Salmon Spawning Habitat Protection Rule

Final Technical Support Document

Water Quality Program

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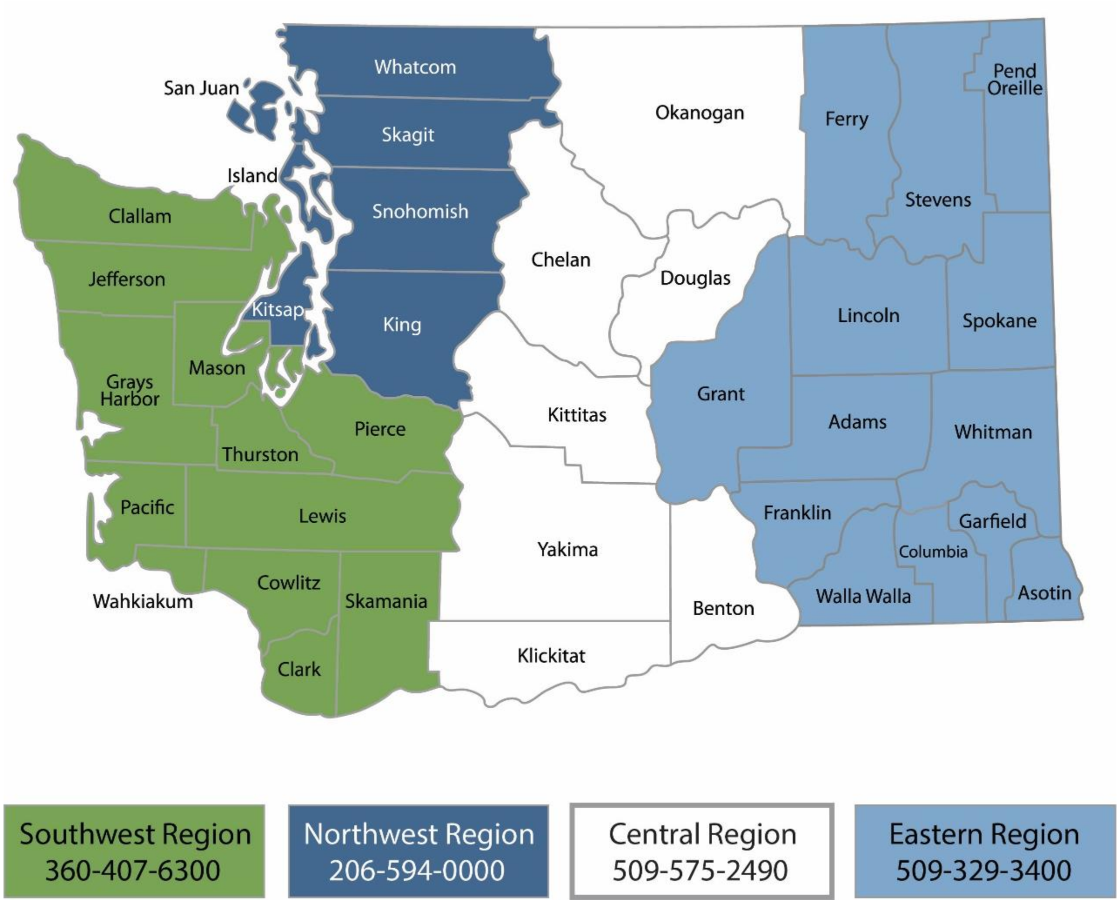

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Acronyms

B-IBI	Benthic Index of Biotic Integrity
CFR	Code of Federal Regulations
CWA	Clean Water Act
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
IGDO	Intragravel Dissolved Oxygen
ESA	Endangered Species Act
LRBS	Logarithmic Relative Bed Stability
m	Meter
mg/L	Milligrams per Liter
mm	Millimeter
NOAA	National Oceanic and Atmospheric Administration
NWEA	Northwest Environmental Advocates
RBS	Relative Bed Stability
RSI	Riffle Stability Index
SSC	Suspended Solids Concentration
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
USFWS	United State Fish and Wildlife Services
WAC	Washington Administrative Code

Executive Summary

The Department of Ecology amended chapter 173-201A WAC Water Quality Standards for Surface Waters of the State of Washington. These changes include:

- Amending WAC 173-201A-200(1)(d), Aquatic life dissolved oxygen criteria for fresh water.
- Adding a subsection WAC 173-201A-200(1)(h) Aquatic life fine sediment narrative criteria.

The purpose of this document is to provide a technical analysis to support the adopted dissolved oxygen and fine sediment criteria. The analysis includes a review of existing scientific literature regarding protective levels of dissolved oxygen and fine sediment and an evaluation of methods used to measure fine sediment.

Ecology accepted comments on the draft rule language and rule adoption documents, including the Technical Support Document, through Dec. 16, 2021.

For more information, view our rulemaking web page[2].

[2] https://ecology.wa.gov/SalmonHabitatRule

Background

Salmon and steelhead populations have been declining in Washington State for more than a decade (State of the Salmon Report[3]). Since 1991, the federal government has declared 14 species of salmon and steelhead in Washington as at-risk of extinction under the Endangered Species Act. Salmonids play a pivotal role in the structure and health of our fresh and marine water ecosystems. Chinook salmon, for example, are the primary food for the endangered Southern Resident Orca, and the decline of Chinook is one of the main factors attributed to the decline of this orca population, according to the 2018 Southern Resident Orca Task Force Final Report[4].

Migrating salmon and steelhead bring essential nutrients from the ocean back to rivers, streams, and surrounding habitat. These nutrients are a significant part of the freshwater food web. Salmonids represent one of the most sensitive aquatic life species in Washington and therefore form the basis for protecting all aquatic life uses, as defined in the Water Quality Standards for Surface Waters of the State of Washington (WAC 173-201A).

The National Oceanic and Atmospheric Association (NOAA) has identified the following four key factors affecting the health of fish: habitat, hydropower, hatchery, and harvest impacts. To improve habitat conditions, NOAA provided comment to Department of Ecology (Ecology) that Washington's DO standards do not fully protect early life stages of salmonids. Specifically, NOAA focused on the oxygen levels that are necessary to maintain healthy conditions for salmon spawning gravels as well as excess sediment pollution that can impair the health of these areas where salmon eggs grow. On December 2, 2019, we formally announced our intent to begin rulemaking on the Salmon Spawning Habitat Protection Rule to revise the surface water quality standards. The purpose of this rule is to increase protection for the early life stages of salmonids and the freshwater gravel nesting areas that support them.

This rulemaking will better protect salmon habitat by improving how we regulate the oxygen requirements for salmon and minimize fine sediment inputs to our waters that can impact how well salmon embryos mature into juvenile fish in our freshwaters. The rule improves the measure and condition requirements of our DO standards and created new fine sediment criteria to limit the human-caused actions that alter both of these conditions.

Review of Dissolved Oxygen Standards

In January 2003, Ecology developed a discussion document and literature summary entitled "Evaluating Criteria for the Protection of Aquatic Life in Washington's Surface Water Quality Standards for Fresh Water – Dissolved Oxygen" (Hicks, 2002). This document provided the basis for adopted changes to the DO criteria as part of a rulemaking in 2003. Public comments questioned these adopted revisions and Ecology postponed changes to the DO criteria until we could gather additional information.

[3] https://stateofsalmon.wa.gov/wp-content/uploads/2020/12/StateofSalmonExecSummary2020.pdf
[4] https://www.governor.wa.gov/sites/default/files/OrcaTaskForce_reportandrecommendations_11.16.18.pdf

In 2006, Ecology revised several sections of the state's Water Quality Standards for Surface Waters of the State of Washington. We did not revise the freshwater DO criteria at that time; therefore those criteria were not subject to EPA review. Although much review of the criteria was done prior to finalizing the rule, there was a lack of consensus on the revisions needed. EPA's final Clean Water Act (CWA) approval of the revised sections of the standards included consultation with the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fishery Service under Section 7(a)(2) of the Endangered Species Act (ESA). That consultation concluded that EPA's approval action was largely beneficial and would not jeopardize the continued existence of any endangered or threatened species. However, as part of that consultation, conditions were set forth to minimize any adverse effects to ESA-listed species, which included comments urging Washington to evaluate and revise the state's DO criteria to ensure protection of early aquatic life stages.

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

As part of the work group research and discussion, Ecology published Washington State Dissolved Oxygen Standard: A Review and Discussion of Freshwater Intragravel Criteria Development (Brown and Hallock, 2009). The study concluded that a percent oxygen saturation criterion may be a more feasible measure of oxygen conditions to protect spawning gravels than increasing the DO concentrations because it takes into account the effect of temperature on DO concentration. The study also concluded that inconsistency in measurement methods may make it difficult to effectively implement DO criteria within spawning gravels.

In this rulemaking, we revisited the past work completed on DO to determine the protections needed for early life stages of salmonids and if DO saturation is an appropriate measurement to account for impacts of temperature and barometric pressure on DO concentrations.

Discussion of Fine Sediment Standards

According to the EPA, fine sediment is considered the nation's most prevalent pollutant in surface waters (US EPA, 2003). Ecology has identified fine sediment as a common pollutant in Washington State that can be implicated in negatively affecting aquatic life health (Larson et al. 2019). In 1998, EPA approximated that 40% of assessed river miles in the United States had impacts due to sediment stress (US EPA, 2000). Sediment stress occurs from changes in sediment load originating from within a watershed, resulting in impacts to the aquatic environment (Nietch and Borst, 2001).

In our 2011 triennial review, Ecology identified the development of fine sediment criteria as a priority for future water quality standards work. In a 2018 U.S. District Court Stipulated Order of Dismissal (Order) between Northwest Environmental Advocates (NWEA), EPA, and Ecology,

Ecology agreed to propose fine sediment criteria to protect early life stages of salmonids (Northwest Environmental Advocates et al. 2018). In this rulemaking, we addressed impacts of fine sediment on early life stages of aquatic life and are developing methods to characterize a fine sediment impairment.

Introduction

Our goal with this rulemaking is to improve rules that protect salmonid spawning habitat in lakes, rivers, and streams. Both DO and the amount of fine sediment in substrate are key factors in ensuring early life stages of salmonids survive and properly develop. DO and fine sediment are interrelated in that the delivery of oxygen to gravels is dependent on the size and permeability of the sediment. The adopted changes provide additional protection to ensure that there are sufficient DO levels in spawning gravels and to ensure the physical structure of salmonid nests (called redds) are conductive to spawning success.

Dissolved oxygen levels fluctuate between the water column and the gravel bed. Water flow is essential for delivering oxygen to the small spaces in between gravels where early life stages of salmonids reside (Figure 1). The oxygen delivered to gravels nourish early life stages of salmonids and other aquatic life and is essential for growth and development. When oxygen is delivered from the water column to gravels, DO levels can decrease. The amount of oxygen available in gravels can be dependent upon many factors including substrate size and permeability, water flow, groundwater influences, biofilms, and temperature. These factors vary site-specifically and ultimately determine the suitability of salmonid spawning habitat.

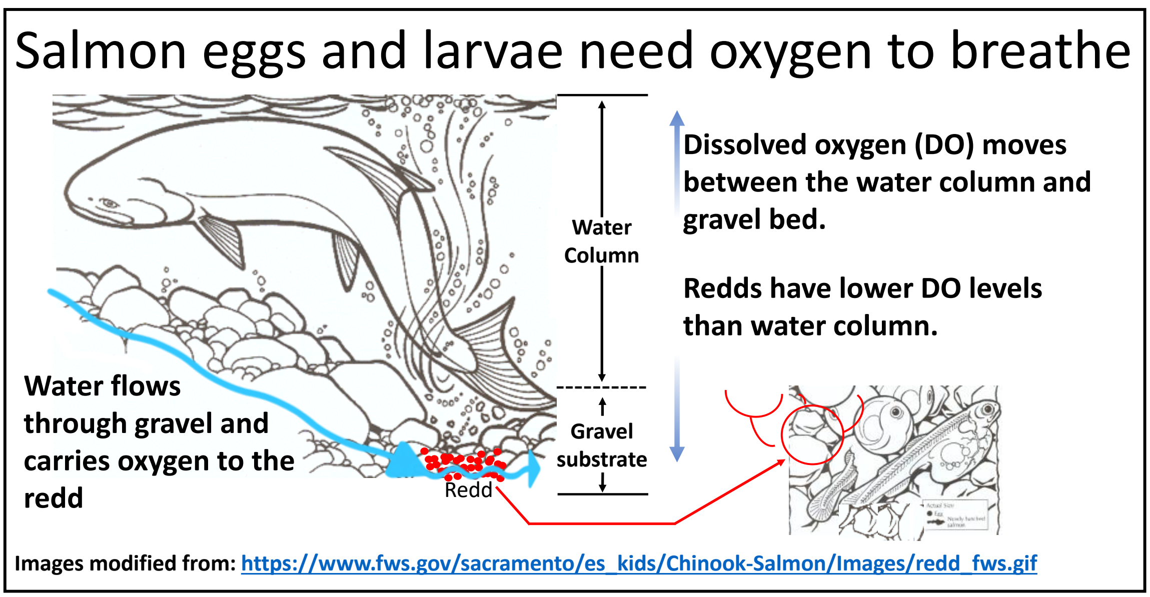

Figure 1 Dissolved oxygen dynamics in a salmonid redd

Sources of DO in the water column primarily stem from diffusion of gaseous oxygen from the atmosphere into surface waters and photosynthesis from aquatic plants. Dissolved oxygen is essential for aquatic life respiration. Reductions in DO in the water column are often attributed to the impact of excess nutrients and increased temperature. Excess nutrients, in the form of phosphorus or nitrogen, can lead to the proliferation of primary producers such as algae and aquatic plants. When blooms of these primary producers die or deteriorate, respiring microorganisms increase in abundance and consume oxygen in the water. Oxygen can also be limited as temperature increases. Higher temperatures limit the ability of oxygen to dissolve in water. Not only are these factors important in determining oxygen levels in the water column but also in the small spaces between gravels (interstitial spaces) where water flow delivers oxygen.

The oxygen dynamics within a redd can vary significantly depending on location within the redd, sediment dynamics within a stream, and where the redd is placed (Chambers, 1956; Greig et al. 2007; Cardenas et al. 2016). During the construction of salmonid redds, a female fish excavates the top layer of substrate, deposits her eggs into the excavated hole below the surface and then covers the eggs back up with gravel. During this building process, water flow carries much of the finer substrate downstream and the medium-sized materials are placed back over the eggs to protect them from predators and from being washed downstream during high flow events.

The removal of finer materials allows for increased water permeability in the gravels and enhanced delivery of oxygen (Groves and Chandler, 2005). Depending on the waterbody, fine sediment suspended in the water column may deposit on the salmonid redd over time and decrease oxygen delivery (Peterson and Quinn, 1996; Soulsby et al. 2001). Salmonids have evolved to place eggs near the upstream portion of the redd to maximize oxygen levels (Chambers, 1956).

Limited oxygen supply to embryos can result in reductions in survival (US EPA, 2003). Fine sediment limits oxygen levels in gravels, and thereby, can affect the survival and emergence of early life stages of salmonids (Figure 2). Quantifying fine sediment is therefore important in establishing protection of early life stages of salmonids. Determining a defined set of representative measures to evaluate fine sediment in a waterbody is an essential step in determining the impact fine sediment may be having on aquatic life. Furthermore, evaluating whether fine sediment is naturally occurring or whether excess sediment from anthropogenic sources is degrading gravel habitat is an important factor in maximizing protection. This rule seeks to set oxygen levels in the water column that are fully protective of early life stages of salmonids and identify a set of measures and procedures to characterize waters impaired by fine sediment.

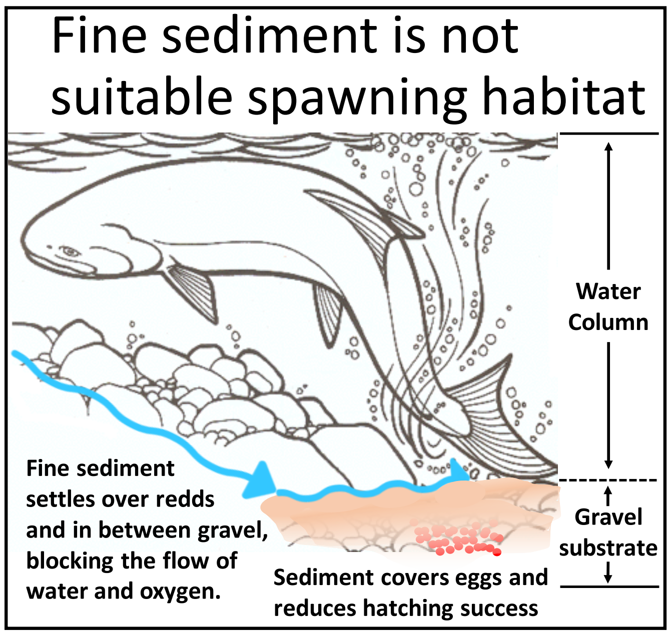

Image modified from: https://www.fws.gov/sacramento/es_kids/Chinook-Salmon/Images/redd_fws.gif

Figure 2 Fine sediment covers salmonid redds, blocking the flow of water and oxygen

Setting Protective Levels

Water quality standards

Under Section 303(c) of the CWA and federal implementing regulations at 40 CFR § 131.4, states and authorized tribes have the primary responsibility for reviewing, establishing, and revising water quality standards. Water quality standards consist primarily of the designated uses of a waterbody or waterbody segment, the water quality criteria that protect those designated uses, and an antidegradation policy to protect high quality waters.

EPA has compiled a list of nationally recommended water quality criteria for the protection of aquatic life and human health in surface waters. These criteria are published pursuant to Section 304(a) of the CWA and provide guidance for states and tribes to establish water quality standards and provide the foundation for controlling the release of pollutants and identifying impaired waters. The state water quality standards are federally approved by EPA and describe the level of protection for Waters of the State.

Dissolved oxygen

Dissolved oxygen (DO) is necessary to support the aquatic life in our state waters. DO levels that are too low can begin to have impacts on behavior, propagation, and success of fish, invertebrates, plankton, and other species. These organisms use oxygen in respiration, similar to organisms that breathe air. We therefore set water quality criteria to help maintain optimal DO conditions that protect the most sensitive species. DO monitoring can then help identify where pollution and other human-caused conditions are affecting optimal DO conditions and potentially harming the aquatic life that utilize a waterbody at some part of their lifestage.

Measures of dissolved oxygen

Concentration

The concentration of DO in the water is typically measured in milligrams per liter (mg/L), and is a measure of the oxygen available to living organisms. The concentration of DO that dissolved in water is affected by the elevation, temperature, and atmospheric conditions at a given location. Monitoring for DO is commonly measured using a scientific probe but can also be measured by collecting a water sample and performing a laboratory analysis.

Percent saturation

Percent saturation is a measure of a equilibrium between oxygen in the surrounding atmosphere and the waterbody. When a waterbody is at 100% saturation, then the water is in equilibrium with the concentration of the oxygen in the air. Because the DO concentration of water is affected by the elevation, temperature, and atmospheric conditions, this measure is better for determining the best (highest) DO concentrations that can be achieved given the location (elevation), local atmospheric conditions, and the water temperature. Waters are not always in precise equilibrium with changing atmospheric conditions, but generally a high percent saturation measure demonstrates that a waterbody is achieving its DO potential. A percent saturation value well under 100% may indicate that concentrations are impacted by pollution such as nutrients.

EPA has not developed recommendations for oxygen saturation values but has approved DO saturation values for several states:

- 95% – Oregon, California, Vermont
- 90% – Idaho, California, Arizona
- less than 90% – Maine, Hawaii, California, New Hampshire, Rhode Island, Vermont.

EPA recommended dissolved oxygen criteria

The EPA has a series of aquatic life recommendations for DO concentrations based on different categories of species and life stages that utilize a waterbody. We refer to these as biologically based criteria because they are developed from studies that evaluate optimally protective conditions for aquatic life present in the waterbody. As a result, optimal conditions rarely account for natural variability, but seek to maintain the best conditions possible for a given parameter.

The most recent EPA recommendation for freshwater DO was published in 1986 (the Gold Book) and includes protective DO concentrations for waterbodies supporting early life stages of salmonids, general salmonid use, non-salmonid early life stages, general non-salmonid use, and invertebrates (US EPA, 1986). This rulemaking will build upon the EPA recommdations for salmonids and increase protections for early life stages of salmonids.

Tables 1 and 2 list recommendations by EPA for DO levels in the water column and intragravel habitat for early life stages of salmonids. The water column-only concentrations are set to protect adult life stages (Table 1).

Table 1. EPA Recommendations for juvenile and adult life stages of salmonids (US EPA, 1986).

Level of Protection	Water Column DO Recommendation
No production impairment	8 mg/L
Slight production impairment	6 mg/L
Moderate production impairment	5 mg/L
Severe production impairment	4 mg/L
Limit to avoid acute mortality	3 mg/L

The DO recommendations for embryo and larval stages (Table 2) focus on the DO concentrations necessary in spawning gravels, including a corresponding water column concentrations necessary to support those intragravel concentrations (US EPA, 1986). EPA derived the water column recommendations from an assumption that DO levels drop by 3 mg/L as measured from the water column to intragravel habitat (referred to as a “DO depression”). Thus an 11 mg/L water column concentration is expected to be equivalent to an 8.0 mg/L intragravel DO concentration to achieve optimal conditions for salmonid embryos and larvae (no production impairment).

Table 2. EPA Recommendations for embryo and larval stages of salmonids (EPA, 1986).

Level of Protection	Water Column DO Recommedation	Intragravel DO Recommendation
No production impairment	11mg/L	8 mg/L
Slight production impairment	9 mg/L	6 mg/L
Moderate production impairment	8 mg/L	5 mg/L
Severe production impairment	7 mg/L	4 mg/L
Limit to avoid acute mortality	6 mg/L	3 mg/L

The 3 mg/L DO depression used in EPA's calculation is based on two field studies prior to 1986 (Koski 1965; Hollender 1981). EPA recognized that limited data were available at the time of the recommendations and that if either greater or lesser DO differentials are known or expected between the water column and gravels, the criteria should be altered accordingly (Chapman, 1986). The EPA Gold Book indicates that for the protection of early life stages it is appropriate to apply the recommended water column criteria of 11.0 mg/L as a mean value and the slight production impairment of 9.0 mg/L as a minima (EPA, 1986).

Prior to this rule adoption, Washington's water quality criteria are set to protect the most sensitive aquatic life uses based on salmonid spawning and rearing (Table 3). However, EPA and NOAA have previously expressed concerns that Washington's DO criteria are not inclusive of salmonid early life stages protection. Washington's water quality criteria are water column based and range from 8.0 to 9.5 mg/L as a one-day minimum value.

Table 3. Washington's water quality criteria for dissolved oxygen (WAC 173-201A-200).

Aquatic Life Use Category	DO Concentration as a one-day Minimum
Char Spawning and Rearing	9.5 mg/L
Core Summer Salmonid Habitat	9.5 mg/L
Salmonid Spawning, Rearing, and Migration	8.0 mg/L
Salmonid Rearing and Migration Only	6.5 mg/L
Non-anadromous Interior Redband Trout	8.0 mg/L
Indigenous Warm Water Species	6.5 mg/L

In this supporting rule document, we review the basis of EPA's recommended criteria and more recent studies that provide information on the relationship between water column and intragravel DO conditions. We also review the options for multiple methods of compliance with DO criteria through water column concentration, percent saturation, and direct intragravel DO measurement.

Fine sediment

The EPA does not currently have recommended criteria for fine sediment. In 2003, EPA reviewed the biological effects of suspended and bedded sediments in aquatic systems and summarized states' criteria set to limit fine sediment pollution (Jha and Swietlik, 2003). In the 2003 review, EPA concluded that generalizing protective criteria for fine sediment is difficult because biological responses vary with species and sediment characteristics. EPA also noted that many states have standards set to address suspended and bedded sediments but that there is little consistency among the criteria.

Washington currently addresses fine sediment through a narrative criterion that states "toxic, radioactive, or deleterious material concentrations must be below those which have the potential, either singularly or cumulatively, to adversely affect characteristic water uses, cause acute or chronic conditions to the most sensitive biota dependent upon those waters, or adversely affect public health" [emphasis added]. Excessive fine sediment can be a deleterious material affecting the physical and chemical conditions necessary to protect aquatic life However, the current narrative criterion does not specifically describe a protective fine sediment criterion nor does it specify when fine sediment is impairing aquatic life.

Related criteria

Washington currently has numeric criteria for turbidity that are based on a change above background turbidity conditions (WAC 173-201A-200(e)). This criteria structure is useful for limiting anthropogenic sources of turbidity and therefore excess sediment entering a waterbody. These criteria rely on the change in turbidity conditions related to a discharge to, or activity within the waterbody to limit human impacts to the aquatic habitat. However, turbidity criteria do not provide information on bedded sediment nor do these criteria differentiate naturally occurring sediment deposition from anthropogenic sources of sediment deposition.

In this supporting rule document, we revisit the difficulties in developing criteria specific to fine sediment by examining a series of metrics to address this pollutant and determine the most representative parameters available to determine when fine sediment is impairing a waterbody.

Dissolved Oxygen Criteria Rule Development

The objective of revising the biologically based DO criteria is to increase protection of early life stages of salmonids. Therefore, we include more stringent water column criteria and the addition of IGDO criteria for those waterbodies designated for salmonid spawning and rearing. IGDO criteria reflects a direct measurement of DO levels where early life stages of salmonids reside, whereas the water column DO levels are dependent on an assumption of DO depression from the water column to the interstitial spaces of gravels. We also include a DO saturation criterion to account for the influence of temperature and barometric pressure on DO levels. Early life stages of salmonids are not present year-round in all waterbodies, and therefore, oxygen levels protective of spawning and rearing of salmonids do not need to be assigned when these uses are not present. DO saturation also accounts for natural seasonal changes in temperatures (such as warmer temperatures in summer months) and the impact that elevation has on the ability of oxygen to dissolve in water.

Adopted criteria

We have adopted changes to the DO criteria that include more stringent water column based DO concentrations and the addition of oxygen saturation and intragravel DO criteria (Table 4). The intragravel DO criteria is measured as a median spatial value, and samples must be taken within the same aquatic habitat area. A spatial median is the middle value of multiple ranked intragravel DO measurements taken within the sampling area.

Table 4. The aquatic life freshwater dissolved oxygen criteria adopted in this rulemaking.

Aquatic Life Use Category	Water column (1-day minimum)
Char Spawning and Rearing*	10.0 mg/L or 90% oxygen saturation
Core Summer Salmonid Habitat*	10.0 mg/L or 95% oxygen saturation
Salmonid Spawning, Rearing, and Migration*	10.0 mg/L or 90% oxygen saturation
Salmonid Rearing and Migration Only	6.5 mg/L
Non-anadromous Interior Redband Trout*	10.0 mg/L or 90% oxygen saturation
Indigenous Warm Water Species	6.5 mg/L

* Note: Intragravel D.O criteria for these aquatic life use categories may be used for compliance purposes. When intragravel DO is used for compliance, the intragravel DO (1-day minimum) concentration must be 8.0 mg/L or greater, and the DO water column (1-day minimum) concentration must be 9.0 mg/L or greater. Intragravel DO must be measured as a spatial median within the same habitat area.

Water Column Concentrations

We adopted a 1-day minimum water column concentration of 10 mg/L DO for protection of salmonid-based designated uses that are protective of early life stages (Table 4). The 10 mg/L DO protection level is intended to be protective of both sublethal and lethal effects. The 10 mg/L DO protective level is based on EPA's recommendation of 11 mg/L as a mean value for full protection and 9 mg/L as a minimum value. Prior to EPA's 1986 recommendations, the National Academy of Sciences (1972) suggested that DO criteria for salmonid eggs be between maximum protection (11 mg/L) and high level of protection (9 mg/L). Given that Washington is continuing to use a 1-day minimum duration value for DO, the 10 mg/L value aligns with federal recommendations for DO.

The primary difference between the 11 mg/L DO level recommended by EPA and the 10 mg/L DO level adopted is the assumed reduction in DO from the water column to gravels and the criteria duration. The 10 mg/L DO protection level was chosen to reflect a maximum 2 mg/L DO depression value (discussed below) from the water column to gravels, whereas EPA assumes a 3 mg/L DO reduction. This is based on scientific literature after EPA's 1986 recommendations. The 10 mg/L DO water column value assumes that 8.0 mg/L DO is present in gravels, which is in alignment with EPA's recommendation of 8.0 mg/L in gravels for the protection of early life stages of salmonids. We agree with EPA and the scientific literature (as summarized by Hicks, 2002) that 8.0 mg/L in gravels is fully protective of early life stages of salmonids.

EPA recommends that 11 mg/L be set as a mean value, presumably a 7- or 30-day average value. We set our water column criteria as a 1-day minimum value. The selection duration is more stringent than recommended by EPA and is considered protective of both acute and chronic effects.

The 11 mg/L EPA recommended value for DO is representative of protection levels for chronic effects to early life stage salmonid embryos present in gravels, and 9 mg/L is considered protective for acute effects to early life stages. This is described in 1986 EPA recommendation as follows:

> "If slight production impairment or a small but undefinable risk of moderate impairment is unacceptable, than, one should use the no production impairment values given in the document as means and the slight production impairment values as minima."

We reviewed the scientific literature since the 1986 recommendations and determined that a 2 mg/L DO depression is more representative of the difference between the water column and intragravel DO conditions for moderate to high quality spawning gravels (see explanation below). Therefore, 10 mg/L is protective of chronic effects based on an assumed 8.0 mg/L DO concentration in the gravels. Rather than develop protection levels for chronic and acute effects, we developed a single criterion that is protective of both acute and chronic conditions for all live stages.

Discussion of Dissolved Oxygen Depression from the Water Column to Gravels

The 1986 EPA DO recommendations for salmonids is 11 mg/L for the water column and 8 mg/L for gravels. EPA assumes a 3 mg/L DO depression from the water column to gravels. EPA states in the 1986 DO recommendations that there is minimal data to support the 3 mg/L assumption (Chapman, 1986) and that the assumption is based on two studies (Koski 1965 and Hollender 1981). EPA also asserts that the DO depression value should be evaluated in the absence of other variables that may impact DO levels. These other variables include poor substrate composition, flow, suspended sediment/solids, high primary productivity, and unsuitable spawning habitat.

Examining the two studies EPA relied upon for their 1986 DO depression assumption, we found that Koski (1965) reported mean IGDO depression values of 2 mg/L and Hollender (1981) reported mean IGDO depression values ranging from 2.1 to 3.7 mg/L. Both studies reported considerable variations in IGDO levels within a single redd and variation among redds in a given area. This is expected given that substrate composition can vary spatially and that IGDO levels can change over the course of incubation from oxygen consumption by the developing embryos and deposition of suspended sediment (Greig et al. 2007; Cardenas et al. 2016). We also reviewed Koski (1965) and Hollender (1981) to determine if these studies met EPA requirement of limited influence from environmental variables (especially fine sediment) that could impact intragravel DO.

Hollender (1981) found redds composed of mostly cobbles and sand, with sand content averaging 40% in natural redds of brook trout (range 12-83%) and 42% (range 24-57%) in artificial redds. This represents a relatively high amount of particles less than 2 mm (categorized as sands and fines) and well below the ideal particle sizes for spawning and incubation (Bell 1986). Hollender (1981) notes that substrate at two sites examined was fine enough to reduce embryo survival and emergence. Koski (1965) reported that fine sediment composed 27 to 51% of the gravel in the redds sampled. The information presented in Koski (1965) and Hollender (1981) suggests that fine sediment likely influenced DO conditions at the selected sites, making the data unusable for assessment of DO depression values. Hausle and Coble (1976) concluded that more than 20% sand (<2 mm particles) reduces emergence from redds, suggesting that these studies may be inadequate for determining DO depression. This raises the question of whether there is data available after 1986 that evaluates DO depression and meets EPA data requirements that DO depression should be evaluated in relatively sediment free gravels.

In 2008, EPA requested that AquaTerra (Project No. 20610-124) conduct a literature review to determine if DO depression between the water column and intragravel habitat ranges from 1.0 to 3.0 mg/L. Furthermore, EPA requested that AquaTerra determine if this assumption is true in relatively sediment-free gravels. We agree that DO depression values should be determined in relatively sediment free gravels with minimal influence from other environmental variables that could influence oxygen levels. AquaTerra identified several articles that were helpful in determining maximum DO depression values in the absence of outlying environmental variables that can substantially alter oxygen in gravels. This information is conveyed below and summarized in Brown and Hallock (2009).

Argent and Flebbe (1999) developed artificial redds with initial fine sediment percentages ranging from 0 to 25%. In the absence of fine sediment, there was no (0 mg/L) IGDO depression observed, and at 25% fine sediment, a 1.8 mg/L DO depression was reported. Bowen and Nelson (2003) measured DO depression in a single redd at two depths over a 5-month period. In November, the reported DO depression was 0.4 mg/L at both depths, and in December, DO depression was 0.3 mg/L (30 cm depth) and 0.7 mg/L (46 cm depth). In March, DO depressions were 7.3 and 6.6 mg/L at the two depths. However, in March a significant amount of fine sediment had been introduced into the stream by storm runoff, rendering the March values irrelevant to determining DO depression in relatively sediment free conditions. In another study, Guimond and Burt (2007) collected water column and IGDO at three sites during salmon incubation season. Interpretation of figures describing relationships between water column DO levels and IGDO suggests that DO depression values are minimal and less than 2 mg/L. In comparing two streams with different sediment loads, Heywood and Walling (2006) found mean DO depression values of 1.1 and 1.8 mg/L in the stream with minimal sediment load, and 4.2 and 5.9 mg/L in the stream with a significantly higher sediment load. When examining DO depression at different gravel depths, Merz and Seika (2004) reported DO depression values of 0.2 to 0.5 mg/L at 15 cm, 0.3 to 0.9 mg/L DO depression at 30 cm, and 0.1 to 2.0 mg/L DO depression at 45 cm. Meyer (2003) found that the lower part of a redd where eggs are deposited is the critical area to limit fine sediments and found a mean DO depression value of 0.6 mg/L.

In our analysis, we excluded DO depression values from upwelling sites. We do not anticipate high spawning success in oxygen deprived groundwater; thus, the oxygen differential from the water column to gravels should not be evaluated at upwelling sites. Groundwater can be severely limited in oxygen resulting in poor embryo survival (Malcolm et al. 2003), while sites dominated by surface water have higher embryo survival (Malcolm et al. 2004). Geist et al. (2002) reported DO depression values of 0.8 and 1.7 mg/L for two downwelling sites and 5.5 to 9.4 mg/L for three upwelling sites. Groundwater oxygen content is influenced by environmental factors that are not relevant to determining oxygen delivery from the water column.

EPA recommends a 3 mg/L DO depression as an average, whereas the literature summarized in the AquaTerra review of DO depression values in streams indicate that a maximum DO depression of 2 mg/L is found in moderate to high quality spawning gravels. The studies supporting the 2 mg/L DO depression value are commensurate with EPA study requirements of limited influence from environmental variables (i.e., fine sediment) that influence oxygen in gravels. The available literature validates the decision to set a 10 mg/L water column based DO value for early life stages of salmonids. The majority of qualified studies found that DO depression may be much less than 2.0 mg/L in streams without excess sedimentation and in the absence of variables that influence oxygen demand.

We support EPA in analyzing DO depression in moderate to high spawning gravels. Streams with naturally high fine sediment loads should not be listed as impaired for DO for natural conditions that preclude attainment. Streams with high sediment loads are expected to have naturally lower salmonid survivorship. The development of DO protection values based on DO depression values in naturally high sediment laden streams is not an appropriate evaluation of protection levels because these streams are never likely to achieve full protection and will never have high quality spawning habitat. If a stream has excessive fine sediment or altered conditions due to anthropogenic sources that lead to poor DO condition in gravels, then focus should be on improving those conditions. Washington State has other water quality criteria that can be used to address environmental conditions or excess material that may inhibit freshwater DO from meeting protective levels, including fine sediment (included in this rule), turbidity, and temperature (See WAC 173-201A).

In the interest of fully protecting salmonids, we determined that 2.0 mg/L DO is a representative maximum DO depression value in streams with suitable spawning habitat. Early life stages of salmonids are considered fully protected at 8.0 mg/L DO (EPA, 1986; Hicks, 2002). The 2.0 mg/L depression value supports our decision to set water column DO levels of 10 mg/L to protect early life stages of salmonids when they are present.

Oxygen Saturation

We have added an oxygen saturation component to the DO criteria for aquatic life uses that include salmonid spawning (i.e., salmond spawning/rearing/migration, core summer salmonid habitat, char spawning, and redband trout). The oxygen saturation component was not added to the salmonid rearing and migration use or the indigenious warm water species use. The focus of this rulemaking is on protection of early life stages of salmonids. These two uses do not include the protection of early life stages of salmonid as it relates to spawning and emergence. We have therefore not revised the current DO criteria for the salmonid rearing and migration use and the indigenious warm water species use.

The purpose of the oxygen saturation component is to account for temperature and elevation impacts on DO levels. Furthermore, oxygen saturation provides needed flexibility to the DO criteria during the summer months when water temperatures rise and, in many streams, early life stages of salmonids are not present. During these warmer seasons, more stringent DO criteria is not necessary and often not physically achievable due to effects of temperature on oxygen capacity in waters. Several other states and tribes use DO saturation criteria, including:

- <90% – Maine, Hawaii, California, New Hampshire, and Rhode Island
- 90% – Idaho; California, and Arizona
- 95% – Oregon; California, and Vermont

Washington currently has a site-specific oxygen saturation criterion of 90% on the Columbia River. In this rulemaking, we include a 95% and a 90% oxygen saturation value depending on the aquatic life use category.

Washington's DO criteria apply year-round and are intended to support characteristic aquatic life uses. Although the DO criteria apply year-round, the aquatic life uses that define a use category may not apply year-round. For example, the salmonid spawning, rearing, and migration use is defined by spawning and emergence outside of the summer season (September 16 – June 14). While protection levels are applicable year-round, the defining characteristic of the aquatic life use (e.g., spawning and emergence) may not occur year-round. Therefore, the DO criteria need to account for environmental factors that lower DO levels during times when aquatic life uses are not present. Oxygen saturation criteria is one such resolution.

A 90% oxygen saturation value is more protective than the current biologically based criteria at sea level at the maximum allowable temperature for all salmonid related aquatic life uses, except for core summer salmonid habitat (Table 5). Bell (1986) found recommended incubation temperatures for salmonids to range from 4.4 to 14.4°C. When evaluating the 90% oxygen saturation value at sea level during winter months, we found 90% oxygen saturation affords increased protection at temperatures ideal for embryo incubation compared with the current water column based DO criteria, except for core summer salmonid habitat between 14-16°C (Table 5). However, Washington also has supplemental spawning temperature criteria that identifies waterbodies that have early life stages of salmonids present during the summer months, and thus require more stringent temperature criteria. When accounting for supplemental spawning temperature criteria, 90% saturation is equivalent or greater than current DO protection concentrations for all aquatic life uses.

The minimum allowable DO concentration at sea level when meeting temperature requirements (max 17.5°C) of the salmonid spawning, rearing, and migration use equates to 9.1 mg/L with a 95% oxygen saturation criteria (Table 5). EPA recommends a water column protection level of 8.0 mg/L for juvenile and adult salmonid life stages. A 95% oxygen saturation criterion would be overly stringent when early life stages are not present and would presume impairment when these conditions are not driven by pollution issues, but rather natural seasonal conditions. This is especially the case during the summer months (see below). Setting a 95% oxygen saturation criteria for aquatic life uses defined by occurrence of spawning and emergence during cooler seasons (i.e., outside of summer) is not required for full protection. There is reasonable assurance that based on spawning timing defined by aquatic life use of salmonid spawning, rearing, and migration, that temperatures will be cooler, flows will increase, biochemical oxygen demand will decrease, and DO conditions will be conducive to spawning success.

The minimum allowable DO concentration at sea level when meeting temperature requirements (max 17.5°C) of the salmonid spawning, rearing, and migration is 8.6 mg/L at a 90% oxygen saturation criterion (Table 5). The minimum 8.6 mg/L DO concentration associated with 90% oxygen saturation is more stringent than EPA recommendations for juvenile and adult salmonid life stages of 8.0 mg/L and, therefore, should provide adequate protection during summer months when environmental conditions preclude attainment of the concentration based DO criteria. The salmonid spawning, rearing, and migration use is defined by spawning timing from September 15 to June 14 (fall, winter, and spring). The spawning timing of this aquatic life use provides reasonable assurance that water temperatures will decrease, water flow will increase, and biochemical oxygen demand will decrease by the time spawning occurs, affording adequate protection for early life stages of salmonids.

Table 5. Comparison of the current DO criteria protection levels with the minimum DO level resulting from a 90% oxygen saturation criteria at sea level for aquatic life designated uses.

Designated Aquatic Life Use	Temperature in (°C)	Minimum DO level at 90% saturation in mg/L	Minimum DO level at 95% saturation in mg/L	Prior Washington DO criteria in mg/L
Salmonid spawning, rearing and migration	17.5 (maximum)	8.6	9.1	8.0
Salmonid spawning, rearing and migration	13	9.5	10	8.0
Salmonid spawning, rearing and migration	10	10.2	10.7	8.0
Salmonid spawning, rearing and migration	8	10.7	11.3	8.0
Salmonid spawning, rearing and migration	5	11.5	12.1	8.0
Core summer salmonid habitat	16 (maximum)	8.9	9.4	9.5
Core summer salmonid habitat	13* (maximum)	9.5	10	9.5
Core summer salmonid habitat	10	10.2	10.7	9.5
Core summer salmonid habitat	8	10.7	11.3	9.5
Core summer salmonid habitat	5	11.5	12.1	9.5
Char Spawning	12 (maximum)	9.7	10.2	9.5
Char Spawning	9* (maximum)	10.4	11	9.5
Char Spawning	7	10.9	11.5	9.5
Char Spawning	5	11.5	12.1	9.5

*Supplemental spawning criteria in effect if there are incubating embryos in gravels.

We recognize that aquatic life uses characterized by salmonid reproduction and rearing during summer may be particularly susceptible to environmental conditions and require additional protection. Washington has identified water bodies in supplemental spawning temperature criteria where spawning occurs in late spring, summer, and early fall where more stringent water temperature criteria are necessary to protect early life stages of salmonids. The Core Summer Salmonid Habitat use is characterized by spawning in summer months. The applicable year-round temperature criterion for the Core Summer Salmonid Habitat use is 16°C, whereas supplemental spawning criteria is 13°C. A 90% oxygen saturation criterion at 13°C equates to a DO concentration of 9.5 mg/L at sea level (Table 5). While 9.5 mg/L may be protective in some streams, a 2 mg/L DO depression may occur in moderate to high quality spawning gravels and not be adequate for full protection (which is considered 10 mg/L). A 95% oxygen saturation criterion is equivalent to 10 mg/L at 13°C at sea level (Table 5). Thus, a 95% oxygen saturation value at 13°C is equivalent to the DO concentration protection level of early life stages of 10 mg/L. We have therefore set the Core Summer Salmonid Habitat use oxygen saturation criterion at 95%.

This brings the question as to why 95% oxygen saturation is not applied to the sensitive Char Spawning use. This can be explained by the applicable temperature criteria for the Char Spawning use versus the Core Summer Salmonid use (Table 5). The applicable year-round temperature criterion for the Char Spawning use is 12°C, whereas the supplemental spawning criteria is 9°C. A 90% oxygen saturation criterion at 12°C is equivalent to 9.7 mg/L at sea level, whereas at the 9°C supplemental spawning criterion, the equivalent oxygen concentration is 10.2 mg/L. Thus, the 90% oxygen saturation criterion is more stringent than the concentration-based DO criteria of 10 mg/L needed during summer reproduction for the Char Spawning use. We have therefore set the Char Spawning use oxygen saturation criterion at 90%. When Char spawning occurs during fall, winter, and spring months there is reasonable assurance that water temperatures will be lower, water flow will increase, biochemical oxygen demand will decrease, and oxygen conditions will be fully protective of early life stages.

In summary, the different temperature requirements for Core Summer Salmonid Habitat and Char Spawning uses influences the applicable oxygen saturation criterion needed for full protection (Table 1). We support the use of 90% oxygen saturation for all uses, except Core Summer Salmonid Habitat use, based on salmonid spawning and rearing timing as well as applicable temperature requirements.

The 90% oxygen saturation value is supported by monitoring data from several waterbodies in Washington considered relatively pristine or undisturbed by human influences, referred to as "Least impacted sites." "Least impacted" sites (LESS) are those with little or no logging, residential development, known cattle grazing, or agriculture, and few roads in the catchment basin. Ecology also monitors "somewhat impacted" sites (DIST), which are defined as sites where a significant (at least 5%) fraction of the catchment basin contains impacts from logging, residential development, or agriculture, or has an increased road density. LESS sites can generally be considered more pristine reference locations and typically are found in either state or national forest or park land. DIST sites can generally be thought of as an achievable target for basins where some level of impact is unavoidable, but land use development is relatively limited.

Several of these relatively pristine sites are reference or sentinel sites in Ecology's long-term monitoring program and have oxygen saturation values naturally below 95% in summer months (Table 6). Of the 63 high quality LESS reference sites analyzed, 13 (20.6%) displayed minimum DOSAT values below 95%. Of the 57 DIST reference sites analyzed, 29 (50.8%) displayed minimum DOSAT values below 95%. Overall, 4 out of 63 (6.3%) LESS sites do not meet 90% saturation only and 13 of 57 (22.8%) DIST sites do not meet 90% oxygen saturation. It is important to note that these discrete measurements are not true daily minimums and likely biased high, compared to actual daily minimums, as they are all measured between the hours of 8am and 8pm. Even relatively unimpacted sites can experience significant decreases in nightime oxygen saturation due to respiration of photosynthetic organisms. Groundwater influences, naturally higher temperatures, and barometric pressure (i.e., elevation) can lower the ability for oxygen to dissolve in water. Oxygen saturation criteria provide the necessary flexibility to account for these confounding factors that occur naturally in streams and rivers.

In another analysis of 136 ambient stations monitored, a 95% oxygen saturation criterion for all uses would result in 67% of stations impaired, and a 11 mg/L or 95% oxygen saturation criteria would result in 53% of stations impaired (Brown and Hallock, 2009). Brown and Hallock (2009) indicated that 34% of ambient stations do not meet 90% saturation. However, if you review Table 3 of Brown and Hallock (2009), only 26% of stations do not meet 11 mg/L or 90% saturation.

Table 6. Dissolved oxygen data collected between July to October for least impacted (LESS) reference sites in Washington State that do not meet 10 mg/L or 95% saturation.

Site	Latitude	Longitude	Number of days sampled	Maximum Temperature (°C)	Minimum DO (mg/L)	Minimum Oxygen Saturation	Average Oxygen Saturation	Percent of Measures <95% Saturation	Aquatic Life Use
Burping Brook	47.88913	-117.13055	13	13.3	7.49	76.8%	96.2%	31%	Core Summer
Lost Creek Tributary	48.64396	-117.43632	10	13.9	8.81	94.1%	97.7%	10%	Core Summer
Mill Creek, Middle Fork	48.65078	-117.68265	4	9.3	8.70	84.4%	92.6%	50%	Core Summer
Goose Creek, North Fork	48.42512	-117.06072	8	11.4	9.40	93.6%	98.5%	25%	Core Summer
Oyster Creek	48.61868	-122.43950	7	14.6	9.70	93.3%	98.4%	29%	Salmon Spawning
Rush Creek Tributary	46.04297	-121.85934	8	8.5	8.87	82.9%	93.8%	50%	Char Spawning
Spangler Creek	46.14830	-117.80350	7	13.7	8.52	92.6%	97.3%	29%	Char Spawning
Tucannon River	46.18462	-117.60728	11	13.4	8.88	94.0%	100.6%	18%	Salmon Spawning
Upper Slate Creek	48.95702	-117.24484	2	9.8	9.57	94.7%	94.8%	100%	Char Spawning
Hamma Hamma River	47.59729	-123.15308	23	13.1	9.58	88.9%	95.0%	65%	Core Summer
Laughingwater Creek	46.75517	-121.54043	22	13.4	8.83	91.2%	95.9%	55%	Core Summer
Twin Creek	47.83303	-123.99350	18	11.9	8.60	79.2%	87.3%	100%	Char Spawning
Umtanum Creek	46.85526	-120.48878	17	21.7	7.90	90.7%	96.8%	47%	Salmon Spawning

Table 7. Dissolved oxygen data collected between July to October for least impacted (DIST) reference sites in Washington State that do not meet 10 mg/L or 95% saturation.

Site	Latitude	Longitude	# of Days	Maximum Temperature (°C)	Minimum DO (mg/L)	Minimum Oxygen Saturation	Average Oxygen Saturation	Percent of Measurements <95% Saturation	Aquatic Life Use
Bear Creek	47.68577	-122.08889	4	16.1	8.62	86.0%	94.9%	50%	Core Summer
Big Beef Creek	47.648	-122.781	4	16.0	9.22	90.4%	93.4%	67%	Core Summer
Anderson Creek	47.56505	-122.95145	2	14.2	9.40	91.8%	93.6%	50%	Core Summer
Boyce Creek	47.60896	-122.90808	2	16.0	9.10	92.4%	94.6%	50%	Core Summer
Christmas Creek	47.6567	-124.22219	3	15.1	9.78	94.1%	100.3%	17%	Core Summer
Chuckanut Creek	48.70193	-122.48191	4	16.5	8.89	89.3%	96.0%	33%	Core Summer
Coal Creek	47.97025	-124.58839	4	16.4	9.17	90.8%	96.8%	25%	Core Summer
Coleman Creek	47.11148	-120.39628	3	13.9	9.31	94.3%	102.1%	17%	Salmonid spawning
Couse Creek	46.1955	-116.99205	3	17.6	6.11	60.3%	75.5%	67%	Salmonid spawning
Crab Creek	47.2972	-118.2485	4	21.1	8.10	88.9%	107.4%	25%	Salmonid rearing & migration
Davis Creek	47.07544	-123.94098	6	13.7	9.50	91.7%	99.1%	18%	Core Summer
Dewatto Creek	47.46906	-123.02571	4	16.3	9.07	91.6%	94.7%	33%	Core Summer
Dry Creek	46.50559	-119.68559	1	21.0	1.80	20.7%	39.5%	100%	Salmonid spawning
Elk Creek	46.05538	-121.19845	1	10.9	9.40	91.3%	91.3%	100%	Core Summer

Site	Latitude	Longitude	# of Days	Maximum Temperature (°C)	Minimum DO (mg/L)	Minimum Oxygen Saturation	Average Oxygen Saturation	Percent of Measurements <95% Saturation	Aquatic Life Use
Hog Canyon Creek	47.36783	-117.81135	4	26.4	4.40	55.8%	66.6%	100%	Core Summer
Taneum Creek, North Fork	47.11458	-120.95882	6	16.5	8.81	95.0%	99.4%	10%	Core Summer
Oak Creek	46.72987	-120.87807	3	15.9	9.31	93.6%	98.9%	33%	Core Summer
Rock Creek	45.91896	-120.6271	1	15.3	8.30	88.8%	95.3%	50%	Core Summer
Schafer Creek	47.22396	-123.6134	4	15.8	8.99	90.1%	96.3%	29%	Core Summer
Seabeck Creek	47.62811	-122.83717	4	15.2	9.50	88.9%	93.8%	75%	Core Summer
Shadow Creek	47.09817	-120.87213	5	13.6	8.54	85.7%	95.8%	44%	Core Summer
Taneum Creek, South Fork	47.09394	-120.9969	4	11.0	8.92	90.5%	92.8%	100%	Core Summer
Tonata Creek	48.86945	-118.76824	5	11.6	9.44	93.1%	98.3%	20%	Core Summer
Wishkah River	47.150935	-123.75488	3	18.1	8.23	87.5%	98.3%	40%	Salmonid Spawning
Youngs Creek	47.80636	-121.82501	2	15.1	6.90	67.1%	76.9%	100%	Core Summer
Battle Creek	48.05936	-122.26612	4	18.6	8.50	86.9%	91.5%	83%	?
Dewatto Rvier	47.46906	-123.02571	2	16.1	8.90	88.0%	92.1%	100%	Core Summer
Tulalip Creek	48.07433	-122.28455	3	15.6	8.40	78.9%	82.8%	100%	?
Griffin Creek	47.60376	-121.88494	11	17.9	9.40	92.2%	100.9%	5%	Core Summer

Intragravel Dissolved Oxygen

We include an IGDO criterion of 8.0 mg/L in this rule, consistent with EPA's 1986 recommendations and Ecology's previous review of the scientific literature (Hicks, 2002). The IGDO criteria are a necessary alternate criteria based on data that indicates pristine waterbodies may not meet 90% oxygen saturation or 10 mg/L during summer months. The 10 mg/L water column criteria are based on the worst-case assumption that there is a 2.0 mg/L drop in DO levels from the water column to gravels.

However, the DO depression of 2.0 mg/L may be overestimated in some waterbodies, especially those with optimal substrate conditions. The IGDO criteria present an alternate method to demonstrate that early life stages of salmonids are being protecting by directly measuring DO levels in the small spaces in between gravels. Furthermore, the IGDO criteria rely on site-specific conditions and not on assumptions regarding DO depression values and the quality of substrate for a given waterbody. While direct IGDO levels may be more difficult to measure accurately, they may be the most relevant method to determine if early life stages of salmonids are protected.

IGDO conditions can vary spatially and temporally depending on the substrate conditions of a waterbody. Therefore, a single IGDO measurement would likely not be representative of a site-specific location or a waterbody (McNeil, 1962). We include a requirement that IGDO measures be collected over the same habitat area and a median spatial value be calculated for a given spawning area. The median spatial value for IGDO is similar to the approach taken by Oregon (Oregon Guidance for median spatial value[5]).

Also associated with the IGDO criteria is a water column criteria. The IGDO criteria requires that 8.0 mg/L or greater be met in gravels and 9.0 mg/L or greater be met in the water column. To clarify, the IGDO criteria must meet both the required gravel and water column concentrations. The water column criteria associated with the IGDO criteria is set to protect juvenile and adult life stages of salmonids and sensitive stages of invertebrates. In Hicks (2002) review, we identified that 9.0 mg/L as fully protective of juvenile life stages of salmonids and invertebrates. EPA recommends 8 mg/L as the "no production impairment" for juvenile and adult life stages of salmonids. We conclude that 9 mg/L water column value is appropriate for full protection of juvenile and adult salmonids and invertebrates.

Function of the dissolved oxygen criteria

The adopted changes to the biologically-based numeric criteria for DO and the addition of the oxygen saturation criteria are intended to work in tandem. In other words, the biologically-based numeric criteria of 10 mg/L for the water column and 8.0 mg/L for gravels for salmonid spawning and rearing uses should always accompany a DO saturation criterion. The primary reason for a two component criteria is that the biologically based numeric criteria are set to protect early life stages of salmonids. However, early life stages of salmonids are not present

[5] https://www.oregon.gov/deq/FilterDocs/iri-dataggr.pdf; Oregon calculated median spatial values of intragravel dissolved oxygen samples for data collected within 200 feet of each other along the same flow path.

year-round in the majority of waterbodies. The majority of salmonids are known to spawn and rear from fall to late spring, although spawn timing is waterbody and species specific. Therefore, protective levels aimed at early life stages may not be applicable during summer months when early life stages of salmonids are not present.

Rather than applying overly stringent criteria for aquatic life uses that are not present in the summer, the oxygen saturation criteria apply. Oxygen saturation accounts for summer-time temperatures effect on DO levels, and therefore, affords some protection against natural climatic changes that occur during the summer and that limit oxygen levels in water. Without the oxygen saturation component, most waters in Washington State would be considered impaired if only applying the biologically based numeric criteria. Therefore, we aim to set biologically based numeric criteria that protect early life stages of salmonids during the specific seasons and environmental conditions that are conducive to salmonid spawning and rearing, while including an oxygen saturation criteria to account for times when early life stages are not present and environmental conditions are a limiting factor. The biologically based and oxygen saturation components of the DO criteria must work in tandem for the criteria to function.

The oxygen saturation criteria also accounts for impacts of barometric pressure due to atmospheric conditions as well as altitude. Altitude can physically limit the ability of oxygen to dissolve in water (Figure 3). For example, an altitude of 500 feet at 17.5°C equates to a maximum oxygen solubility of 9.4 mg/L. At an altitude of 2000 feet at 17.5°C, the maximum solubility of DO is 8.9 mg/L. The maximum oxygen solubility at these high elevation areas with streams will preclude attainment of concentration based oxygen criteria. There are several high altitude streams in Washington that include salmonid spawning and where altitude would preclude the attainment of concentration-based criteria and only oxygen saturation criteria are applicable.

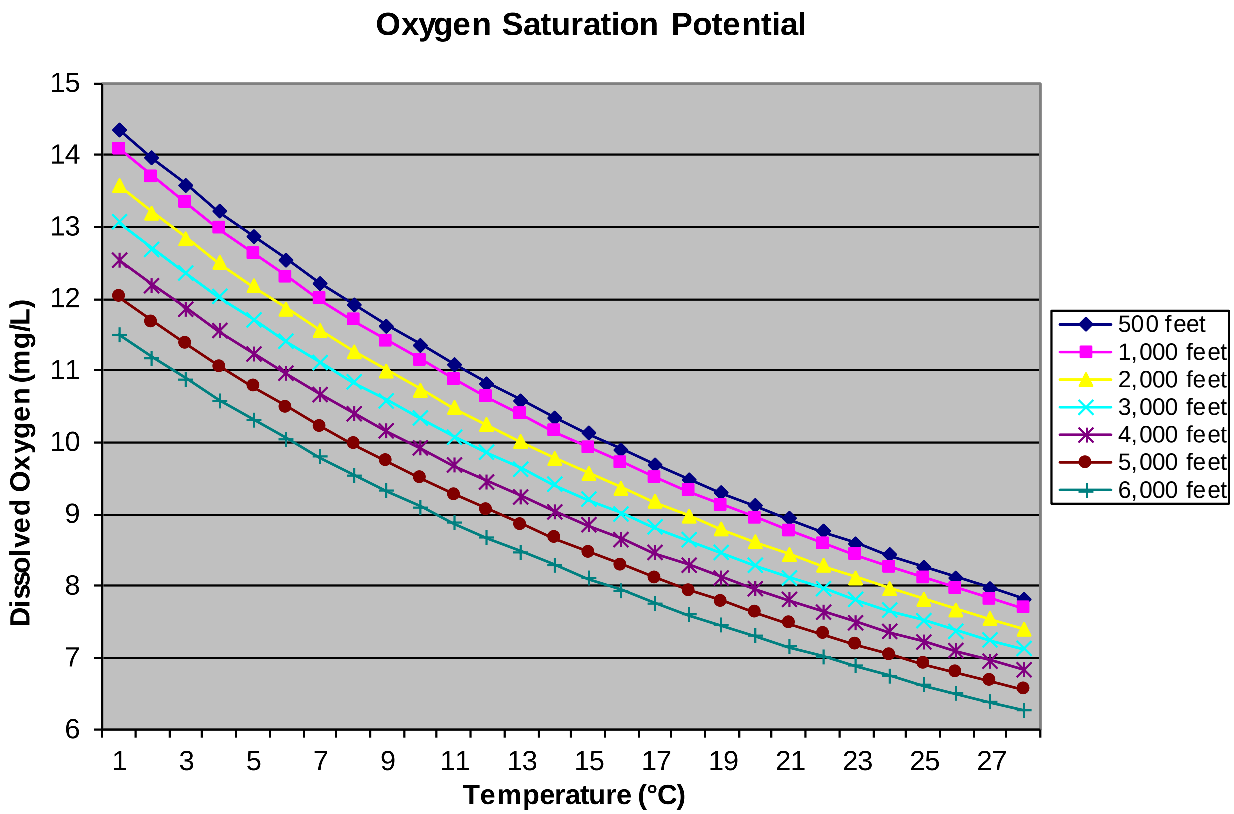

Figure 3. Relationship between dissolved oxygen concentration and altitude from 500 to 6,000 feet.

Fine Sediment Criteria Rule Development

Adopted criteria

We adopted narrative criteria for fine sediment. The proposed narrative criteri a is:

"Water bodies shall not contain excess fine sediment (<2 mm) from human-caused sources that impair designated uses. When reference values are used to demonstrate compliance with the fine sediment criteria, measured conditions shall be compared to those from reference sites or regional data that represent least disturbed site conditions of a comparable water body or ecoregion. Reference locations should be comparable in hydrograhy, geology, ecology, and habitat to that of the water body evaluated." Fine sediments will be defined at those sediments classified as fines or sands and are less than 2 mm in diameter. The proposed narrative criteria are accompanied with a draft guidance document that describes methodology for characterizing a fine sediment exceedance. The draft guidance document can found in Appendix A of the Implementation Plan[6] for this rulemaking.

Narrative vs. numeric criteria

Water quality criteria may be expressed narratively or numerically. We evaluated whether narrative or numeric criteria for fine sediment is most appropriate. We reviewed literature to determine if a quantitative relationship could be established between fine sediment-based parameters and a biological effect. Furthermore, we presented this question to a science advisory group comprised of experts in the field (see rulemaking webpage[7]). Through both of these avenues, we concluded that there are limited quantitative relationships established between parameters used to quantify fine sediment and biological endpoints. While some parameters,such as percent fines, indicate a threshold for the presence of successfully spawning salmonids, they do not represent all aspects that contribute to a fine sediment impairment, nor is a relationship established across the full spectrum of sublethal effects. A single numeric value cannot adequately describe a dynamic waterbody and the geological processes related to fine sediment inputs.

A more holistic understanding of the dynamics of a waterbody is needed to make the determination of a fine sediment impairment. Narrative criteria provide more flexibility to build in a procedure to characterize fine sediment that is based on multiple parameters and qualitative determinations (a weight of evidence approach, for example). For these reasons, we have decided narrative criteria for fine sediment is most appropriate.

Fine sediment sources

Waterbodies can vary drastically depending on the geology, hydrology, and watershed characteristics. Streams that are fed by glaciers will have defining characteristics that are

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[6] https://apps.ecology.wa.gov/publications/summarypages/2110049.html
[7] Ecology.wa.gov/SalmonHabitatRule

different from streams fed by groundwater. Fine sediment occurs naturally in some waterbodies while in other waterbodies, anthropogenic influences contribute to the amount of fine sediment present. Streams that contain excessive fine sediment often have a period of accelerated channel widening and streambank erosion before returning to a stable form (Rosgen 1996).

The impacts of morphological and streambed changes in a waterbody can be evaluated to determine if excessive fine sediment exists compared to reference conditions. In some waterbodies, there are both naturally occurring and anthropogenic inputs of fine sediment. The purpose of this rulemaking is to evaluate and limit anthropogenic sources of fine sediment that may adversely affect early life stages of salmonids and result in a waterbody impairment. To determine a fine sediment impairment there must be a demonstration that sources of sediment are related to anthropogenic inputs. Naturally occurring sources of sediment will not result in a fine sediment impairment.

When evaluating human disturbance, a randomized design is not appropriate due to the desire to seek out specific anthropogenic sources of fine sediment inputs into waterbodies. A random sampling design would not capture all sources of fine sediment inputs because evaluation would only be directed at particular assessment sites. Thus, we propose to use field and metric calculation methods, as opposed to the randomized design, from Ecology's Watershed Health Monitoring program that assesses human riparian disturbance.

Water column measures considered

We considered water column measures for characterizing fine sediment in the water column. Water column measures address the conveyance of fine or light materials in a waterbody. During the building of salmonid nests, fine materials are often removed during the excavation of gravels and the covering of embryos with gravels. However, the water column can transport and deposit fine materials that can fill the interstitial spaces of gravels and limit the flow of DO to early life stages of salmonids in the gravels. We are seeking a method to characterize the water column of waterbodies to limit the flow of fine materials that could affect early life stages of salmonids.

We evaluated the following streambed measures:

- Light penetration,
- Turbidity,
- Total suspended solids, and
- Suspended solids concentration.

Light Penetration

Light penetration measures the attenuation of light as it moves through the water column. Each waterbody has unique characteristics that result in different water clarity that vary both temporally and spatially. EPA recommendations for light penetration standards in the 1986 EPA Gold Book are as follows: "settleable and suspended solids should not reduce the depth of compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life" (EPA, 1986).

Suspended materials in the water column can originate from both inorganic and organic materials and can consist of materials of many different shapes and sizes. Natural detritus (such as leaf matter, decomposing algae, and decomposing aquatic life) has a significant presence in many waterbodies and may affect light penetration. Limitations in light penetration can reduce primary production that form the basis of fish diets (EPA, 1986), but is not specific to fine materials that penetrate interstitial spaces of gravels. Each waterbody differs in the amount of natural detritus and suspended sediment. Effectively implementing a light penetration standard requires background data to determine if light penetration has changed over time. We are not recommending a light penetration standard for fine sediment characterization because light penetration does not specifically focus on fine materials suspended in the water column. The natural variability in light penetration and the number of factors contributing to light penetration makes this an inadequate measure of fine sediment. Light penetration does not specifically address the goal of this rulemaking to characterize fine sediment materials.

Turbidity

Turbidity can be described the "haziness" or "cloudiness" of water and refers to the light scattering properties of a sample. Turbidity is a reduction in water clarity because of the presence of suspended matter comprised of inorganic or organic materials. Inorganic materials included in turbidity measurements are comprised of fines less than 2 mm (APHA et al. 1995). Organic materials can include leaf matter, decomposing algae, and decomposing aquatic life.

Relationships between turbidity levels and biological effects have been established (Robertson et al. 2007; Hansen et al. 2013). Inorganic materials can result in physiological effects to fish and macroinvertebrates (Wood and Armitrage, 1997). Organic suspended materials have been known to contribute to sediment oxygen demand that may have an impact on early life stages of salmonids (Sear et al. 2017). Effects from turbidity are dependent on the concentration and, equally important, the duration of exposure.

While controlling turbidity in a waterbody is useful for limiting impacts of suspended materials to aquatic life, it does not specifically target fine sediments. Natural detritus (such as leaf matter, decomposing algae, and decomposing aquatic life) has a significant presence in many waterbodies and may affect turbidity. Turbidity levels are not directly related to fine sediment particles that may influence oxygen levels in gravels. Therefore, we are not recommending using Washington's current turbidity standards in the assessment of fine sediment.

Total Suspended Solids and Suspended Solids Concentration

Total suspended solids (TSS) and suspended solids concentration (SSC) are measures aimed at quantifying the solid-phase material in surface waters. SSC includes inorganic sand, silt, and clay particles transported in waterbodies. SSC measures all the sediment and mass of a sample, whereas TSS measures a portion of the original sample for which some of the denser materials such as sand may not be included. TSS, turbidity, and optical backscatter instruments are often used as a surrogate for SSC.

TSS has been shown to be an unreliable measure of solid-phase material in natural water samples with sand-size material (Gray et al. 2000). The work of Gray et al. (2000) and Glysson et al. (2000) demonstrated inconsistent relationships between SSC and surrogate measures that may lead to erroneous data. However, on site-specific levels, Glysson et al. (2000) suggested that it may be possible to develop a relation between SSC and TSS with robust paired sampling data over a range of flows.

Measuring SSC can produce reliable results regardless of the amount of sand-size material (Gray et al. 2000). TSS measures were originally designed for wastewater discharge analyses and later used for natural waters (Gray et al. 2000). Gray et al. (2000) recommended that TSS and SSC not be used interchangeably and that the accuracy of suspended solid-phase materials in natural waters is best evaluated using SSC. Given that fine sediment levels will be evaluated in natural waters and that sand-size materials are the target, ***we recommend that the SSC measure be used as an optional representative measure of water column concentrations of fine sediment.***

Given that the content of the water column, specifically suspended sediment particles, can vary drastically with water flow, guidance on sample collection will be necessary to ensure representative measurements are evaluated under average flow conditions.

Streambed measures considered

Streambed measures of fine sediment focus on the content on the streambed as it relates to suitability of substrate for salmonid spawning and the stability of the substrate. Streambed measures relate directly to the physical structure of salmonid nests and habitat and may be the most pertinent measures related to successful spawning and development of early life stages of salmonids. Most states that have guidance on characterizing fine sediment include at least one streambed measure.

We evaluated the following streambed measures:

- Percent surface substrate
- Percent subsurface sediment
- Embeddedness
- Riffle stability index
- Relative bed stability

Percent Surface Substrate (Visual)

Measuring the size and composition of streambed substrate is integral to determining if suitable salmonid habitat exists. Generally, and in EPA's National Rivers and Streams surveys, substrate can be classified by:

- bedrock (>4 m)
- pavement/concrete (>4 m)
- hardpan (>4 m)
- large boulders (>1 to 4 m)
- small boulders (250 to 1000 mm)
- cobble (64 to 250 mm)
- coarse gravel (16 to 64 mm)
- fine gravel (2 to 16 mm)

- sand (0.06 to 2 mm)
- fines (≤0.06 mm)

Researchers do not have a standardized definition for the size of "fine sediment." Reported "fine sediment" sizes include less than 0.833 mm, 0.85 mm, 1 mm, 2 mm, 3.3 mm, 6 mm, and 6.35 mm (McNeil and Ahnell, 1964; Tagart 1976; Lisle and Eads, 1991; Koski, 1981; Weaver and Fraley, 1993; Bjornn et al. 1977; Kondolf et al. 1993). Anadromous salmon and trout prefer substrate size ranging from 13 to 102 mm in diameter for spawning (Bell, 1986). Salmon have been observed spawning in gravels larger than 30 mm and in most observations, the substrate is less than 150 mm (Shepherd et al. 1986). Analysis of substrate size and composition is necessary to characterize if salmonids will successfully spawn and develop during early life stages.

Stream substrate with minimal fine sediment filling the interstitial spaces provides optimum habitat for salmonid spawning. Chapman and McLeod (1987) found that substrate size is related to habitat suitability for fish and macroinvertebrates and that excessive fine sediment reduced prey availability for fish. Excessive fine sediment results in substrate being inundated by fine sediment resulting in decreased intragravel oxygen that can lead to the elimination of the quantity and quality habitat for aquatic life (Maret et al. 1993; Waters 1995).

A quantitative relationship between the amount of fine sediment and survival to emergence is not well understood. However, some studies have suggested thresholds beyond which early life stages of salmonids do not survive. Stowell et al. (1983) found that fine sediments are harmful when sizes are less than 6.4 mm and that adverse effects occur when 20% of sediments are less than 0.84 mm. Bjorn (1969) and McCuddin (1977) concluded that survival and emergence of steelhead were reduced with sediments less than 6.4 mm diameter made up 20-25% or more of substrate. In laboratory studies of Chinook salmon and steelhead, emergence was significantly affected when the percentage of fine sediments exceeded 30-40% (Phillips et al. 1975; Hausle and Coble, 1976; McCuddin, 1977). In an analysis of 15 measures in laboratory studies that evaluated survival to emergence of cutthroat trout, the percentage of substrate less than 0.85 mm was the most sensitive measure of known changes in substrate compositions in the field (Young et al. 1991).

When salmonids excavate their nests, fine sediment and organic matter are removed from the pocket where eggs are deposited (McNeil and Ahnell 1964; Ringler 1970; Everest et al. 1987). Sources of fine sediment in newly constructed redds can originate from upstream deposition of streambed materials or suspended sediments in the water column. The amount of fine sediment deposited is dependent on substrate size in the redd, power of the water flow, and the mobility of sediment transported in the waterbody (Cooper 1965; Beschta and Jackson 1979). Decreases in the mean particle size and increases in quantity of streambed fine sediments can destabilize stream channels (Wilcock 1997;Wilcock, 1998) and may indicate increases in the rates of upland erosion and sediment supply (Lisle 1982, Dietrich et al. 1989).

The Forest Service and Bureau of Land Management for the Upper Columbia River established levels for surface fine sediment (< 6 mm) for channel and geologic type that ranged from 14 to 37%, depending on conditions (Interior Columbia Basin Ecosystem Management Project, 1997). The State of New Mexico has established thresholds for surface sediment that fully support aquatic life uses at less than 20% fines (< 2 mm). Above 20% fines, site-specific conditions should be compared to reference sites (NMED, 2002).

Literature has demonstrated that percent substrate, particularly percent fines, can be a useful metric to determine the quality of salmonid spawning habitat and provide valuable information in determining a fine sediment impairment (Larson et al. 2019; Sutherland et al. 2010; Bjornn and Reiser, 1991). Furthermore, Ecology uses percent of bankfull bed surface substrate, including percent fines, as metrics in our Watershed Health Monitoring program. This program evaluates the health of the state's rivers and streams. They also assess river/stream conditions for seven Salmon Recovery Regions in support of the biennial State of the Salmon Reports.

The Watershed Health Monitoring program has been collecting information pertaining to fine sediment, particular percent substrate, for over a decade, and has an existing public database that can provide information from various projects that use their habitat methods. The database includes data on minimally disturbed reference sites, including annually-sampled sentinel sites. The database also reports biological community data and chemical stressor data, all collected concurrently with the habitat data.

We recommend percent substrate, specifically percent sand and fines (<0.06mm to < 2 mm), be included as one of the measures to characterize fine sediment.

Percent Subsurface Sediment

Percent subsurface sediment composition is another measure considered to evaluate fine sediment. Kondolf (2000) found that salmonid redds typically have one third less fine sediment than the surrounding streambed surface throughout the incubation period. Relationships between survival of early life stages of salmonids and subsurface fines have been studied. Hall (1986) reported 7-10% survival of salmon in gravel mixtures made up to 10% fines that measure less than 0.85 mm, compared with 50-75% survival in gravels with no fines that measure less than 0.85 mm. Reiser and White (1988) examined the effects of different mixtures of sediment on salmonid survival and found poor survival at 10-20% fines that measure less than 0.84 mm.

Platts and Nelson (1988) recommended tiers of subsurface sediments in relation to quality of habitat for embryo incubation. When subsurface fines (less than 6.3 mm) were less than 20%, conditions were considered good for incubation and survival. At 20 to 27%, there was marginal impacts to survivability, and greater than 27% subsurface fines, survival was predicted to be low. Burton et al. (1990) set a target at 27% for subsurface fines (less than 6.5 mm) in Idaho. California has set targets for subsurface sediments smaller than 0.85 mm to be less than 14% of substrate composition, and less than 30% for sediments smaller than 6.4 mm in spawning areas in waterbodies with approved TMDLs. The thresholds set are intended to account for the cleaning effect that spawning has on fine sediments and include the expectation of 50% survival, which is considered within the normal survival range (Maret et al. 2003). The state of Idaho recommends that particles less than 6.35 mm account for no more than 27% of subsurface sediment and that fines less than 0.85 mm not exceed 10% of subsurface sediment.

Sutherland et al. (2010) evaluated the relationship between land disturbance and stream habitat for 25 commonly used sediment parameters and found subsurface percent fines as the best indicator of land use.

In the state of Washington, salmonid spawning and rearing occurs in most waterbodies and the timing of spawning and rearing is different depending on location. If subsurface sediments can be sampled at periods that will not interfere with early life stages of salmonids, then it is appropriate to evaluate subsurface sediments in the characterization of fine sediments. However, we have concerns regarding the invasiveness of core sediment sampling and the potential disturbances to early life stages of salmonids. Furthermore, the analysis of subsurface sediment can be laborious on a large scale and may be better used to evaluate specific sites rather than waterbodies or waterbody segments.

We recommend that subsurface fines be assessed (0.06 to < 2 mm and <0.06 mm). However, sampling protocols should be limited to periods when salmonid spawning and rearing is not occurring or ensure that areas assessed are absent of early life stages of salmonids. If subsurface fines cannot be collected, measurement of IGDO may be substituted. This is consistent with the requirement to collect IGDO or percent subsurface fines to assess subsurface conditions in streambeds.

Embeddedness

Excess fine sediment can change the physical composition and structure of salmonid spawning habitat. Embeddedness is a measure of the amount of silt and sediment deposited in and around the larger gravel, cobble, and boulders in the streambed. Embedded substrate suggests that fine sediments that had been suspended in the water column were deposited in the streambed.

Documented relationships between embeddedness and effects to salmonid spawning and early life stages of salmonids are limited. Chapman and McLeod (1987) were unable to generalize different levels of embeddedness of surface fines and salmonid rearing densities. One of the inadequacies of using embeddedness to characterize fine sediment is the number of various methods used to measure embeddedness and the degree of subjectivity from each observer. Embeddedness includes naked eye estimation of surface fines surrounding larger substrates and the inundation of spaces between substrate.

New Mexico has established thresholds for embeddedness levels for aquatic life. Streambeds that are less than 33% embedded are considered fully supporting aquatic life under all conditions. For waterbodies with embeddedness levels greater than 33%, reference conditions are used to evaluate aquatic life health (NMED, 2002).

Ecology uses embeddedness as a measure in our Watershed Monitoring Program. The Watershed Monitoring Program has been collecting embeddedness levels for several years, and has an existing database that can provide information on sentinel sites and background information for many waterbodies. Embeddedness is useful for evaluating trends over time in specific waterbodies or at specific sites but is inadequate in determining if a waterbody is impaired for fine sediment due to subjectivity of the measurement and the lack of biological relationships with different degrees of embedded substrate. Furthermore, embeddedness is similar to percent substrate and requiring both parameters would result in concerns regarding covariance or the influence that one parameter has on another.

We are not recommending embeddedness as a measure for determining fine sediment impairments in Washington.

Riffle Stability Index

Riffle Stability Index (RSI) is an index used to measure the mobile percentage of particles in a stream. RSI is measured as a percentage of substrate particles (from a Wolman pebble count) that are smaller than the largest particles transported during channel forming flows. The largest mobile particles are determined by measuring particles on the inside bend of a river or stream (referred to as a point bar).

Riffle stability is important in the assessment of fine sediments because as riffle stability degrades, pool habitat decreases (Lisle 1982). Pools are critical habitat for salmonids (Spangler 1997;, Harwood et al. 2002; Kruzic et al. 2001l Jakober et al. 2000; Solazzi et al. 2000). Benthic macroinvertebrate density and composition may also be related to substrate mobility that can be characterized by RSI (Kappesser 1993). Cobb et al. (1992) reported reductions in insect density up to 94% in unstable riffles compared with no reduction in stable riffles.

There is limited information regarding thresholds for RSI. One approach may be to compare RSI to reference conditions within the same watershed with similar geological characteristics. The state of Idaho recommends the RSI not to exceed 70 based on data that suggests that an RSI less than 70 indicates systems are in dynamic equilibrium (Kappesser 1993).

We are not recommending using RSI as a measure to characterize fine sediment. RSI is limited to assessment of riffles and may not comprehensively represent a catchment scale analysis or widespread analysis of the surrounding area of fine sediment inputs into a waterbody. Furthermore, Ecology does not have data for RSI in Washington streams as it does for similar metrics, such as relative bed stability. Relative bed stability is measured as part of Ecology's Watershed Monitoring Program and is useful for providing a catchment scale analysis of sediment dynamics within a waterbody.

Relative Bed Stability

Relative bed stability (RBS) is a measure of the relationship of median particle size in a stream reach compared to the critical particle size, which is the particle size that is moved at bankfull flow events (Peck et al. 2006). Critical particle size is calculated from channel dimensions, flow characteristics, and channel roughness factors (Kaufmann et al. 2008). RBS is expressed as a logarithm of the ratio of geometric mean to critical particle size. RBS is similar to the Riffle Stability Index of Kappesser (1993) and the metric discussed by Dietrich et al. (1989) of median diameters of the substrate armor layer divided by the substrate beneath that layer (called the bedload).

Logarithmic RBS (LRBS) was developed by EPA as a measure to provide information on expected substrate size distribution. Fluvial site conditions can be used to determine substrate conditions in stream channels. The critical particle size calculated from fluvial characteristics such as stream channel, shape, slope, flow, and sediment supply, is used to predict the stability of the streambed. The sediment conditions relative to fluvial potential represents a more holistic and catchment level approach of sediment stability under natural conditions rather than direct measures of site-specific fine sediment levels that may not be representative of sediment dynamics within the entire waterbody. Excess fine sediment can destabilize streambeds when the supply of sediments from the landscape exceeds the ability for the stream to move particles downstream. The main human activities that can influence this imbalance include agriculture, road building, construction, and grazing. Low stream stability may be the result of high inputs of fine sediment from erosion or increases in flood magnitude or frequency that result in poor ecological conditions (Bryce et al. 2008; Bryce et al. 2010).

In undisturbed streams or streams within minimal anthropogenic influences, the geometric mean particle size should be similar to the critical particle size (the particle size that is moved at bankfull flow events). A LRBS value near or at zero indicates a stable streambed, while increasingly negative values indicates excess fine sediment. A LRBS value of negative one would mean that the geometric mean particle size is ten times finer than the critical particle size. A LRBS of negative two would mean that particle size is 100 times finer than the critical particle size. A large positive LRBS value indicates a stable, immovable stream substrate where sediment supply is low relative to the ability of the stream to transport sediment downstream. Exceptionally stable streams can also be a condition of ecology stress, where hard, armored streambeds limit the movement of fine sediment.

The ratio of geometric mean particle size and critical particle size (RBS ratio) also provides information on the supply of sediment to the stream channel. Buffington (1998) suggested that streambed substrate size is inversely related to sediment supply because sediment supplies that exceed local sediment transport capacity reduces the bed-surface substrate size through the deposition of fine particles. The RBS ratio can therefore be an indicator of sediment supply. Natural erosion rates dependent upon climate, basin geology, geomorphology, channel position, natural landslides, and features of the headwaters may influence RBS. Relatively undisturbed watersheds should tend to RBS values typical to the region and landscape that it drains and thus, even in a natural disturbance regime, such as landslides or channel erosion, sediment supply should be roughly in long-term equilibrium with transport (Kaufmann et al. 1999).

We recommend that LRBS be used as a measure to characterize fine sediment in a waterbody. LRBS is currently measured in Ecology's Watershed Monitoring Program and is a measure that has been vetted by EPA and the State of Washington for use in monitoring stream health and fine sediment.

Chemical measures considered

Intragravel dissolved oxygen

IGDO is a direct measure of oxygen content in subsurface sediments where early life stages of salmonids reside. Intragravel oxygen levels accounts for several factors that contribute to oxygen levels in subsurface sediments such as substrate size, permeability, biological and sediment oxygen demand, water flow, hyporheic conditions, and groundwater influences. Whether water flow is originating from the overlying water column or from groundwater can make significant impacts on oxygen levels in gravels. Groundwater can be severely limited in oxygen resulting in poor embryo survival, while sites dominated by surface water have higher embryo survival (Malcolm et al. 2004).

Research has suggested that early life stages of salmonids require IGDO levels of 8.0 mg/L (Hicks, 2002; EPA, 1986). Relationships between IGDO and survival of early life stages of salmonids have been observed in steelhead (Coble 1961) and brown trout (Maret et al. 2003). Philips and Campbell (1961) found that an IGDO level of 8 mg/L was necessary to support high survival of coho and steelhead. Wells and McNeil (1970) reported that embryo survival to emergence was greater in gravels with oxygen levels of 7.8 mg/L (77% survival) versus 5.9 and 5.4 mg/L (30% survival). Koski (1975) and ODEQ (1995) found that survival of embryos were substantially lower when IGDO levels were less than 6 mg/L. Similarly, Sowden and Power (1985) reported negligible rainbow trout survival until mean oxygen concentrations exceeded 5.2 mg/L in redds and that oxygen concentrations in gravels should exceed 8 mg/L to ensure 50% survival before early life stages emerge from gravels.

IGDO measurements provide a key piece of information regarding oxygen levels in gravels. However, IGDO measures are very specific to the site of interest. IGDO is known to have high spatial variability (Heywood and Walling, 2007). To understand DO levels in gravels, sampling will need to involve a spatial analysis of IGDO concentration over a given area or transect. Furthermore, IGDO measures are intrusive in that they disturb the sediment and may potentially have adverse effects on early life stages of salmonids if they are present. Sampling for IGDO may need to occur outside of salmonid spawning periods and near visible spawning sites rather than inside the redd itself. Sampling should also be focused on sites that represent suitable spawning habitat rather than areas where salmonids are unlikely to spawn and rear.

Early life stages of salmonids are not present in all water bodies year-round. Therefore, an evaluation of IGDO concentration is less relevant than DO depression during the summer field sampling season. DO depression is measured by determining the differential in DO concentrations between the water column and gravels. In our analysis of moderate to high quality spawning gravels, the IGDO depression is limited to a maximum of 2 mg/L.

We recommend that IGDO depression value measurements be taken, if and when, there is little risk of effects on early life stages of salmonids. If IGDO measurements are deemed not appropriate, subsurface measures of fines may be substituted. This is consistent with the requirement to collect IGDO or percent subsurface fines to assess subsurface conditions in streambeds.

Biological measures considered

Benthic indexes

Aquatic benthic macroinvertebrate community composition indexes, based on species relative abundances, are often used to estimate the health of a waterbody and can be a reflection of the physical and chemical conditions. Some macroinvertebrate species are more tolerant to pollutants and habitat alteration than other species. The sensitivity or tolerance of invertebrate taxa provide the foundation for evaluating stream conditions. Excessive fine sediment is known to have negative impacts on the benthic macroinvertebrate community by filling interstitial spaces between cobbles and gravels, leading to a reduction in macroinvertebrate habitat (Wohl, 2000). Waters (1995) concludes that the abundance of invertebrate taxa is dependent on substrate particle size. Reductions in substrate particle size reduces the abundance of invertebrates that do not tolerate small sediments by reducing habitat, which ultimately results in disruptions in feeding strategies and behavior. The percentage of fine sediment, the concentration of suspended sediment, and the duration of exposure are primary factors that determine the integrity of the benthic macroinvertebrate community (Culp et al. 1986; Doeg and Milledge 1991; Newcombe and MacDonald 1991).

Benthic macroinvertebrate indexes have been developed to evaluate the impacts of pollution on aquatic life health. Macroinvertebrate community response metrics can be used to develop biologically-based sediment criteria that evaluates excessive fine sediments in a waterbody (Relyea et al. 2000; Carlisle et al. 2007; Bryce et al. 2010; Relyea et al. 2012; Extence et al. 2013). Waters (1995) has suggested that changes in macroinvertebrate density may be one of the most sensitive indicators to sedimentation changes in streams. More recently, focus has been on methods to characterize sediment impacts based on assigned sensitivity of individual taxa to sediment (Carlisle et al. 2007; Relyea et al. 2012; Extence et al. 2013).

The Watershed Health Monitoring program at Ecology currently monitors benthic macroinvertebrates in streams throughout Washington State. Data collected are used to calculate the Benthic Index of Biotic Integrity (B-IBI), Hilsenhoff Biotic Tolerance index, Metals Tolerance Index, and the Fine Sediment Biotic Index (FSBI). The Fine Sediment Biotic Index is a diagnostic metric used to identify samples with a high degree of taxa sensitive to fine sediment (particles less than 2 mm) and is perhaps the most pertinent macroinvertebrate index for the characterization of impacts of fine sediment in waterbodies (Relyea et al. 2012).

Benthic macroinvertebrates are considered sentinel species for waterbody health and should be included in an assessment of fine sediment. ***We recommended that the fine sediment biotic index be used as one of the lines of evidence for the determination of fine sediment impairment.***

Summary of Recommended Parameters

The selected parameters used for the assessment of fine sediment (particles less than 2 mm) are based on their relationship with the biological health of streams, land use, representation of the sediment condition, established sampling methods, and predictability in determining a waterbody impairment. Ecology's Environmental Assessment Program monitors the biological health in perennial streams in Washington State. Larson et al. (2019) evaluated 346 sites in Washington and classified their biological health by comparing against regional reference conditions. Larson et al. (2019) reported that, in Washington, percent sand/fines (sediment less than 2 mm) was the stressor metric with the highest attributable risk to invertebrate community health, followed by LRBS.

Sutherland et al. (2010) evaluated the relationship between land disturbance and stream habitat by comparing 25 commonly used sediment parameters. They found that 16 metrics significantly related to watershed agriculture, with subsurface percent fines as the best indicator of land use, while visual assessments of percent fines was the second best parameter. Sutherland et al. (2010) concludes that this information may improve the ability to predict deposited sediment by considering land use, specifically as it relates to human activities. We are recommending parameters that are representative of the streambed condition, water chemistry, and biology and have been shown as the best measures of fine sediment as it related to stream and aquatic life health (Table 8).

Table 8. Summary of parameters considered most appropriate for analyzing fine sediment.

Environmental Compartment	**Measure**
Water Column	Suspended Solids
Streambed	Percent Substrate
Streambed	Subsurface Fines
Streambed	Relative Bed Stability
Chemical	Intragravel Dissolved Oxygen Depression
Biological	Fine Sediment Biotic Index

Conclusions

The proposed DO criteria represents an increase in early life stage protection levels for salmonids while affording flexibility for natural conditions of waterbodies that vary in elevation and temperature. The literature supports protection levels of 8.0 mg/L in the small spaces between gravels. We have therefore included IGDO criteria for aquatic life uses to allow for direct measurement of DO conditions in streambeds. The DO depression from the water column to gravels is known to vary significantly due to environmental variables. In evaluating literature of DO depression in the absence of outlying variables, a maximum of 2.0 mg/L depression was found. The outlying variables that can influence DO depression should be addressed using other water quality criteria. The oxygen saturation criteria developed is used in conjunction with water column and Intragravel criteria to account for natural variables, such as temperature and elevation, that can affect DO levels in a waterbody. The combination of these three measures allow for a comprehensive criteria that addresses protection needs for salmonids.

One of the variables known to influence DO levels in the interstitial spaces of gravels is fine sediment. We have evaluated a series of parameters that have or can be used to characterize fine sediment. The parameters we selected to evaluate fine sediment were found to have the strongest relationship between biological effects, habitat condition, and sediment quality and represent different compartments of a waterbody (such as the water column, streambed surface, subsurface, and water chemistry). The information provided herein will be used to develop a methodology that will be used to characterize fine sediment and develop impairment listings.

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