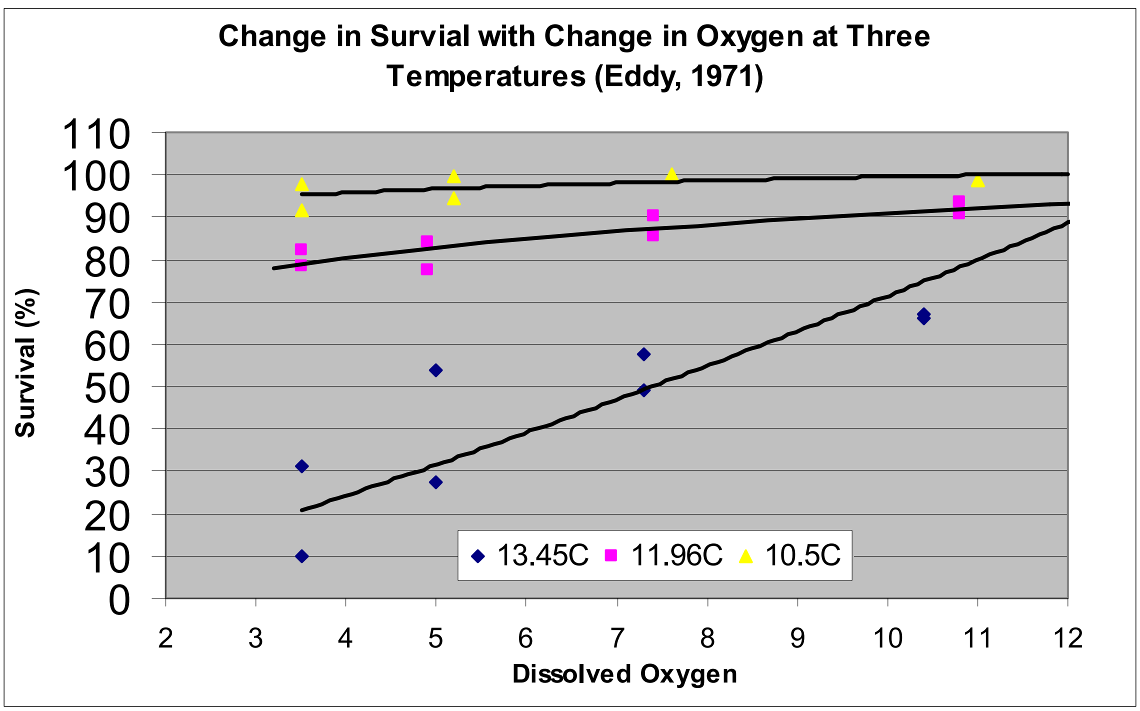

Figure 1. Relationship between incubation survival rates of chinook salmon at three temperatures (10.5, 12, and 13.5°C) and four oxygen concentrations (based on the data from Eddy, 1971).

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.

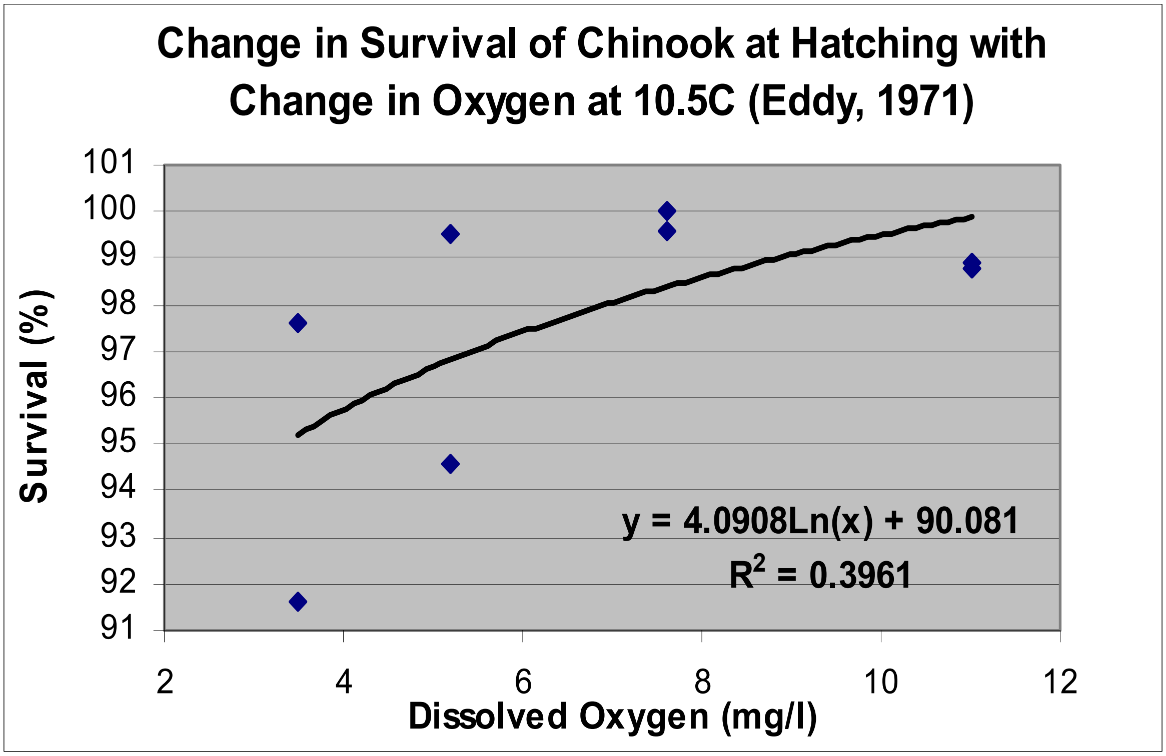

Figure 2. Survival to hatching of chinook salmon with changes in dissolved oxygen level at 10.5°C (Eddy 1971).

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.

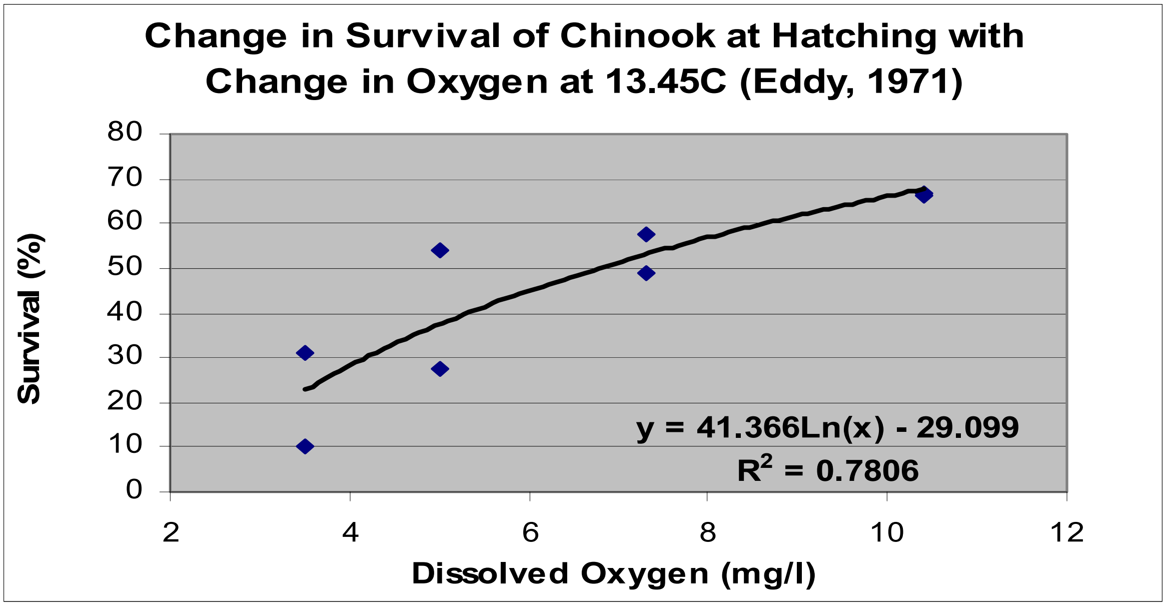

Figure 3. Change in survival at hatching of chinook salmon with changes in dissolved oxygen level at 13.45°C (Eddy 1971).

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.

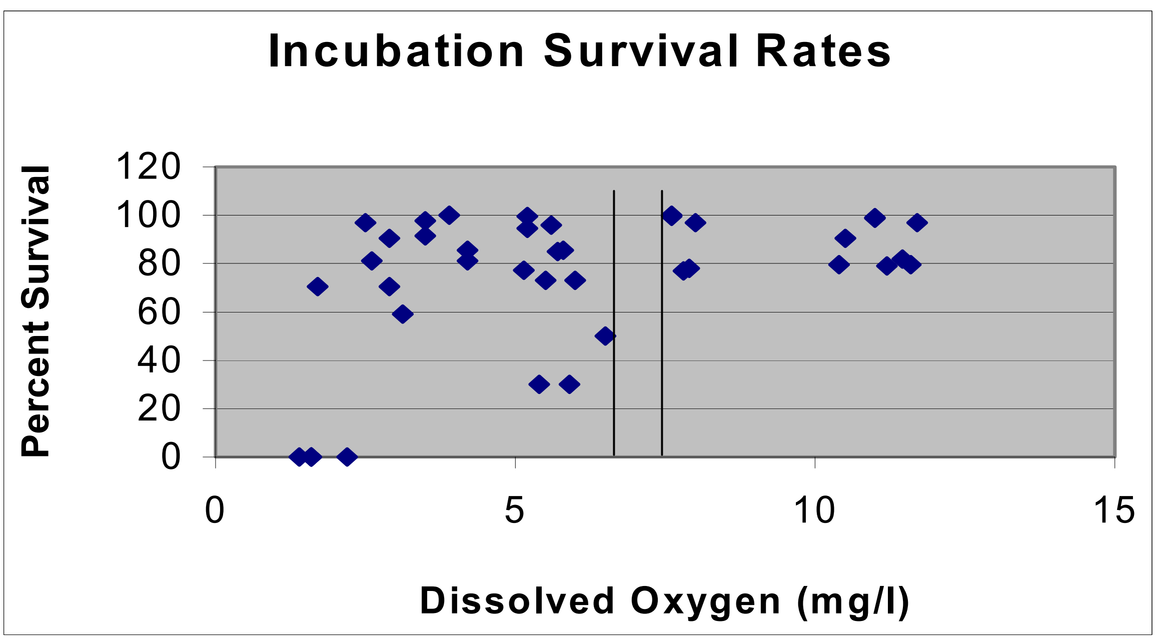

Figure 4. Incubation survival rates versus dissolved oxygen levels reported in the literature

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.

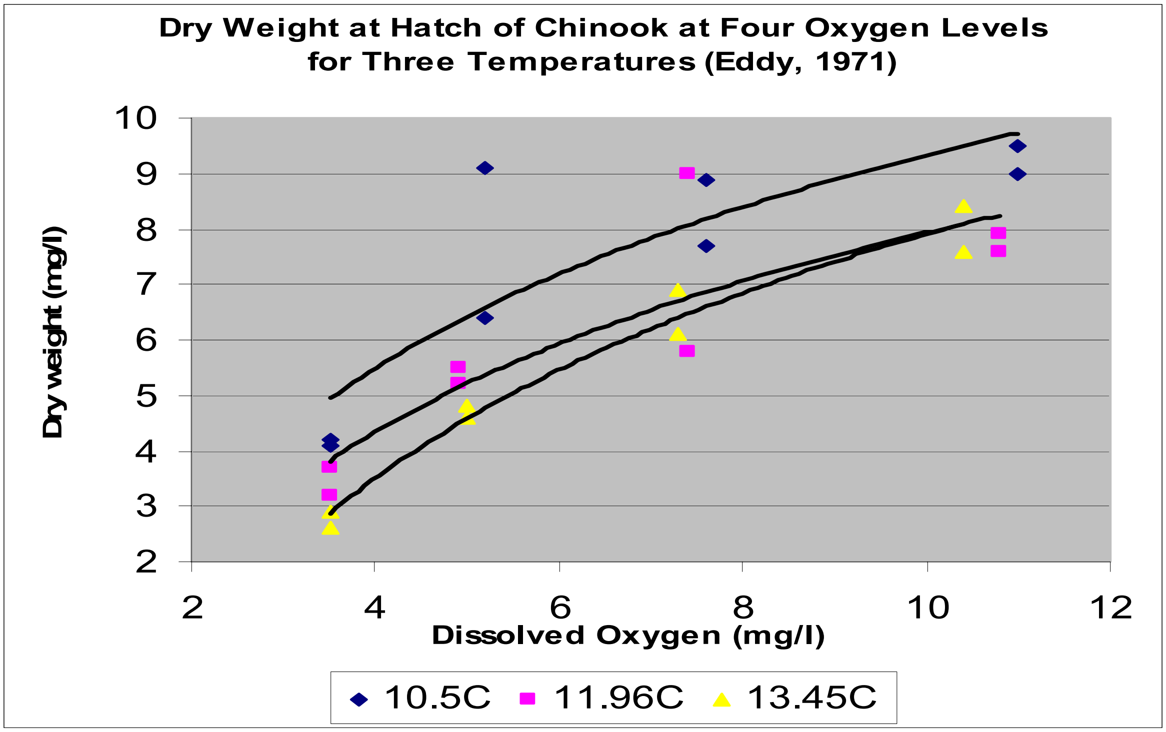

Figure 5. Change in dry weight of chinook salmon at hatching at four oxygen levels for three temperatures (Eddy, 1971)

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.

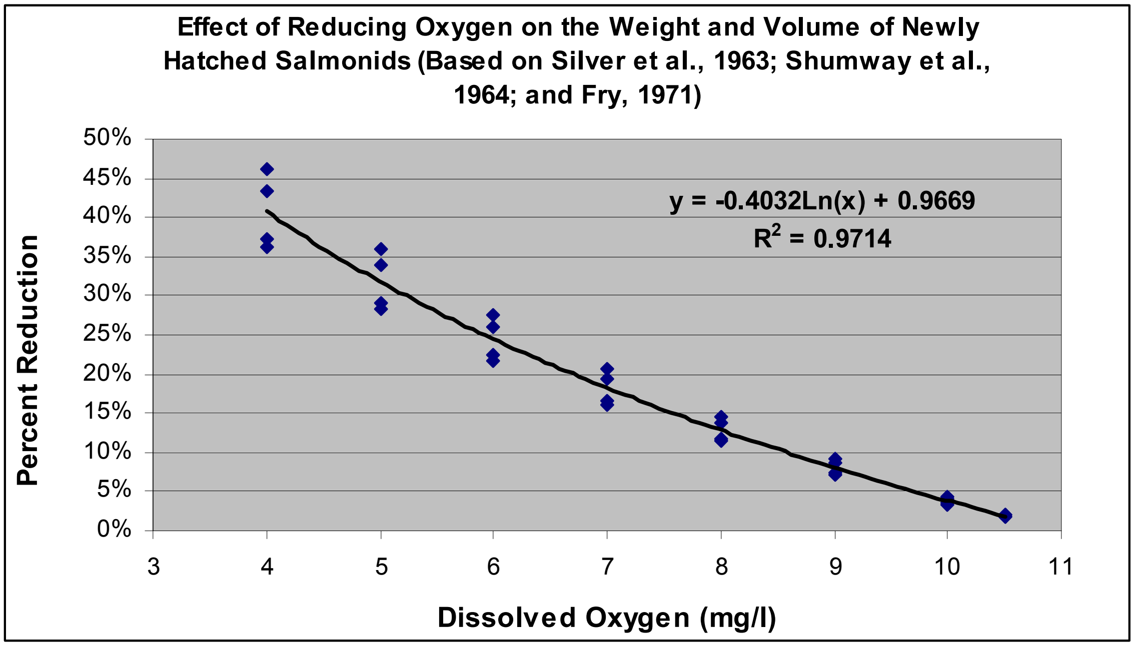

Figure 6. Overall effect on weight and volume of newly hatched salmonids of varying mean oxygen concentrations over the development period. (based on data from Silver, 1963; Shumway, 1964; and Fry, 1971).

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.

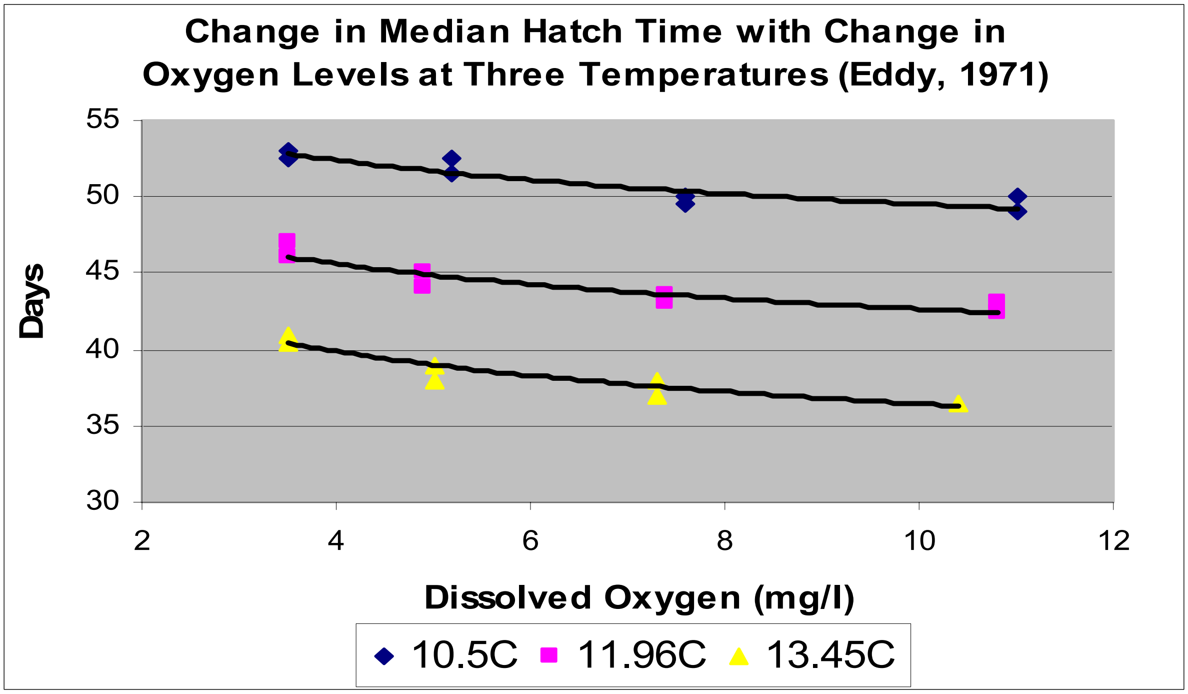

Figure 7. Change in median hatch date with change in oxygen levels in chinook salmon at three temperatures (Eddy, 1971).

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.

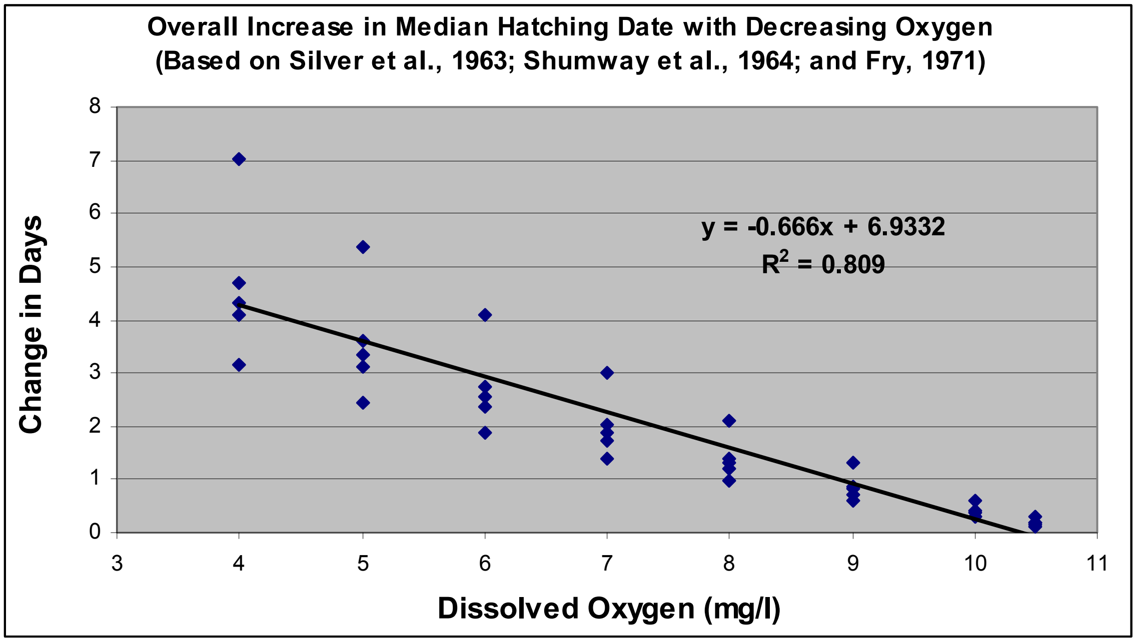

Figure 8. Overall increase in the median hatching date with decreasing oxygen concentrations (Combined data from Silver et al. 1963; Shumway et al., 1964, and Fry, 1971).

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).

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.

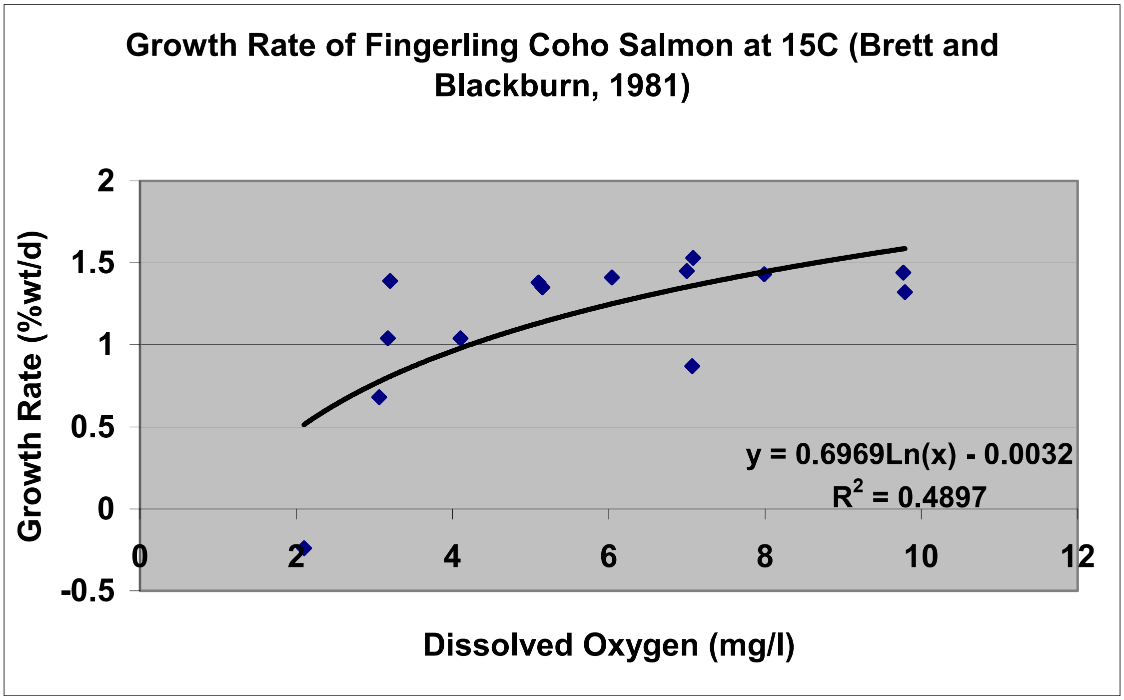

Figure 9. Growth rates of coho salmon in 6-8 week tests at 15°C (data of Brett and Blackburn, 1981).

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.

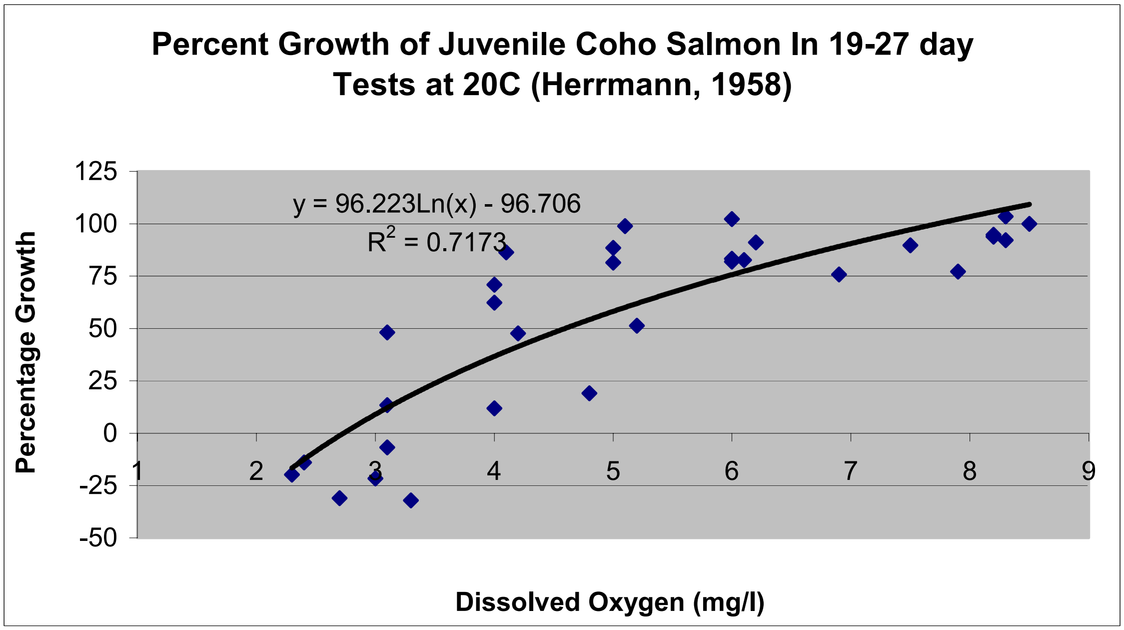

Figure 10. Percentage increase in growth of juvenile coho salmon over 19-27 days at 20°C (Herrmann, 1958).

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.

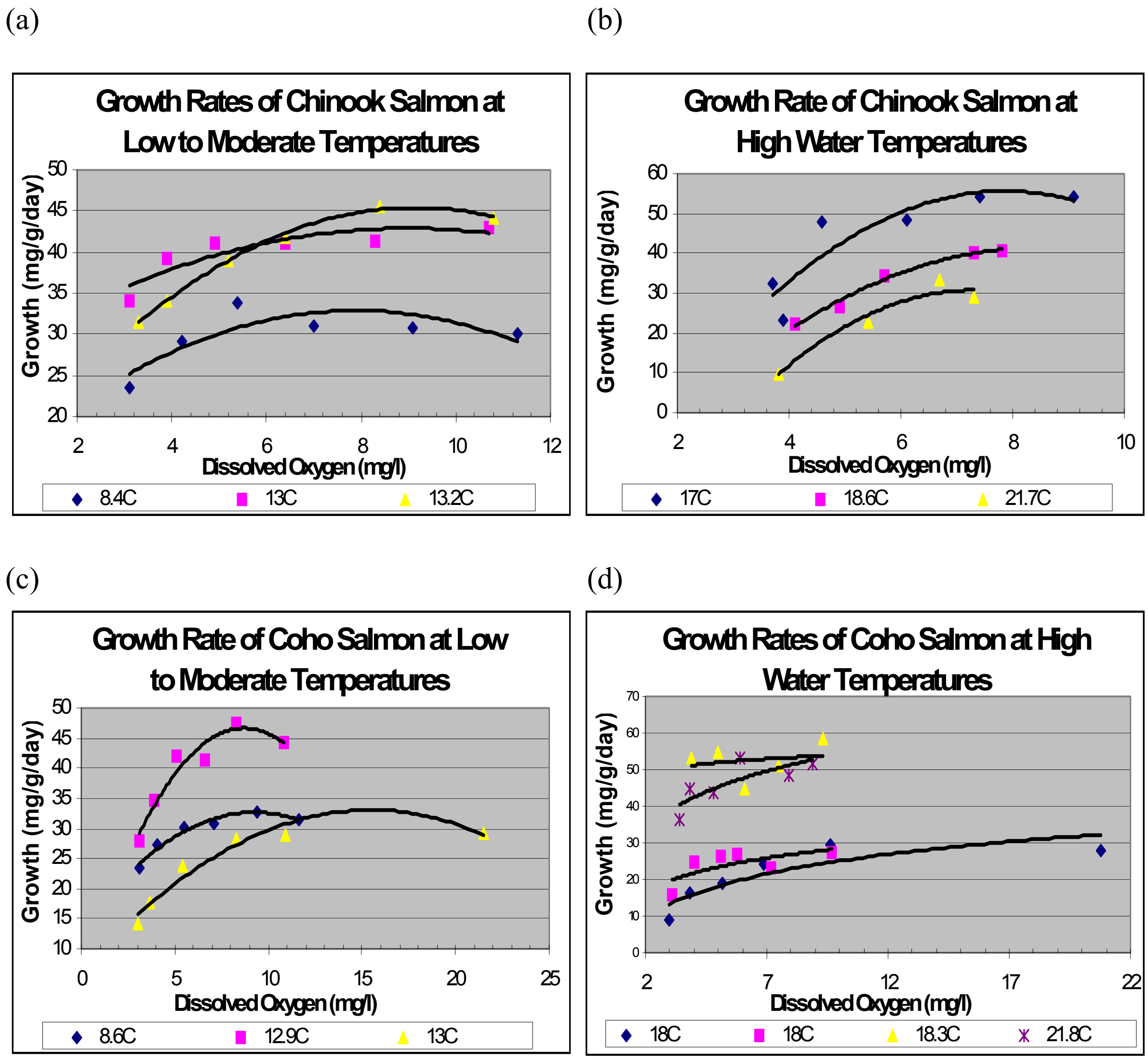

Figure 11(a)-(d). Relationship of dissolved oxygen concentration and temperature on the growth of chinook and coho salmon fed to repletion (Warren et al., 1973).

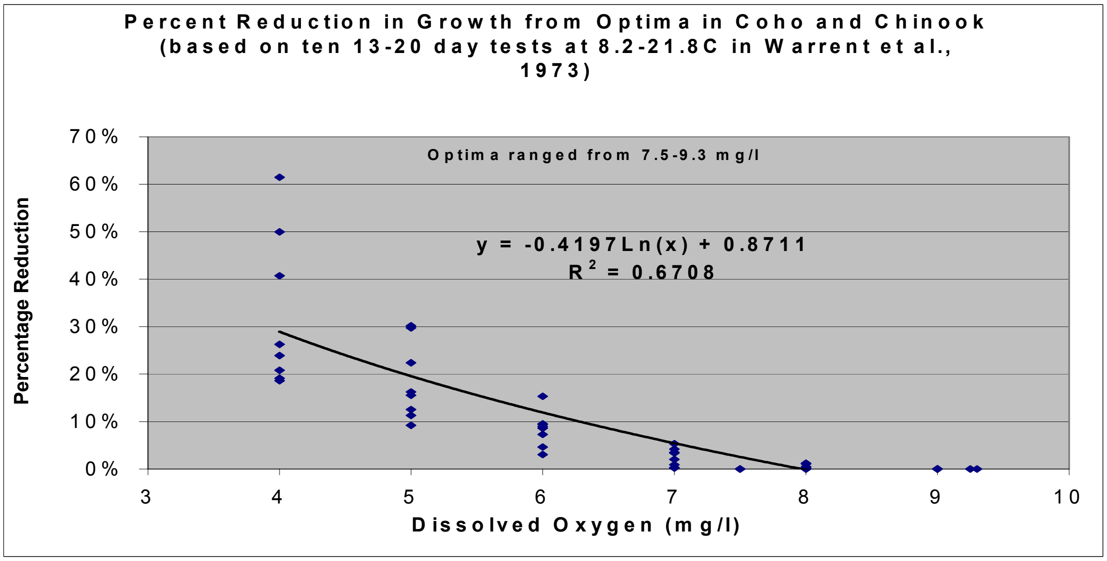

Figure 12. Percent reduction in growth from estimated optimum in coho and chinook salmon in ten tests conducted from 13-20 days at temperature ranging from 8.4-21.8°C (based on Warren et al., 1973). Optimal or near optimal (-1.2%) growth occurred at 8 mg/l or more in all tests. Declines to 7 mg/l and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

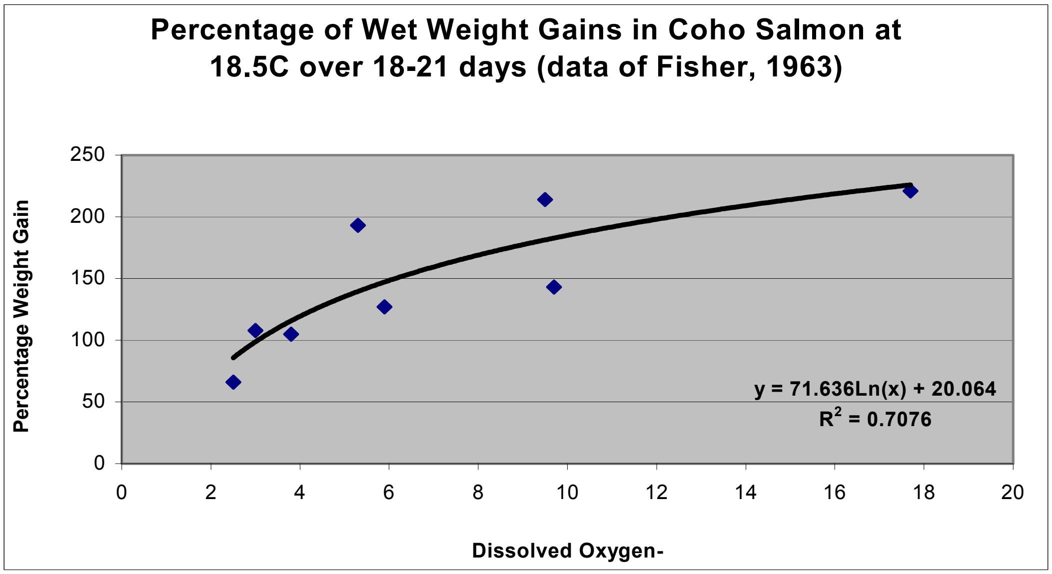

Figure 13. The percentage of wet weight gains with increasing oxygen concentrations at 18.5°C over 18-21 days (data of Fisher, 1963).

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%.

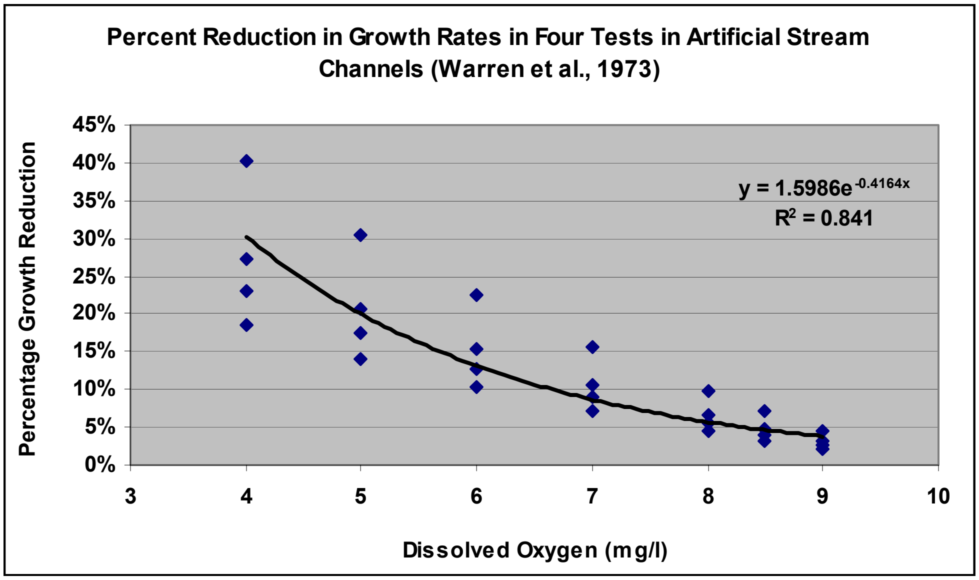

Figure 14. Percentage change in growth rates over a range of DO concentrations of juvenile chinook salmon. Composite of data from four experiments conducted in artificial stream channels over 10-20 days at average temperatures from 9.5-14.3°C. Tests included are those the authors noted as having sufficient 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.

<u>**Summary of Field Growth Tests**</u>: 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).

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 <u>salmonid species</u> 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*) **<u>and</u>** 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*) **<u>and</u>** ≥**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.

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