

**Listing Methodology
for Determining Water Quality Impairments
from Turbidity**

GUIDANCE

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Alaska Department of Environmental Conservation
Division of Water

Listing Methodology for Determining Water Quality Impairments from Turbidity

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Acronyms

18 AAC 70	Title 18, Chapter 70 of the Alaska Administrative Code
CALM	Consolidated Assessment and Listing Methodology
CFD	concentration frequency distribution
DEC	Alaska Department of Environmental Conservation
CWA	Clean Water Act
EPA	U.S. Environmental Protection Agency
LCL	Lower Confidence Limit
NTU	nephelometric turbidity units
ODEQ	Oregon Department of Environmental Quality
PUF	Public Use Facility
QAPP	quality assurance project plan
TMDL	total maximum daily load

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TSS	total suspended solids
UCL	Upper Confidence Limit
WQS	Water Quality Standards

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1 Purpose and Background

This listing methodology is intended to be used by Alaska Department of Environmental Conservation (DEC) staff as guidance for listing or delisting a waterbody under the Clean Water Act (CWA) §303(d) as impaired from turbidity. The methodology presents the applicable regulations as adopted in the Alaska Water Quality Standards (WQS) in Title 18, Chapter 70 of the Alaska Administrative Code (18 AAC 70) and includes information on the quantity and characteristics of data needed to be deemed sufficient and credible for these decisions. The goals of the methodology are to provide direction on:

- How to evaluate turbidity data sets.
- How to determine if a waterbody is impaired or attaining water quality standards.

This methodology applies primarily to evaluating turbidity in rivers and streams, but may also be adapted to lakes and marine waters on a case-by-case basis.

Elevated turbidity can effect multiple uses. The most stringent criteria protect the Water Supply – drinking, culinary, and food processing use and the Water Recreation – contact recreation use. High turbidity in drinking water or recreational waters can shield bacteria or other pathogens so that chlorine or other treatment cannot disinfect the water as effectively. Some organisms found in water with high turbidity can cause symptoms such as nausea, cramps, and headaches. Besides affecting water quality, many common contaminants that increase turbidity can also change the taste and odors of the water. Water that has high turbidity may cause staining or even clog pipes over time. It may also foul laundry and interfere with the proper function of your dishwasher, hot water heater, showerheads, etc.

Turbidity can also result in numerous effects on the growth and propagation of aquatic life. Scientific literature indicates that chronic and low levels of turbidity are correlated with adverse effects of aquatic life (e.g., phytoplankton and invertebrates), and that effects may cascade to higher trophic levels leading to reductions in fish populations. Small increases in turbidity can also directly affect fish behavior, e.g. reactive distance, affecting growth and/or survival. In *Turbidity as a Water Quality Standard for Salmonid Habitats in Alaska* (Lloyd 1987), Denby Lloyd stated:

“On the basis of current information, the continued application of Alaska’s present water quality standard for the propagation of fish and wildlife (25 NTUs above natural conditions in stream and 5 NTUs in lakes) can be expected to provide a moderate level of protection for clear cold water habitats. A higher level of protection would require a more restrictive turbidity standard, perhaps similar to the one currently applied to drinking water in Alaska (5 NTUs above natural conditions in streams and lakes). Even stricter limits may be warranted to protect extremely clear waters, due to the dramatic initial impact of turbidity on light penetration. However such stringent limits do not appear to be necessary to protect naturally turbid systems where it may be possible to establish tiered or graded standards based on ambient water quality.”

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The sensitivity of aquatic life in clear water systems is also confirmed by more recent scientific studies (ODEQ, 2015).

Appendix A provides a summary of effects of increased turbidity at various durations of exposure to elevated turbidity. Some effects of turbidity on aquatic life can occur at durations as short as one hour or less. Other direct adverse effects on fish are reported when elevated turbidity levels last two to three weeks (ODEQ 2014).

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2 Parameter-Specific Criteria

The turbidity criteria are specified in WQS in 18 AAC 70.020(b)(12) and (24). The turbidity criteria are as follows:

Table 2.1. Turbidity criteria for fresh water uses

(12) TURBIDITY, FOR FRESH WATER USES (criteria are not applicable to groundwater)	
(A) Water Supply (i) drinking, culinary, and food processing	May not exceed 5 nephelometric turbidity units (NTU) above natural conditions when the natural turbidity is 50 NTU or less, and may not have more than 10% increase in turbidity when the natural turbidity is more than 50 NTU, not to exceed a maximum increase of 25 NTU.
(A) Water Supply (ii) agriculture, including irrigation and stock watering	May not cause detrimental effects on indicated use.
(A) Water Supply (iii) aquaculture	May not exceed 25 NTU above natural conditions. For all lake waters, may not exceed 5 NTU above natural conditions.
(A) Water Supply (iv) industrial	May not cause detrimental effects on established water supply treatment levels.
(B) Water Recreation (i) contact recreation	May not exceed 5 NTU above natural conditions when the natural turbidity is 50 NTU or less, and may not have more than 10% increase in turbidity when the natural turbidity is more than 50 NTU, not to exceed a maximum increase of 15 NTU. May not exceed 5 NTU above natural turbidity for all lake waters.
(B) Water Recreation (ii) secondary recreation	May not exceed 10 NTU above natural conditions when natural turbidity is 50 NTU or less, and may not have more than 20% increase in turbidity when the natural turbidity is greater than 50 NTU, not to exceed a maximum increase of 15 NTU. For all lake waters, turbidity may not exceed 5 NTU above natural turbidity.
(C) Growth and Propagation of Fish, Shellfish, Other Aquatic Life, and Wildlife	Same as (12)(A)(iii).

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Table 2.2. Turbidity criteria for marine water uses

(24) TURBIDITY, FOR MARINE WATER USES	
(A) Water Supply (i) aquaculture	May not exceed 25 nephelometric turbidity units (NTU).
(A) Water Supply (ii) seafood processing	May not interfere with disinfection.
(A) Water Supply (iii) industrial	May not cause detrimental effects on established levels of water supply treatment.
(B) Water Recreation (i) contact recreation	Same as (24)(A)(i).
(B) Water Recreation (ii) secondary recreation	Same as (24)(A)(i).
(C) Growth and Propagation of Fish, Shellfish, Other Aquatic Life, and Wildlife	May not reduce the depth of the compensation point for photosynthetic activity by more than 10%. May not reduce the maximum secchi disk depth by more than 10%.
(D) Harvesting for Consumption of Raw Mollusks or Other Raw Aquatic Life	Same as (24)(C).

Establishing Natural Conditions for Fresh Water Uses

The term “above natural conditions” is included in the criteria narrative for five of the seven fresh water uses protected from turbidity. Turbidity data should not be considered in any fresh water impairment determination without an established natural conditions evaluation for comparison. The most recent guidance and tools in determining the natural conditions should be used (DEC 2006). The Quality Assurance Project Plan (QAPP)/Sampling Plan should describe the criteria used to select the natural conditions site including factors such as flow time between natural and impacted sites, influence of tributaries in the waterbody segment assessed, and rationale for monitoring approach (continuous versus grab sampling).

Alaska recognizes that variability in turbidity—among sites and over time—complicates the task of determining a natural conditions level. Many of Alaska’s waters have naturally occurring turbid flows, especially glacially fed or tidally influenced waters, and care must be taken to effectively

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characterize the natural conditions in a scientifically defensible way to establish numeric turbidity criteria.

Sampling approaches to characterize natural conditions include:

- Upstream/downstream: Paired data measurements are taken concurrently in the water at upstream (natural conditions) and downstream (impacted from a particular pollutant source) sites. The upstream site to establish the natural conditions should be above any anthropogenic point or nonpoint sources of turbidity and should have similar stream geomorphology. Concurrent comparisons of values (natural conditions and impacted sites) may be difficult especially when grab samples are used. Samples from the natural conditions site and impacted sites may be collected several hours apart, but should occur within a reasonable period of time, e.g. no more than one day of flow time between upstream and downstream sites to be considered concurrent. **This is the preferred approach.**
- Paired watershed: a nearby water with similar hydrology, morphology, topography, and other characteristics to the impacted water is identified for use in establishing the natural conditions. The watershed used to establish the natural conditions should be free of any anthropogenic point or nonpoint sources of turbidity (EPA 1993, Hughes et al. 1986).
- Historic versus current condition: Historic data collected pre-impact is compared to more recent data collected post-impact in a water.

Magnitude

Magnitude is the numeric threshold for establishing impairment. The criteria component of Alaska's WQS sets the magnitude threshold. For turbidity, the criteria are set as a numeric threshold above the established natural conditions level. In Alaska, the most stringent criterion of the designated uses applies. For example, the most stringent fresh water criterion protects the contact recreation use, for which turbidity "**may not exceed 5 NTU above natural conditions** when the natural turbidity is 50 NTU or less, and may not have more than 10% increase in turbidity when the natural turbidity is more than 50 NTU, not to exceed a maximum increase of 15 NTU, and may not exceed 5 NTU above natural turbidity for all lake waters." The magnitude for most waters has natural turbidity below 50 NTU, such that the most stringent criterion is usually 5 NTU above natural conditions (NTU₀₊₅) (Table 2.1).

This methodology is written with the assumption that the critical magnitude threshold for impairment is 5 NTUs above natural conditions. For particular waters, where this is not the applicable criterion (e.g. marine waters, glacial rivers and streams with natural conditions above 50 NTUs, waters with site specific criteria or modified uses) then the magnitude threshold and significance testing procedures should be adjusted to reflect the most stringent applicable criterion.

The designated use for growth and propagation of fish, shellfish, other aquatic life and wildlife is protected by a criterion allowing turbidity up to 25 NTU above the natural conditions. However, turbidity has a variety of effects on aquatic life at levels as low as 1-5 NTU above background

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(ODEQ 2015 and Appendix A). As a result, for clear water rivers and streams where the median turbidity of the natural condition site is less than 5 NTU, water quality may be considered *threatened* and subsequently placed on the CWA §303(d) list for the designated use of growth and propagation of fish at turbidity levels lower than 25 NTUs above background. In such cases, the water will already be considered impaired for other uses (e.g. recreation) with more stringent criteria set at 5 NTU over natural background. Adding a threatened status for the growth and propagation use simply ensures that fish habitat concerns are also addressed.

Duration

In the context of water quality criteria, duration is the period of time (averaging period) over which ambient water quality data is averaged for comparison with the magnitude threshold (most stringent criterion). For the purposes of assessing impairment or attainment, a **24-hour daily average** is recommended to evaluate the duration of a turbidity exceedance.

Continuous data collection is preferred with one or more samples collected per hour. Collecting multiple samples during each day provides more precision in characterizing the 24-hour average, which makes it easier to distinguish between natural and impacted conditions. Continuous data also allows evaluations of diurnal or other patterns that may be useful in evaluating potential pollutant sources and restoration strategies.

However, replicate grab samples taken at the same time during one day are also considered as representative of the 24-hour averaging period. Even a very small set of samples during each day may be sufficient to indicate impairment as long as the samples are part of a larger dataset (i.e., at least 20 days of sampling). A determination of whether a single grab sample can reasonably be construed to be representative of (i.e., close in value to) average conditions over a specified period is an important step in the assessment process. The fact that only one grab sample is available for a particular period (and may not be truly representative of average conditions over the 24-hour period) does not necessarily mean that it could not be used as the basis of an impairment determination. For instance, despite being non-representative of the average concentration, it may be indicative of the average, or at least a fairly reliable indicator of whether or not the average concentration in the waterbody over a 24-hour period is above or below the level specified in the water quality criterion (USEPA 2005).

Frequency

The frequency component describes how often an exceedance occurs. Data sets should be evaluated using the frequency threshold of exceedance during **more than 10% of the days sampled** to determine whether a waterbody is considered impaired and listed under CWA §303(d). The U.S. Environmental Protection Agency (EPA) *Consolidated Assessment and Listing Methodology* (CALM) recommends that for conventional pollutants, whenever more than 10% of the water quality samples collected exceed the criterion threshold, WQS are not attained (USEPA 2002). Turbidity is a conventional pollutant, so the 10% frequency threshold has been incorporated into this listing methodology.

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Impairment Threshold Criteria Statement

- **The 24-hour daily average (duration)**
- **may not exceed 5 NTU above natural conditions (magnitude)**
- **during more than 10% of the days sampled (frequency).**

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3 Implementing Methods

Data Requirements

Turbidity data should be collected using in-water instruments that measure turbidity in nephelometric turbidity units (NTU) and meet EPA method 180.1 requirements (USEPA 1983).

The assessment period over which data is collected should span a minimum of two years. The years do not need to be consecutive, but should be within five years, if possible. During each year of data collection, samples should be collected over a minimum three-week annual period of concern, to ensure isolated impacts or weather events do not skew the dataset. The annual period of concern can range from three weeks to the entire year depending on the characteristics of the pollutant source(s). A minimum of 20 days sampled at both the natural conditions and impacted sites should be collected over the assessment period. A minimum of 20 samples was chosen as a balance between the expense of data collection and the need for sufficient statistical power. Larger data sets are desirable. The binomial test (See Section 4.2.1) provides statistical confidence in the impairment or attainment decision.

A “sample” refers to the 24-hour average, as described in section 2.3, which may be calculated from one or more data points taken during the sampling “day”. Thus, samples should be collected at each site on a minimum of 20 days over the assessment period.

If using single daily grab samples, DEC recommends collecting more than the minimum number of samples to increase statistical power of analyses. The preferred method for detecting potential turbidity impairments is to employ continuous sampling data loggers, which are capable of recording large data sets (i.e., sampling is performed on an hourly or 15-minute basis) for use in calculating more representative 24-hour daily averages.

Current data (less than five years old) are generally used for evaluation of turbidity, although some documentation of data greater than five years old may be relevant if the characteristics of the pollutant sources remain similar. Older data are generally given less significance when reviewing information for an impairment determination.

Data should be collected in accordance with a Quality Assurance Project Plan (QAPP). *Elements of a Tier 2 Water Quality QAPP* (http://dec.alaska.gov/water/wqapp/wqapp_index.htm) should be used to ensure the QAPP contains the necessary requirements. For example, the QAPP should outline the actions that will be taken to reduce data collection errors (e.g., calibration and verification requirements, recordkeeping requirements). In addition, the QAPP should describe sampling methods to ensure documentation of any seasonal variations in turbidity sources and the areal extent of impact.

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Table 3.1. Summary of data requirements

	<i>Description</i>	<i>Minimum Requirement</i>
Data Objectives	Site selection criteria	Select at least one each: natural conditions site and impacted site <ul style="list-style-type: none"> • The natural conditions site must be a nearby water with waterbody geomorphology similar to impacted site(s). • The impacted site should be representative of anthropogenic impacts and pollutant sources.
	Assessment period	Two years
	Annual period of concern	Within each year, samples should be collected over a minimum three week time span.
	Minimum sample size	Samples must be collected on at least 20 days at both the natural conditions and impacted sites.
	Representative data	Samples collected must be spatially and temporally representative of the areas and period of concern and the natural conditions.
Data Analysis	Magnitude	Are there exceedances of the turbidity criteria (i.e., natural conditions + 5 NTU)?
	Duration	Does the exceedance persist over a 24 hour averaging period?
	Frequency	Do the exceedances occur on more than 10% of the days sampled?

Visual Turbidity Observations

Although visual observations of elevated turbidity may often be noted and lead to identification of suspected water quality criteria exceedances, Alaska does not make impairment determinations and the associated CWA §303(d) listings based solely on visual turbidity observations. To confirm suspected visual exceedances, the results of in-water nephelometric turbidity unit sampling at an impacted site are compared to the natural conditions.

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Supplemental data

In order to determine important characteristics of an impaired water, other types of information may be collected in addition to turbidity data, such as:

- Biological, habitat or geomorphology information (e.g., macroinvertebrates, habitat assessment, riverbank erosion).
- Observance of natural or human activities (e.g., storms, recreation activities, nearby discharge compliance issues) occurring during sampling.
- Flow data highly recommended and preferably collected concurrently with turbidity samples. Historic flow information is also useful for establishing flow rates and patterns that affect natural turbidity background levels. Flow information will help establish sediment loading if a total maximum daily load (TMDL) is prepared.
- Total Suspended Solids (TSS) data to provide the basis for a weight based load allocation in a TMDL.
- Settleable Solids data to determine if there are exceedances of water quality criteria for sediment and to characterize potential impacts to the stream bed.

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4 Data Analysis

Data Review

A quality assurance/quality control data validation review should be conducted prior to analyzing the data. The methods described in the QAPP should be used to identify outliers. Outliers, or results that are numerically distant from other data, are fully scrutinized. In certain documented instances, outliers may be discounted, for example where fouling of equipment occurred. Discounted outliers may not be used to meet the minimum data requirements or to determine impairment, attainment or natural conditions.

Impacts from storm events should not be discounted if they are a part of the normal variation in turbidity during the period of sampling. Storms of unusual magnitude (e.g., 50 or 100 year events), may be discounted.

The data should be analyzed to determine if there are significant differences between the impacted and natural conditions sites. Both large and small datasets should be evaluated to determine the magnitude, frequency and duration of exceedances.

Data Evaluation

Data evaluation techniques will vary depending on the characteristics of the datasets. The sampling approach used will drive the appropriate data evaluation. The use of statistical tests (hypothesis tests, confidence intervals) is allowed in the evaluation, when necessary, e.g. to confirm borderline cases. The flowchart in Figure 4.2 shows the decision process for selecting the appropriate statistical hypothesis test for evaluating data sets for impairment. The binomial test is recommended for concurrent (i.e., temporally paired) datasets such as the upstream/downstream approach. Application of the Distribution of Differences (DoD) is recommended for datasets where data collected at the natural conditions and impacted sites are not concurrent or temporally paired, such as the paired watershed or historic versus current conditions approaches.

Data evaluation steps for listing determinations:

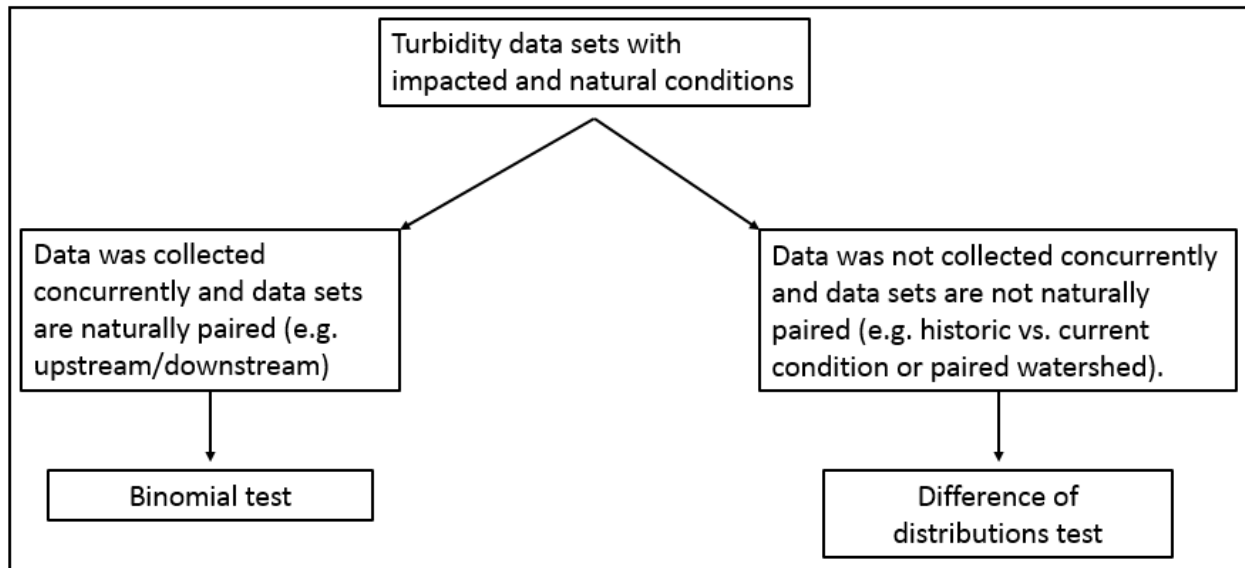
1. **Evaluate the raw exceedance/attainment estimate.**
 - a. For impairment, the daily average turbidity at the impacted site exceeds the natural conditions site by 5 NTU on more than 10% of the days sampled (impairment threshold criteria statement).
 - b. Conversely, for attainment decisions, the daily average should be less than 5 NTUs over natural conditions on 90% or more of the days sampled.
2. **Conduct the appropriate statistical test** (see sections 4.2.1 and 4.2.2) to evaluate the significance of the raw exceedance or attainment estimate.
3. **Based on the results of the statistical test, make the final impairment or attainment recommendation.**

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Figure 4.2 Flowchart of data evaluation techniques for different sampling approaches



4.1.1 Binomial statistical significance test

The binomial test is a non-parametric, robust, and well known method for characterizing the probability of proportions. The two data sets must be dependent, which can be confirmed by statistical testing, if needed. In the case of turbidity, the binomial test is used to determine if the turbidity criterion (usually natural conditions plus 5 NTUs) is exceeded in more than 10% of the samples (critical impairment threshold) or in less than 10% of the samples (critical attainment threshold). The formula for the binomial probability distribution and applications to impairment decisions were taken from EPA CALM Guidance (USEPA 2002). Following appropriate pairing of upstream and downstream samples to meet the test requirement for data dependence, the binomial test is performed on downstream impacted site data from criteria determined by upstream samples representing the natural conditions site.

Appendix B. provides a full description of the data evaluation and binomial test procedure.

4.1.2 Distribution of Differences statistical significance test

A distribution of differences (DoD) test is recommended for datasets that are not concurrently measured, i.e. paired watersheds or historic vs current dataset comparisons. The two datasets are assumed to be independent of each other in time and/or space.

DoD can be used to describe the range of differences between two variables (Hogg et al. 2012; Ott and Longnecker 2015). In the case of evaluating the impairment threshold for turbidity, the two variables are daily average turbidity measurements from two locations (e.g., natural conditions and impacted sites). Given the allowable exceedance frequency for turbidity criteria is 10%, the location of interest on the DoD curve is the 90th percentile. On this basis, if the 90th percentile of the turbidity difference is greater than +5 NTU (magnitude threshold), an impairment may be present.

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Confidence limits around the 90th percentile (Gibbons 2001; US EPA 2002) of the DoD may be used to determine if there is more (impairment) or less (attainment) than a +5 NTU difference 10% of the time with statistical significance. Use of confidence limits about the 90th percentile turbidity difference is therefore termed the 'DoD test'.

Appendix C. provides a full description of the data evaluation and DoD test procedures.

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5 Listing Determination Thresholds

Impairment Determination

Before a final decision to add a waterbody impaired by turbidity to the Section 303(d) list/Category 5 (or Category 4b if other pollution controls are in effect), DEC reviews the data for the basic concepts employed in any listing, including magnitude, frequency and duration. Implementation tools such as enforcement and permit limitations, should also be evaluated, as necessary, to help identify ways to effectively reduce the exceedances in future TMDLs or other pollution controls.

The waterbody will be considered impaired if turbidity conditions meet the impairment thresholds listed below. The most stringent water quality criterion for turbidity impairment can be summarized as:

Impairment Threshold Criteria Statement:

- **The 24-hour daily average (duration)**
- **may not exceed 5 NTU above natural conditions (magnitude)**
- **during more than 10% of the days sampled (frequency).**

The impairment determination is based on a dataset that

- represents the condition of a waterbody segment (spatially and temporally) during **an assessment period of at least two years,**
- includes **a minimum of 20 days sampled** (at both natural conditions and impacted sites), and
- characterizes **an annual period of concern of at least 3 weeks.**

The years of the assessment do not have to be consecutive, but should be within a reasonably short timeframe, i.e., within 5 years if possible.

In addition, statistical significance testing and other factors may also be considered to corroborate a listing determination. Other factors may include, but are not limited to: biological data, flow data, settleable solids measurements and TSS measurements.

Attainment Determination

A waterbody may be evaluated for attainment of the water quality criteria for turbidity and placed in Categories 1 or 2 of Alaska's Integrated Water Quality Monitoring and Assessment Report as the result of the following assessments:

1. Initial assessment of a waterbody in Category 3 (insufficient information) of the biennial Integrated Report
2. Re-assessment of a waterbody with a TMDL for turbidity
3. Re-assessment of a waterbody listed on Alaska's CWA §303(d) list

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In general, waterbody attainment determinations should use the listing determination thresholds that were used to list the waterbodies. For the purposes of evaluating a waterbody for attainment using a binomial or DoD test, the test should be designed to determine if the daily average turbidity at impacted site has exceedances (5 NTU over natural conditions) at frequency of less than 10% of the days sampled.

For a waterbody with an EPA-approved TMDL that uses TSS as an established surrogate for turbidity, an attainment determination may also need to determine if the point source discharges and nonpoint source contributions are meeting the wasteload and/or load allocations established in the TMDL.

For removal of a waterbody from the CWA §303(d) list, both the level of data to support the removal determination and the burden of proof are no greater than those used in the initial CWA §303(d) listing determination. If a waterbody was placed on the CWA §303(d) list for turbidity impairment based on only visual turbidity observations and best professional judgment (in 2008 or earlier), then a determination to remove the waterbody from the CWA §303(d) list may be based on visual turbidity observations and best professional judgment alone.

6 References

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Appendix A. Tables of Effects on Aquatic Life

Table A.1. Summary of effects of turbidity on aquatic life in streams¹

Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
Effects at reported turbidity levels at ≤10 turbidity units					
4-8 NTU	n/a (reference site approach)	Decrease in <i>Epeorus</i> species in Umatilla River	Scherr, et al. (2011)	LaMotte 2020	Field
4.4 NTU	n/a (reference site approach)	85% chance of stream being impacted (EPT index <18)	Paul (unpub.)	Various	Field
5 NTU	none given	Modelled decrease in primary productivity in clear Alaska streams by 3-13% (stream depth 0.1 – 0.5 m)	Lloyd, et al. 1987	Hach “PortaLab”	Field
7 NTU	Two months	75% decrease in benthic algal biomass	Davies-Colley, et al. 1992	Hach 2100A	Field
7 NTU	Two months	70% decrease in macroinvertebrate density	Quinn, et al. 1992	Hach 2100A	Field

¹ Copied from Oregon Department of Environmental Quality (ODEQ). 2014. Turbidity Technical Review: Summary of Sources, Effects, and Issues Related to Revising the Statewide Water Quality Standard for Turbidity. ODEQ, Portland, Oregon.

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
7-25 NTU	n/a	Decrease in macroinvertebrate density and other measures of macroinvertebrate health	Prussian, et al. 1999		
9 NTU	n/a	20% decrease in PREDATOR score using Oregon data	ODEQ turbidity data	n/a	Field
10 NTU	15 minutes	50% decrease in brook trout reactive distance	Sweka and Hartman 2001a	Lamotte 2020 turbidimeter	Laboratory
10 NTU	5 days	20% decrease in brook trout growth	Sweka and Hartman 2001b	Lamotte 2020 turbidimeter	Laboratory
10-60 NTU	4-6 days	Decrease in prey consumption by juvenile coho salmon after initial exposure to 60 NTU; also, higher response time and increased number of missed strikes at prey.	Berg 1982	DRT-150 Turbidimeter	Laboratory

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
Effects at reported turbidity levels from 11-20 turbidity units					
11-32 NTU	14 days	Reduced weight and length gains in newly emerged coho salmon (raceway channels)	Sigler, et al. 1984	Hach 2100A Turbidimeter	Laboratory
15 NTU	n/a	20% reduction in rainbow trout reactive distance	Barrett, et al. 1992	Not reported	Laboratory (artificial stream channel)
18 NTU	1-10 minutes	Reduced feeding rates of small-medium juvenile Chinook salmon on surface prey	Gregory 1994	Fisher DRT-400 Turbidimeter	Laboratory
20 NTU	One hour	Reduced prey capture success by juvenile coho salmon	Berg and Northcote 1985	Fisher 400 DRT Turbidimeter	Laboratory
Effects at turbidity levels from 21-30 turbidity units					
22 NTU	11 days	Reduced weight and length gains in newly emerged coho salmon (oval channels)	Sigler, et al. 1984	Hach 2100A Turbidimeter	Laboratory

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
23 NTU	1-6 hour daily pulses over 9 and 19 days	Reduced abundance and species richness of benthic macroinvertebrates . In addition, reduced rainbow trout length and weight gain when turbidity pulses lasted 4-5 and 5-6 hours, respectively.	Shaw and Richardson 2001	Not reported (converted from suspended sediment concentrations, but does not report relationship)	Laboratory
23 NTU	12 days	Reduced startle response by juvenile Chinook salmon	Gregory 1993	Fisher DRT-400 Turbidimeter	Laboratory
25 NTU	none given	Modelled decrease in primary productivity in clear Alaska streams by 13-50% (stream depth 0.1 – 0.5 m)	Lloyd, et al. 1987	Based on information using Hach “Portalab”	
25 NTU	15 minute	Reduced drift prey foraging success	Harvey and White 2008	DTS-12	Laboratory
25-35 NTU	3 months	Decrease in whole stream metabolism	Parkhill and Gulliver 2002	Not reported	Controlled field (laboratory streams)

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
27+ NTU	1.5 hours	Predation rates on juvenile Chinook salmon by piscivorous fish significantly reduced in the Fraser River	Gregory and Levings 1998	Fisher DRT-100 Turbidimeter	Field
30 NTU	n/a	55% reduction in rainbow trout reactive distance	Barrett, et al. 1992	Not reported	Laboratory (artificial stream channel)
30 NTU	One hour	Decrease in reactive distance, capture success and percentage of prey ingested for juvenile coho salmon. In addition, dominance hierarchies broke down and gill flaring occurred more frequently	Berg and Northcote 1985	Fisher 400 DRT Turbidimeter	Laboratory
30 NTU	24 hours	Increased cough frequencies in coho salmon	Servizi and Martens 1992	HF Instruments DRT 100	Laboratory

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
Effects at turbidity levels from 31-50 turbidity units					
38 NTU	19 days	Decreased weight and length gains of newly emerged steelhead (raceway channel)	Sigler, et al. 1984	Hach 2100A Turbidimeter	Laboratory
42 NTU	96 hours	25% increase in blood sugar levels in coho salmon	Servizi and Martens 1992	HF Instruments DRT 100	Laboratory
45 NTU	19 days	Decreased weight and length gains of newly emerged steelhead (oval channel)	Sigler, et al. 1984	Hach 2100A Turbidimeter	Laboratory
50 NTU	5 days	50% decrease in brook trout growth rate	Sweka and Hartman 2001b	Lamotte 2020 Turbidimeter	Laboratory
50 NTU	15 minutes	Decrease in proportion of drift prey consumed in juvenile cutthroat trout and coho salmon	Harvey and White 2008	DTS-12	Laboratory

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
50 NTU	15 minutes	Decrease in proportion of live oligochaetes drifting along an experimental stream bottom by juvenile cutthroat trout	Harvey and White 2008	DTS-12	Laboratory
Effects at turbidity levels >50 turbidity units					
60 NTU	One hour	66% reduction in juvenile coho salmon reactive distance (did not return to normal levels after pulse decreased)	Berg and Northcote 1985	Fisher 400 DRT Turbidimeter	Laboratory
70 NTU	30 minutes	Avoidance of juvenile coho salmon to turbid waters	Bisson and Bilby 1982	Not reported	Laboratory
80 NTU	96 hours	50% increase in blood sugar level in coho salmon	Servizi and Martens 1992	HF Instruments DRT 100	Laboratory
150 NTU	15 minutes	Decrease in proportion of benthic prey consumed by juvenile cutthroat trout and coho salmon	Harvey and White 2008	DTS-12	Laboratory

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Turbidity Level (margin of error)	Duration	Effect	Source	Turbidity Measurement	Type of Study
170 NTU	Ten days	50% decrease in productivity and 60% decrease in chlorophyll <i>a</i> concentrations	Van Nieuwenhuysse and LaPerrerie (1986)	Hach Portalab	Laboratory

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Table A.2. Summary of effects of turbidity on aquatic life in lakes and reservoirs²

Turbidity Level	Duration	Effect	Source	Turbidity Measurement	Lab or Field
Effects at turbidity levels ≤10 turbidity units					
~1.2 NTU	chronic	50% decrease in reactive distance of bluegill trout to avoid largemouth bass	Miner and Stein 1996	Not reported	Laboratory
1.5 NTU	4 hours	Minimum turbidity to decrease reactive distance of lake, rainbow, and cutthroat trout	Mazur and Beauchamp 2003	LaMotte 2008	Laboratory
1.65 NTU	1 hour		Hansen, et al. (2013)	LaMotte 2020e h	Laboratory
3.18 NTU	4 hours	Decrease in reactive distance of lake trout to juvenile rainbow and cutthroat trout at optimum light intensity	Vogel and Beauchamp 1999	LaMotte 2008	Laboratory
5 NTU	n/a	80% reduction in compensation depth	Lloyd, et al. 1987	HF DRT-150 Turbidimeter	Field
5 NTU	3.5 – 42.6 hours	Significant decrease in consumption of prey by smallmouth bass	Carter, et al. 2010	LaMotte 2020	Laboratory
10 NTU	19-49 hour	Change in size selectivity of prey by largemouth bass	Shoup and Wahl 2009	Cole-Parmer Model 8391–40	Laboratory

² Copied from Oregon Department of Environmental Quality (ODEQ). 2014. Turbidity Technical Review: Summary of Sources, Effects, and Issues Related to Revising the Statewide Water Quality Standard for Turbidity. ODEQ, Portland, Oregon.

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Turbidity Level	Duration	Effect	Source	Turbidity Measurement	Lab or Field
Effects at turbidity levels from 11-20 turbidity units					
17-19 NTU	n/a	Decrease in reactive distance of largemouth bass to crayfish	Crowl 1989	Not reported (Jackson turbidimeter)	Laboratory
Effects at turbidity levels from 21-30 turbidity units					
25 NTU	2 hours	60-80% decrease in feeding rates of Lahontan redbreasted sunfish and cutthroat trout on daphnia	Vinyard and Yuan 1996	DRT-15 Turbidimeter	Laboratory
Effects at turbidity levels from 31-50 turbidity units					
30+ NTU	n/a	Limitation in compensation of photosynthetic efficiency for low-light conditions	Lloyd, et al. 1987	n/a	Field
33 NTU	n/a (mean turbidity over multiple lakes and years)	Reduction in chlorophyll <i>a</i> levels in glacial lakes	Koenings, et al. 1990	DRT-100	Field
40 NTU	42-77 hours	Decrease in predation rate by largemouth bass	Shoup and Wahl 2009	Cole-Parmer Model 8391-40	Laboratory
Effects at turbidity levels >50 turbidity units					
60 NTU	3 minutes	Decrease in prey consumption by bluegill	Gardner 1981	DRT-100	Laboratory

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Turbidity Level	Duration	Effect	Source	Turbidity Measurement	Lab or Field
70 NTU	one hour	Decrease in predation rates by largemouth bass	Reid, et al. 1999	DRT-15B	Laboratory
100 NTU	n/a	Population level declines of centrarchids in a Louisiana bottomwood backwater system	Ewing 1991	Hach DR-EL/1	Field
144 NTU	25 weeks	No effect on growth rate of adult crappie	Spier and Heidinger 2002	Hach DR-2000	Field
160 NTU	3 hours	No decrease in predation rate by rainbow trout; however, size selectivity was affected	Rowe, et al. 2003	Hach 18910 Turbidimeter	Laboratory
174 NTU	25 weeks	No decrease in growth rates of juvenile white and black crappie	Spier and Heidinger 2002	Hach DR-2000	Field

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Appendix B. Binomial statistical test

B.1 Binomial raw exceedances

For paired datasets that were collected concurrently, the raw exceedance frequency is calculated by comparing the 24-hour daily averages of the impacted site dataset to the natural conditions dataset. If the daily average at the impacted site exceeds the natural conditions site by more than 5 NTU (the magnitude threshold,) then it is counted as a raw exceedance.

Figure B.1 shows an example time series plot of the daily averages of an impacted site and natural conditions site. In this example, the impacted site and natural conditions site were monitored continuously via data loggers that collected 24 hourly samples each day for 84 days. Daily averages were calculated for each day. In the figure, the most stringent criterion (for water recreation, contact recreation) is calculated by adding 5 NTU to the 24-hour daily averages at the natural conditions site.

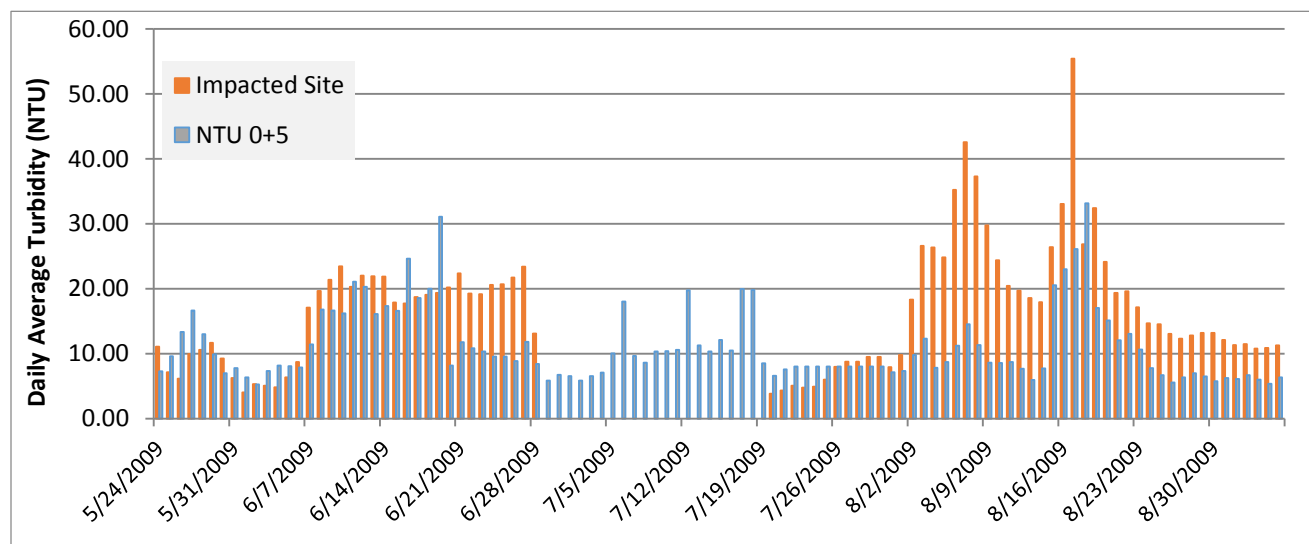


Figure B.1. Time series plot of average daily turbidity for the criterion (natural conditions + 5 NTU) and impacted site.⁴

The daily average criterion was exceeded at the impacted site on 63 of 84 days (as shown in Figure B.1), resulting in a raw exceedance frequency of 75%. Table B.1 shows the exceedance frequencies for the designated uses of water recreation, contact recreation (natural conditions +5 NTU), water recreation, secondary recreation (natural conditions +10 NTU) and growth and propagation of fish, shellfish, other aquatic life and wildlife (natural conditions +25 NTU). In this example, the impacted site exceeds all criteria for water recreation by a frequency more than 10%. The next step would be to conduct a statistical test to make an impairment determination.

⁴ Turbidity was not measured at the impacted site from June 29 through July 20, so these days are not included in the raw frequency.

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Table B.1. Example raw exceedance frequency calculation

	Water recreation, contact recreation (natural conditions + 5 NTU)	Water recreation, secondary recreation (natural conditions + 10 NTU)	Growth and propagation of fish, shellfish, other aquatic life and wildlife (natural conditions + 25 NTU)
Total exceedances	63	42	5
Total samples (24- hour daily averages)	84	84	84
Raw exceedance frequency	75%	50%	6%

B.2 Binomial statistical significance test

If the raw exceedance frequency exceeds 10% at the downstream or impacted site, then the binomial test should be conducted. Example inputs, outputs, and decisions of the test are listed in Table B.2. Additional detail and discussion of the binomial test is provided by US EPA (2002). The calculations for the binomial test can be done using the ADEC Turbidity Hypothesis Test Template (DEC 2016).

Table B.2. Example binomial test inputs and outputs for secondary recreation listing case

	Description	Value	Comments
Input	Total Exceedances	42	Number of downstream samples greater than criterion
	Total Trials	84	Number of comparisons of downstream site to the criterion obtained from upstream data. Equals number of matched pair upstream/downstream samples.
	Raw Exceedance Frequency	50%	Calculated as Exceedances / Trials
	Target Type I Error (α)	0.2	$\alpha = 0.2$ for trials ≤ 40 , $\alpha = 0.1$ for trials > 40 . Alternate values of α considered to balance or improve statistical power of test.
	Allowed Exceedance Rate	10%	Allowed by US EPA guidance for conventional parameters
Output	Actual Type I Error (α_a)	0.1330	Actual Type 1 error calculated from discrete trial and exceedance combinations. Intermediate output.
	Minimum Exceedances to Reject	4	Number of exceedances needed to reject null hypothesis at the acceptable Type 1 error level. Intermediate output.
	Binomial Test Statistic (P)	0.0000	p-value, or attained significance level, of Binomial Test.
Final Result	Impaired?*	Yes	If p-value $<$ Target Type 1 error, then reject null hypothesis and conclude waterbody exceeds criterion greater than 10% of the time.

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*For impairment determination:

Null Hypothesis: Exceedance Frequency $\leq 10\%$ (not impaired)

Alternate Hypothesis: Exceedance Frequency $> 10\%$ (impaired)

For attainment determination:

Null Hypothesis: Exceedance Frequency $> 10\%$ (not attaining)

Alternate Hypothesis: Exceedance Frequency $\leq 10\%$ (attaining)

The binomial P-value (Table B.2) is the test statistic. If the test statistic is less than the Actual Type I Error rate, then the null hypothesis should be rejected and the water should be considered impaired (or attaining).

The final result from the binomial test will be used to determine if the turbidity significantly exceeds or attains the 10% frequency threshold.

B.3 References

DEC. 2016. ADEC Turbidity Hypothesis Tests Template., dated March 31, 2016.

[<http://dec.alaska.gov/water/wqsar/waterbody/integratedreport.htm>]

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Appendix C. Distribution of Differences test

A distribution of differences (DoD) test is recommended for datasets of daily average turbidity that are not concurrently measured, i.e. paired watersheds or historic vs current dataset comparisons. The DoD test requires random, independent, and normally distributed data. Note that turbidity data usually must be transformed to achieve a normal distribution. In most instances this is a log transformation. The calculations for the binomial test can be done using the ADEC Turbidity Hypothesis Test Template (DEC 2016).

C.1 Distribution of Differences raw percentile inspection

The raw criterion exceedance frequency can be determined from inspection of the cumulative DoD. The cumulative DoD (see example in Table 4.2.3) is calculated as follows:

1. Transform reference and impacted site datasets to achieve a normal distribution. Unless otherwise informed, a log transform is assumed.
2. Calculate the mean and standard deviation of the DoD.
The difference [impacted (X) – natural conditions (Y)] between two random, independent and normally distributed variables (X and Y) is a normal distribution having the following mean and standard deviation (in log units).

mean difference = $\mu_{X-Y} = \mu_X - \mu_Y$ and standard deviation of difference =

$$\sigma_{X-Y} = \sqrt{\frac{s_X^2}{n_X} + \frac{s_Y^2}{n_Y}}$$

where:

μ_X is the mean of variable X

μ_Y is mean of variable Y

s_X sample standard deviation of variable x

s_Y is sample standard deviation for Y

n_X is sample size for variable X

n_Y is sample size for variable Y

3. Calculate ascending percentiles of the DoD using the inverse function for a normal distribution to obtain the cumulative DoD. The inverse function is available in several software packages, including MS Excel as the 'Norm.Inv' function.
4. Convert inverse function output from log units to NTU.

Table C.1 shows an example cumulative DoD having a mean difference of 6.7 NTU and standard deviation difference of 1.9 NTU. Two important observations may be obtained from Table C.1 First, the magnitude of the 90th percentile (10% exceedance frequency) is greater than +5 NTU suggesting an impairment may exist. Second, a 5 NTU difference occurs at approximately the 35th percentile. Since exceedance frequency is calculated as 100 percentile, the latter observation indicates a raw exceedance frequency of approximately 100 – 35 = 65%.

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Table C.1. Percentiles of the Difference Distribution between Impacted and Natural Conditions Datasets

Difference Percentile	Impacted – Natural Conditions (Difference in NTU)
99	31.2
90	15.6
80	11.7
70	9.4
60	7.9
50	6.7
40	5.6
30	4.7
20	3.8
10	2.9
1	1.4

C.2 Distribution of Differences statistical significance test

If inspection of DoD percentiles indicates the impacted site exceeds the criterion at or above the 10% frequency threshold, i.e. the NTU difference at the 90th percentile is greater than +5, then the DoD test should be conducted. The DoD test implements the confidence interval approach to listing and delisting decisions (Gibbons 2001, US EPA 2002). With this approach, a difference of +5 NTU is compared to confidence limits of the 90th percentile.

For impairment determination purposes, the hypothesis test of interest is a one-sided Lower Confidence Limit (LCL) on the 90th percentile of the difference distribution. If the LCL is greater than +5 NTU, then we can infer that the difference between impact and reference is significantly greater than 5 NTU (i.e. exceeds the magnitude threshold for impairment) at the frequency threshold of 10%. Figure C.2.1 shows an example distribution where the LCL is greater than +5 NTU, thus impaired. Figure C.2.2 shows an example distribution where the LCL is less than +5 NTU. In this case, the waterbody would not be considered impaired.

For attainment determination purposes, the hypothesis test of interest is a one-sided Upper Confidence Limit (UCL) on the 90th percentile of the difference distribution. If the UCL is less than +5 NTU, then we can infer that the difference between impacted site and natural conditions site is significantly less than +5 NTU (attaining) at the frequency threshold of 10%. Figure C.2.3 shows a distribution where the UCL is greater than +5 NTU. This waterbody would not be attaining WQS and could not be delisted. Alternately, figure C.2.4 shows a distribution where the UCL is less than +5 NTU. This would lead to an attainment decision and delisting.

A one-sided confidence limit is calculated using a Wald type confidence interval given as:

Confidence Limit (as percentile, CL_p) = $(0.90 \pm z_\alpha * \sigma_\pi)$ where z_α is the z associated with alpha (e.g., 1.28 for alpha = 0.1) and σ_π is the standard error of the proportion difference given by the variance sum law below:

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$$\sigma_{\pi} = \sqrt{\frac{\pi_X (1 - \pi_X)}{n_X} + \frac{\pi_Y (1 - \pi_Y)}{n_Y}}$$

Where π_X and $\pi_Y = 0.90$ as percentiles of interest and alpha (α) is the Type 1 error rate assumed for the test.

The one-sided LCL expressed as a percentile (LCL_p) is calculated as $0.90 - z_{\alpha} * \sigma_{\pi}$. Two steps are required to convert the LCL_p into NTUs. First, the LCL_p is used as input to the inverse function for a normal distribution along with $\mu_{X,Y}$ (log units) and $\sigma_{X,Y}$ (log units). Output from the first step is the LCL in log NTUs. The second step is to reverse the log transform (e.g., e^{LCL} for natural log transform). Similarly, for attainment the one-sided UCL expressed as a percentile (UCL_p) is calculated as $0.90 + z_{\alpha} * \sigma_{\pi}$ and converted to NTUs as described above.

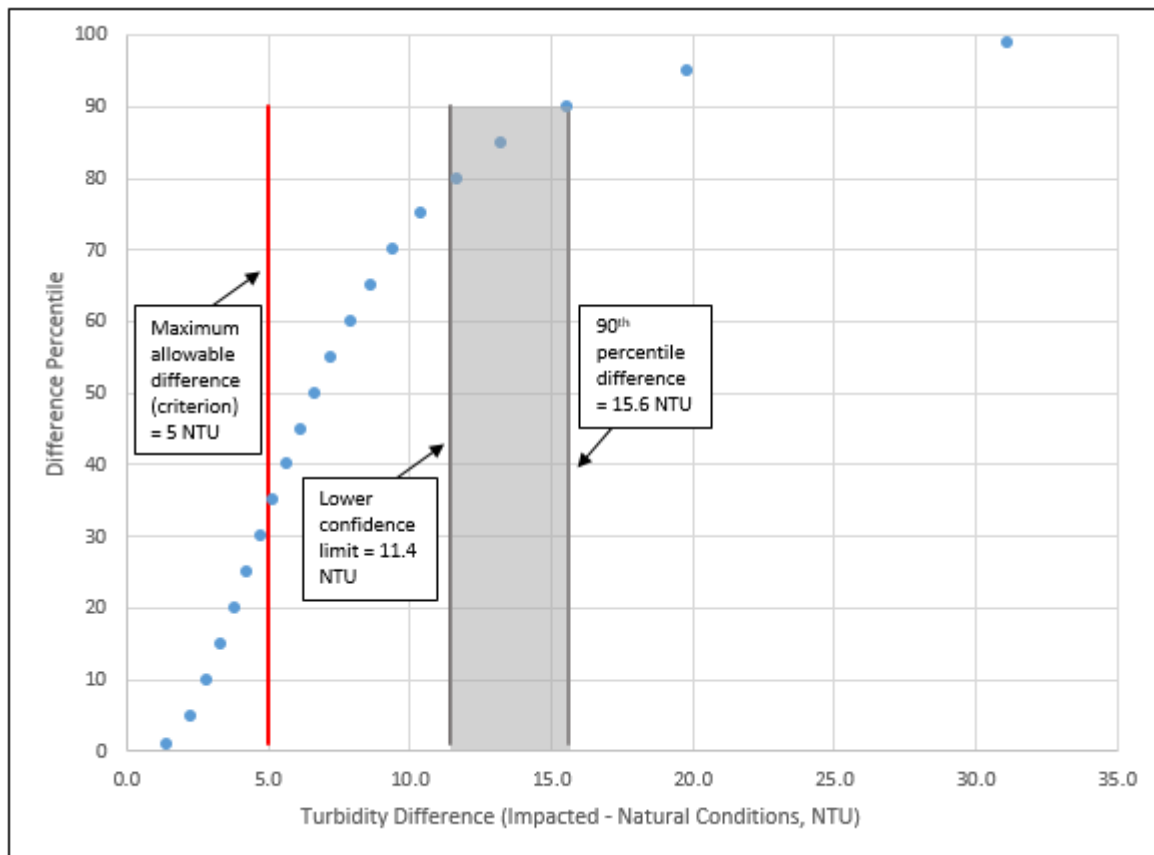


Figure C.2.1. Example listing determination – the LCL is greater than +5 NTU = Impaired.

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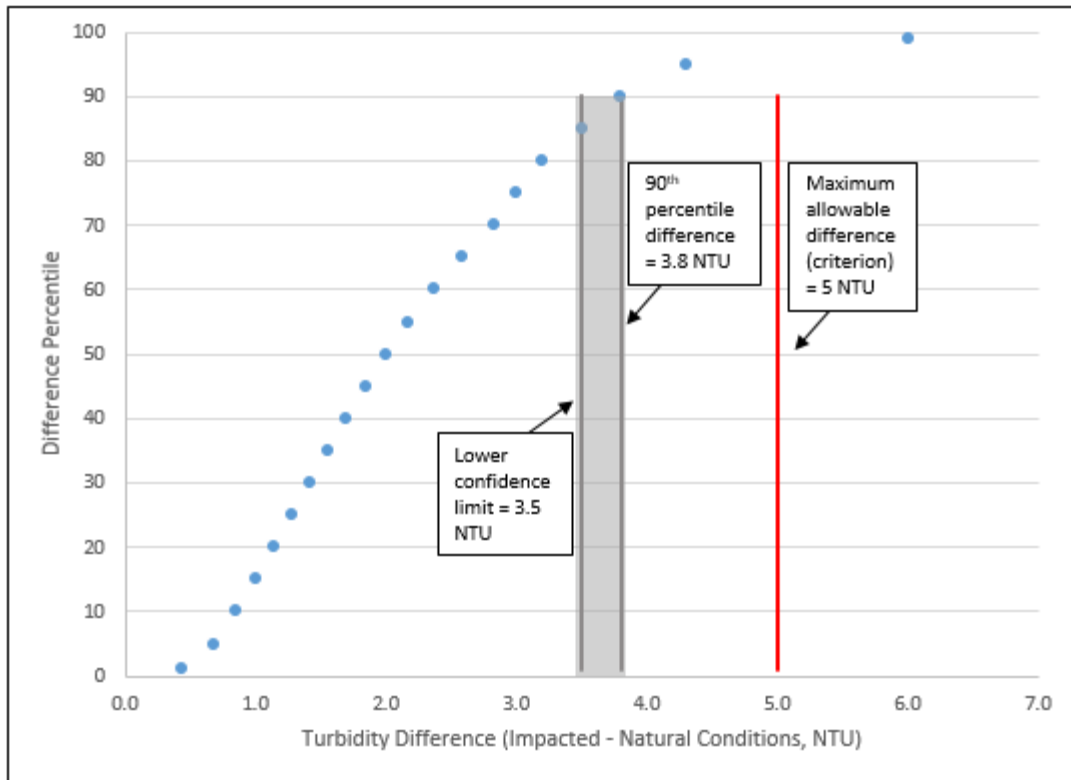


Figure C.2.2. Example listing determination – the LCL is less than +5 NTU = Not impaired

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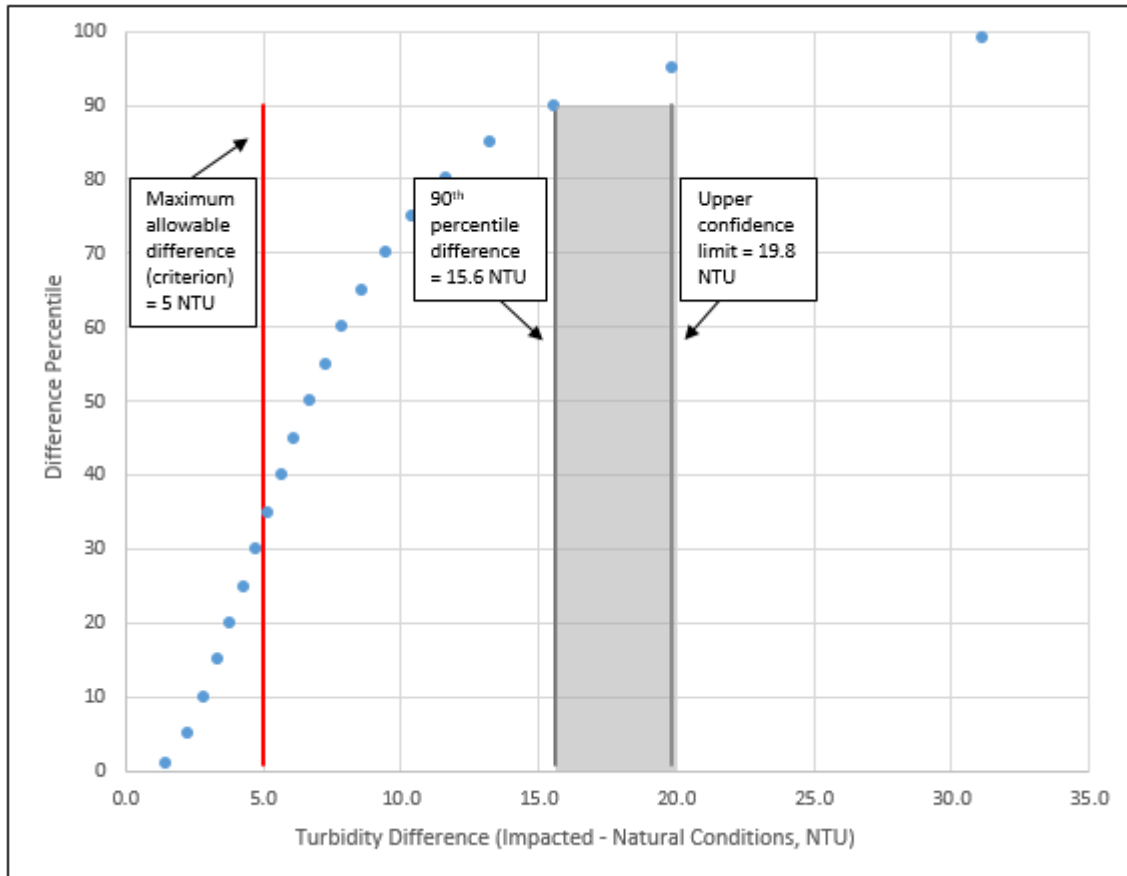


Figure C.2.3. Example attainment determination – the UCL is greater than +5 NTU = Not attaining

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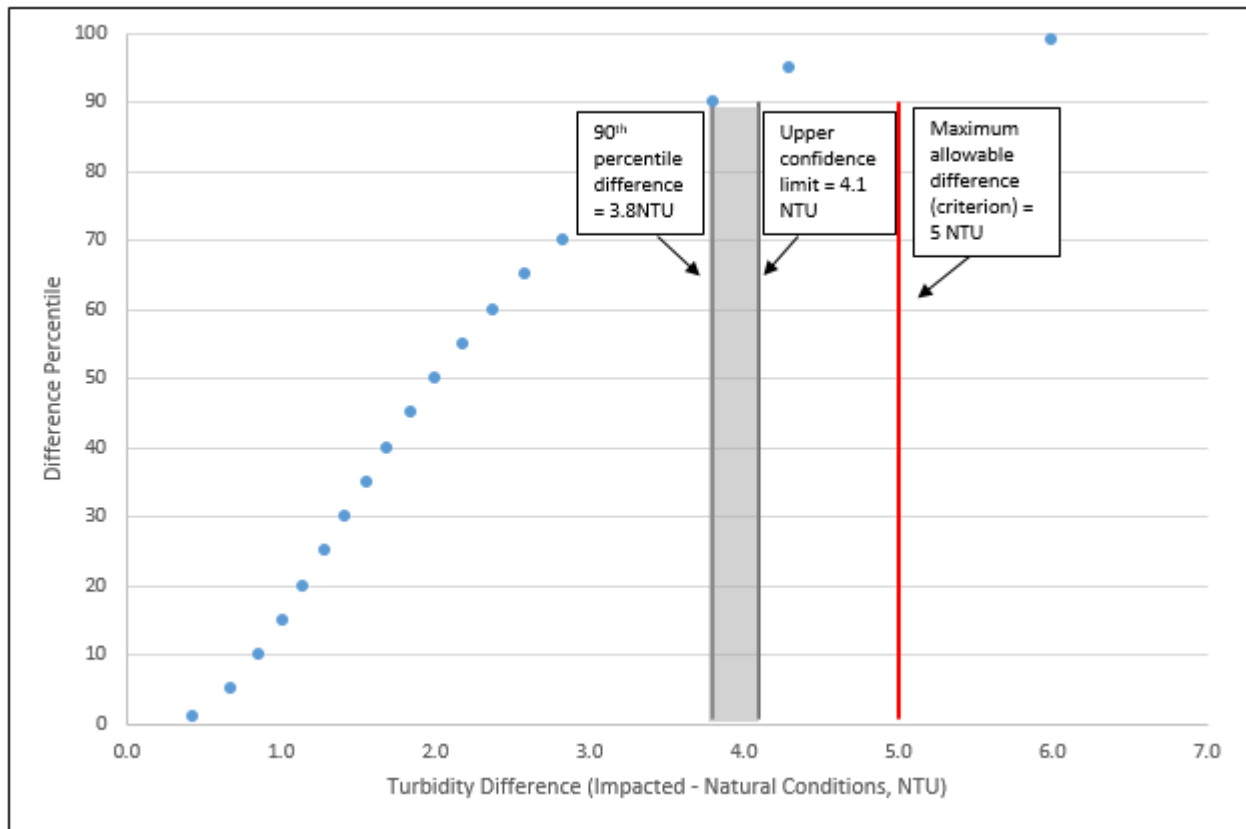


Figure C.2.4. Example attainment determination – the UCL is less than +5 NTU = Attaining

C.3 References

DEC. 2016. ADEC Turbidity Hypothesis Tests Template., dated March 31, 2016. [website TBD]