Appendix C

Deschutes River Fine Sediment TMDL Technical Analysis

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
µm	Micrometers
ArcGIS	Environmental Systems Research Institute - Geographic Information System
BPS	Biophysical Settings
CC	Canopy Cover
cfs	Cubic Feet per Second
CRWQCB	California Regional Water Quality Control Board
DEM	Digital Elevation Model
Ecology	Washington Department of Ecology
EPA	U.S. Environmental Protection Agency
EVT	Existing Vegetation Type
g/cm^3	Grams per Cubic Centimeter
GIS	Geographical Information System
gSSURGO	Gridded Soil Survey Geographic Database
HSPF	Hydrological Simulation Program-Fortran
IC	Index of Connectivity
LiDAR	Light Detection and Ranging
m	Meter
mg/L	Milligrams per Liter
mm	Millimeter
NHD	National Hydrography Dataset
NTU	Nephelometric Turbidity Units
PLU	Prior Land Use
QAPP	Quality Assurance Project Plan
RM	River Mile
RUSLE	Revised Universal Soil Loss Equation
SC	Surface Cover
SDR	Sediment Delivery Ratio
SLR	Soil Loss Rate
SM	Soil Moisture
SR	Surface Roughness
TMDL	Total Maximum Daily Load
tons/ac/yr	Tons per Acre per Year
tons/day	Tons per Day
$tons/yd^3$	Tons per Cubic Yard
tons/yr	Tons per Year
TSS	Total Suspended Solids
USEPA	U.S. Environmental Protection Agency

Acronyms/Abbreviations	Definition
USGS	United States Geological Survey
WARSEM	Washington Road Surface Erosion Model
WRIA	Water Resources Inventory Area
yd^3/yr	Cubic Yards per Year

1.0 INTRODUCTION

This appendix is based a report prepared by Tetra Tech under contract with the Environmental Protection Agency, Region 10. All work was conducted in accordance with an approved Quality Assurance Project Plan (QAPP; Tetra Tech, 2019). The objectives of the technical analyses presented in this appendix include identifying and quantifying key sources of sediment to the impaired segment of the Deschutes River (Figure 1), linking sediment sources to the fine sediment target, and establishing a Total Maximum Daily Load (TMDL).

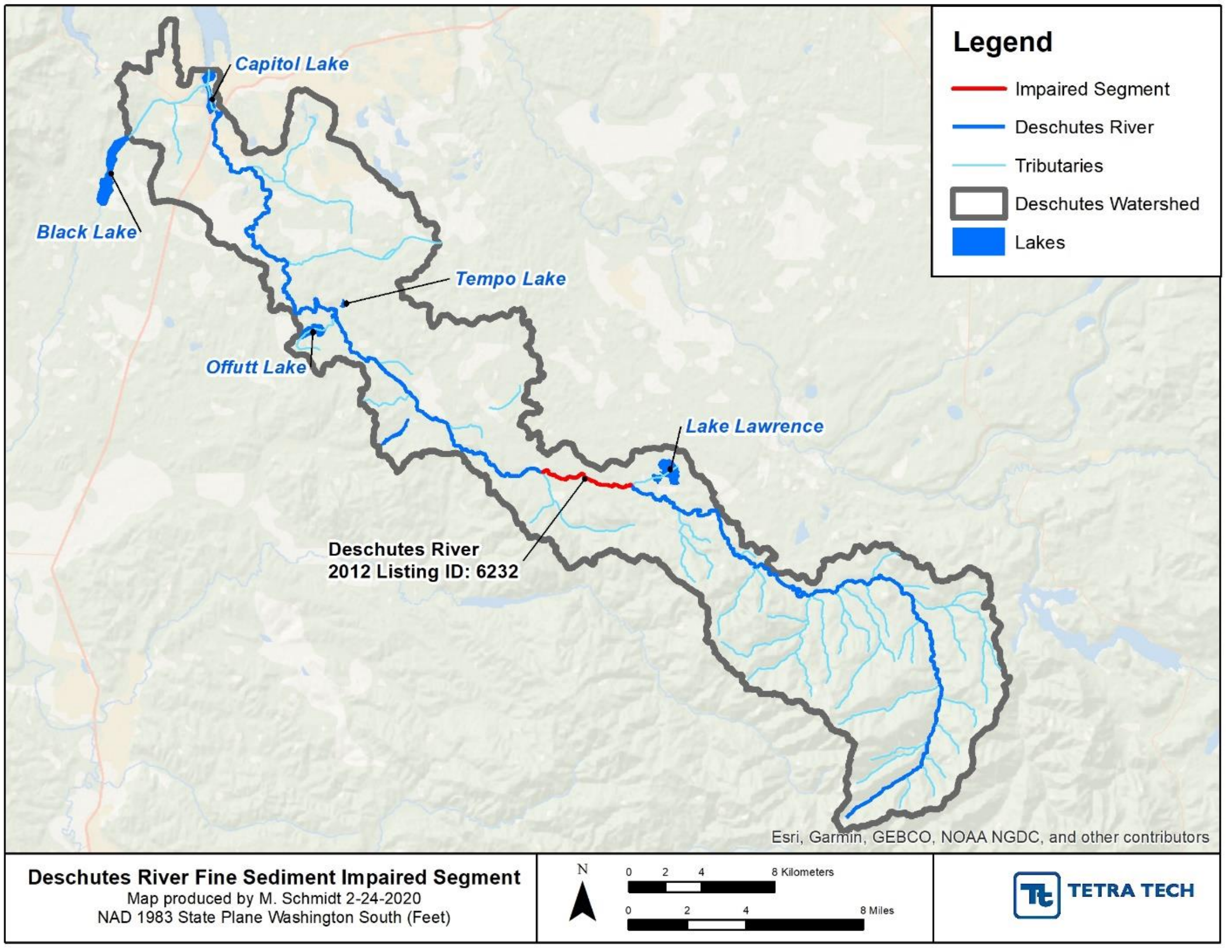

Figure 1. Sediment impaired segment of the Deschutes River.

1.1 BACKGROUND

The source assessment for the sediment TMDL in the *Deschutes River, Percival Creek, and Budd Inlet Tributaries Total Maximum Daily Loads* (“*2015 Deschutes TMDLs*”) relied on an analysis conducted for the Squaxin Island Tribe that quantified annual fine sediment loads to the Deschutes River from bank erosion (hillslope and glacial terraces), landslides, and unpaved roads (Raines, 2007). The annual sediment budget was compared to loading inputs to Capitol Lake based on dredging and bathymetric records of Capitol Lake collected between 1972 and 2003. Based on this comparison, the sediment budget from Raines (2007) did not account for approximately 28 percent of the fine sediment load to Capitol Lake from the Deschutes watershed. Ecology set the TMDL based on the sum of the natural and unaccounted portion of the annual sediment load to Capital Lake, which assumed all identified human sources (i.e., unpaved roads and associated landslides) could be eliminated. Because an extensive amount of work went into identifying sources of excess sediment and controllable loading for the *2015 Deschutes TMDLs*, EPA determined it was appropriate to utilize Ecology's source assessment to characterize the sources of existing fine sediment loading and to identify the natural background load. However, based on information in Raines (2007) that states non-road associated landslides tend to be associated with timber harvest, all sediment originating from landslides was reclassified anthropogenic for this TMDL.

It should be noted that various studies use different particle sizes to define fine sediment. Raines (2007) used < 2 mm, whereas Deschutes River field assessments of percent embeddedness used <0.85 mm (Konovsky and Puhn, 2005). Although both size classes fall under the definition of sand, <0.85 mm ties more closely to research showing a reduction in salmonid egg-to-fry survival (see summary and meta-analysis in Jensen et al., 2009). Research has also found statistically significant decreases in eyed egg survival to be associated with percent embedded fine sediment up to 6.3 mm in diameter (Jensen et al. 2009). This report uses the 0.85 mm definition for embeddedness but analyzes fine sediment supply based on the 2-mm cutoff to protect against other deleterious impacts, which matches the approach Ecology used for the *2015 Deschutes TMDLs*.

2.0 EXISTING SEDIMENT SOURCE ASSESSMENT

The sediment-impaired section of the Deschutes River is in the upper watershed between the Lake Lawrence Creek and Reichel Creek (Figure 1). The fine sediment loads associated with unpaved roads and landslides from Ecology's source assessment (Roberts et al., 2012) are from within the drainage area of the impaired segment, but the bank erosion loads are for most of the mainstem. Therefore, the bank erosion loads in this report differ from those applied in the *2015 Deschutes TMDLs* because EPA used a subset of the bank erosion loads from the Raines study (2007) that reflect those contributed within and upstream of the impaired segment.

Upland sheet and rill erosion, which is source of fine sediment commonly evaluated for sediment TMDLs and accounted for in watershed models (EPA 2009), was not assessed in the *2015 Deschutes TMDLs* and has been identified as a contributor to much of the unattributable portion of sediment budget. EPA estimated the average annual soil loss from sheet and rill erosion in the contributing drainage area using the U.S. Department of Agriculture Agricultural Research Service's Revised Universal Soil Loss Equation (RUSLE; Renard, 1997). While RUSLE was originally developed for agricultural land, it has been widely adapted to estimate erosion from other disturbed landscapes such as forests (Dissmeyer and Foster, 1980; Toy and Osterkamp, 1995), which comprise much of the upper watershed. RUSLE was selected because heterogenous landscape attributes, such as soil erodibility, can be varied spatially across the landscape.

EPA combined Ecology's loading estimates for unpaved roads and landslides from its *2015 Deschutes TMDLs* with the revised loading estimate for streambank erosion and the upland sheet and rill erosion loads to calculate the total existing sediment load from sources upstream of the impaired segment.

2.1 EXISTING LOADING BASED ON THE *2015 DESCHUTES TMDLS*

This section provides a synopsis of the source assessment for each source category included in the *2015 Deschutes TMDLs*, as it is being used for the bulk of the source assessment for this TMDL. A more detailed description of the Raines report (2007), which is the basis of the loadings presented below, is included in the *2015 Deschutes TMDLs*, as well as its Technical Report (Roberts et al., 2012).

2.1.1 Bank Erosion

Evidence of bank erosion was evaluated and then digitized along the mainstem of the Deschutes River from Deschutes Falls (River Mile RM 42) to the mouth using digital orthophotographs from 1991 and 2003 and LiDAR (Light Detection and Ranging) data from a 2002 flight. Data from field studies were combined with the mapped eroded areas to estimate the volume of sediment less than 2 mm contributed to the river from bank erosion. Based on tabulating just the upper watershed loads from Raines (2007), the average annual contribution of fine sediment from hillslope and glacial terrace bank erosion to the impaired segment of the Deschutes River is approximately 1,200 yd^3/yr.

2.1.2 Landslides

Weyerhaeuser Company inventoried and mapped over 100 landslides in the upper Deschutes River watershed from 1966 to 2001, and those data were the basis for the loading estimate in the Raines report (2007) and the *2015 Deschutes TMDLs*. Particle attribution assumptions from an earlier study (Collins, 1994) were applied to estimate the fine sediment fraction of the total delivered load from landslides (70 percent). Landslides associated with roads are reported as contributing nearly three times as much sediment per year compared to landslides not associated with roads (which are assumed to be associated with historical timber harvest). Based on this source assessment, the average annual fine sediment load from landslides is approximately 4,500 yd^3/yr.

2.1.3 Unpaved Roads

More than half of the roads in the Deschutes River basin are unpaved and susceptible to erosion. Road surface erosion was quantified by Raines (2007) for the Upland Transition Zone (above RM 34), which is fully upstream of the fine sediment impaired segment, using the Washington Road Surface Erosion Model (WARSEM; Dubé et al. 2004). Average annual sediment loads from unpaved roads were modeled with WARSEM based on road characteristics such as length of road, geologic erosion factor (low, moderate, high), road classes that represent traffic (main haul roads and other unpaved roads), and connectivity to the stream network (direct to stream (e.g., connected by drainage ditch) or partial within 200 feet). The annual load of fine sediment contributed to the impaired segment by unpaved roads which was applied in the *2015 Deschutes TMDLs* and used in this report is 3,000 yd^3/yr.

2.2 UPLAND SHEET AND RILL EROSION

A quasi-steady-state, grid-based approach was used to estimate existing average annual soil loss with RUSLE. The RUSLE method estimates the average sheet and rill erosion (A) in short tons/ac/year caused by rainfall and its associated runoff through five multiplicative factors in the equation below and summarized in Table 1:

$$A = R * K * LS * C * P$$

Table 1. RUSLE Factors.

RUSLE Variable	RUSLE Factor
R	Rainfall-Runoff Erosivity Factor
K	Soil Erodibility Factor
LS	Slope Length and Steepness Factor
C	Cover-Management Factor
P	Support Practice Factor

For this study, the RUSLE approach was implemented spatially (grid-based) and parameter inputs were built on equations and recommendations in the RUSLE's user guide to estimate upland soil loss from sheet and rill erosion. The methods used to calculate the RUSLE input parameters are described below and the spatial coverages used to develop gridded input parameters are listed in Table 2.

Table 2. Gridded Data Sources for RUSLE Modeling.

RUSLE Factor	Data Source
Rainfall-Runoff Erosivity (R)	Isoerodent Map for Washington and Oregon developed by EPA in 2001
Soil Erodibility (K)	Gridded Soil Survey Geographic (gSSURGO) variable KFFACT (10 meter)
Slope Length and Steepness (LS)	United States Geological Survey (USGS) National Elevation Dataset (10-meter DEM)
Cover-Management (C)	LANDFIRE Existing Vegetation Types (current vegetation); LANDFIRE Biophysical Setting for pre-Euro-American settlement vegetation (natural vegetation); representative C factors for the western U.S. (Theobald, et al., 2010)
Support Practice (P)	Assumed to be one

2.2.1 Rainfall-Runoff Erosivity Factor (R)

The rainfall erosivity factor is a function of total storm energy and of the maximum 30-minute intensity, expressed by the following equation (Renard et al., 1997):

$$R = \sum_{year} E_{storm} I_{30}$$

Where R is the rainfall erosion index in 100s of ft tonf in ac^{-1} hr^{-1} yr^{-1} (also denoted in some references as *EI*), E_{storm} is the total storm energy in 100s of ft tonf ac^{-1} and I_{30} is the maximum 30-minute intensity in inches per hour. Tonf stands for ton-force, the weight of one ton due to standard gravity. Rainfall erosivities from individual storms are summed across a year to establish the average annual rainfall erosion index.

E_{storm} represents the energy of a rainstorm and is evaluated as a function of storm intensity as follows (Wischmeier and Smith, 1958):

$$E_{storm} = \ 916 + 331 \ \log_{10} i \, , i \leq 3 \ in \cdot hr^{-1}$$

$$E_{storm} = 1074, i > 3 \ in \cdot hr^{-1}$$

An isoerodent map representing contours of R across Washington and Oregon was previously developed using historic rain gage data. The isoerodent map was published in the United States Department of Agriculture Agricultural Research Service's *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (*Renard et al., 1997; Pitt, 2004). The isoerodent map was digitized to contours to generate an interpolated R raster for RUSLE modeling (Figure 2).

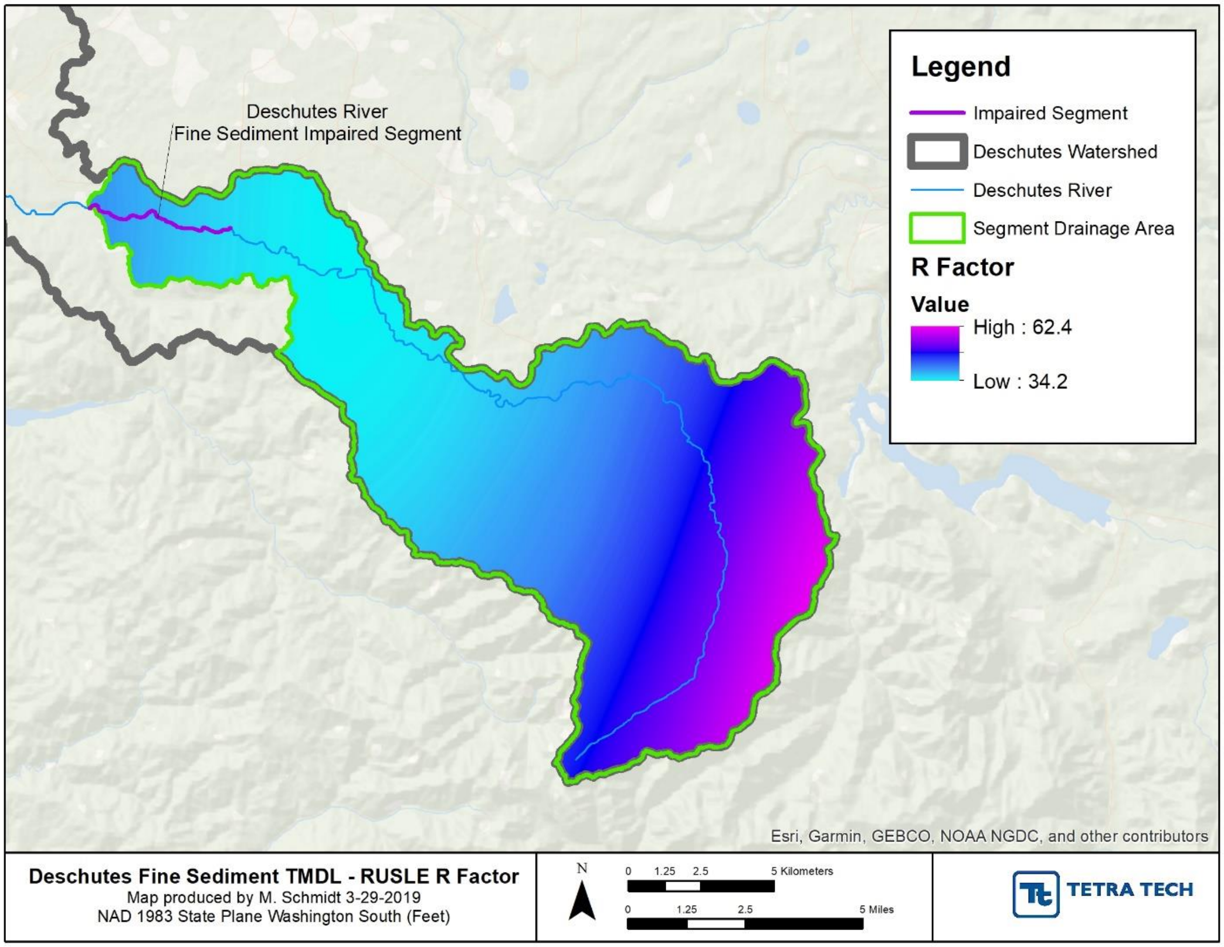

Figure 2. RUSLE R Factor.

2.2.2 Soil Erodibility Factor (K)

The soil erodibility factor quantifies erosion vulnerability due to physical soil traits that are available in a gridded format through the U.S. Department of Agriculture, Natural Resources Conservation Service Gridded Soil Survey Geographic Database. The soil erodibility factor (K; ton ac hr 100s^{-1} acft^{-1} tonf^{-1} in^{-1}) represents the susceptibility of soil to erosion during precipitation events due to physical soil traits. K factor ranges from zero to the possible maximum of one, with higher values reflecting a higher susceptibility to erosion. K factor was extracted from the nation-wide gSSURGO dataset (KFFACT, 30 m resolution; USDA, 2016) for RUSLE (Figure 3, resampled to 10 m resolution).

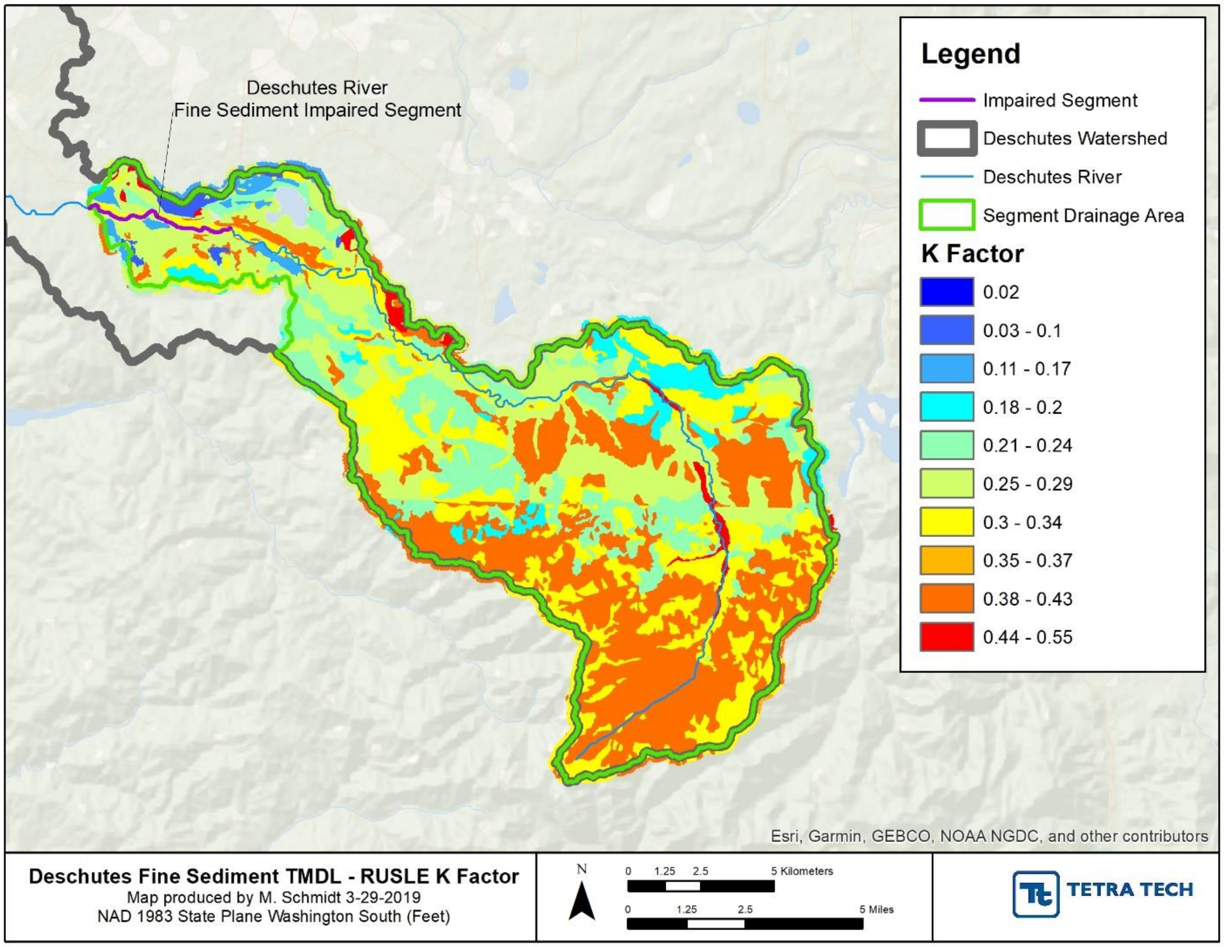

Figure 3. RUSLE K Factor.

2.2.3 Slope Length and Steepness Factor (LS)

Slope Length (L) and Steepness (S) Factors, which represent the combined effects of slope steepness and length on erosion, were estimated using a 10-meter resolution Digital Elevation Model (DEM) for the study area. Mitasova et al. (1996) developed Geographical Information System (GIS) based approach incorporating impacts of flow convergences by replacing hillslope length with upslope contributing area. The equation from Mitasova was refined by Fernandez et al. (2003) to calculate the S factor separately for high and low slopes to allow for variable types of erosion which occur on different slopes. Pits in the DEM, which may not be true sediment traps due to the resolution of the DEM, were filled prior to development of the L factor and S factor grids, as recommended in Cavalli et al., 2014. L factor was calculated as:

$$L = (m+1) * \left(\frac{A}{a_0}\right)^m$$

The value m was set to 0.6, as determined by Moore and Wilson (1992) to provide RUSLE results consistent with theoretical sediment transport equations for slope lengths less than 100 m (328 ft) and slope angles less than 14 degrees. The parameter a_0 is the standard RUSLE plot length, 22.13 m (72.6 ft), and A is the upslope contributing area in square-meters per unit width in meters (or square-feet per unit width in feet). A grid of contributing area per unit grid width was generated as an intermediate step in the development of the Index of Connectivity grid

(Section 2.2.6) and it was used for input parameter *A.* A maximum limit on slope length of 150 m (492 ft) was imposed based on Fernandez et al. (2003).

As refined by Fernandez et al. (2003), the S factor can be calculated for slopes (*b*) above and below 5.14 degrees as follows:

$$S(b < 5.14°) = 10.8 * \sin(b) + 0.03 \qquad\qquad S(b \geq 5.14°) = 16.8 * \sin(b) - 0.5$$

The slope grid from the Index of Connectivity (Section 2.2.6) was used for *b* to generate the S factor grid. The LS Factor grid was created by multiplying the L Factor by the S Factor, and LS was limited to a maximum of 72.15 to be consistent with the RUSLE User's Manual (Figure 4).

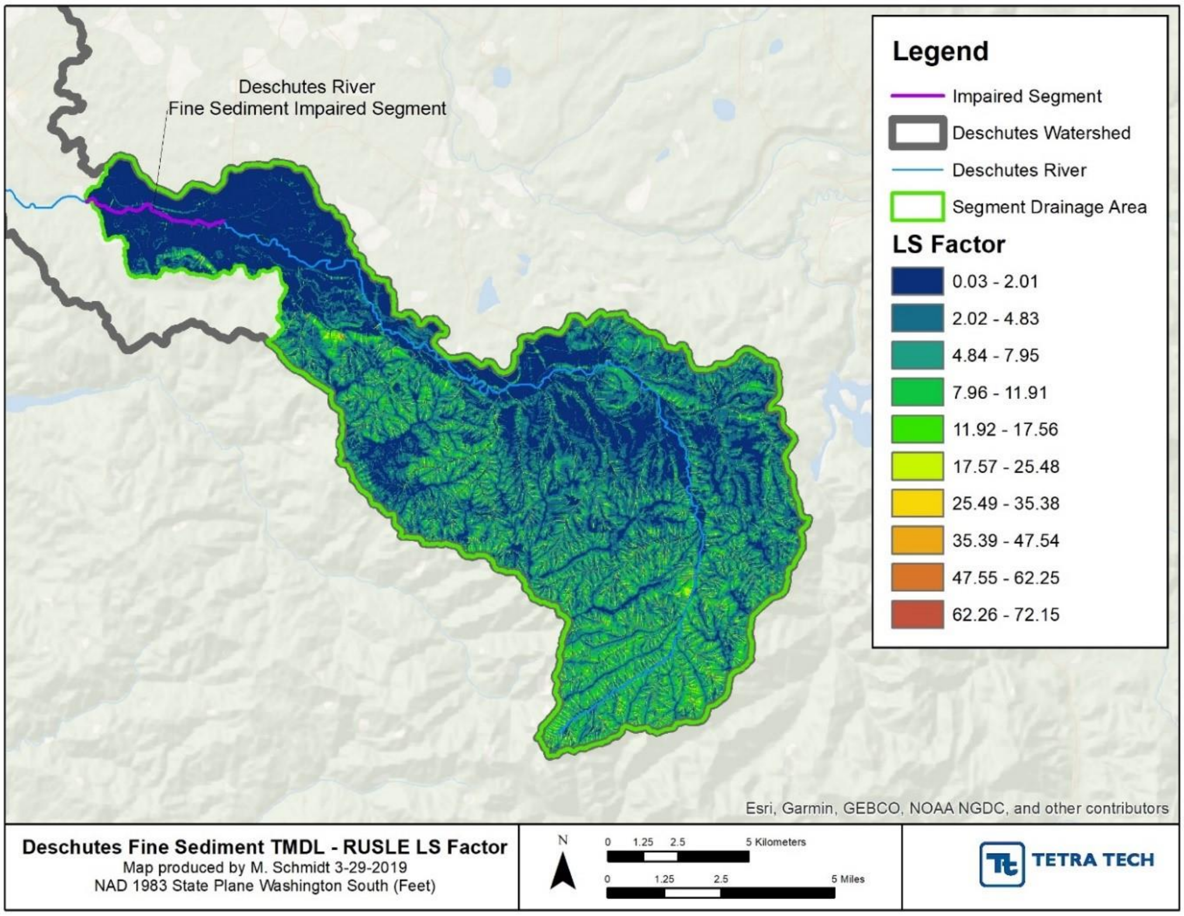

Figure 4. RUSLE LS Factor.

2.2.4 Cover Management Factor (C)

The Cover-Management Factor (C) is used to represent the effect of vegetative cover and management practices employed to reduce erosion, with lower values representing more soil cover and lower erosion potential. The mix of vegetative canopy, soil surface cover, soil surface roughness, and impacts of low soil moisture on the reduction of runoff from lower intensity rainfall events impact the C factor (Renard, et al., 1997). The C factor is often developed as a weighted average of the soil loss rate (SLR) over the year, with weighting by the erosivity index for each time period. However, because most of the watershed land cover does not rapidly change, it is suggested by Renard et al. (1997) that a single annual factor can be used, in which case C is simply equal to SLR.

SLR can be determined as the product of five subfactors:

$$C = SLR = PLU * CC * SC * SR * SM$$

Where the subfactors are: Prior Land Use subfactor (PLU), Canopy Cover subfactor (CC), Surface Cover subfactor (SC), Surface Roughness subfactor (SR), and Soil Moisture subfactor (SM).

The data required for these subfactors was not available for the study area, therefore, an alternative approach to C factor grid creation was employed. Theobald et al. (2010) compiled C factor values from multiple studies to establish representative C factors for aggregated LANDFIRE (Existing Vegetation Type (EVT) classes; Figure 5) for the western U.S., including natural and human-modified covers. The C factor grid was developed for RUSLE based on the reference C factors (Theobald, et al., 2010) and LANDFIRE EVT for the study area, as shown in Figure 3 and Figure 6. Lower C factors represent higher vegetative cover that protects soils from rainfall impact and erosion. A value of 1 is recommended for barren land in Theobald et al., 2010. Barren land does not provide appropriate media to support plant growth; therefore, a high C factor is representative of negligible vegetative cover and is applied in this evaluation, however, barren land constitutes only a small portion of the drainage area. Roads were excluded from the RUSLE analysis (C factor = 0) since they were assessed as part of a separate analysis.

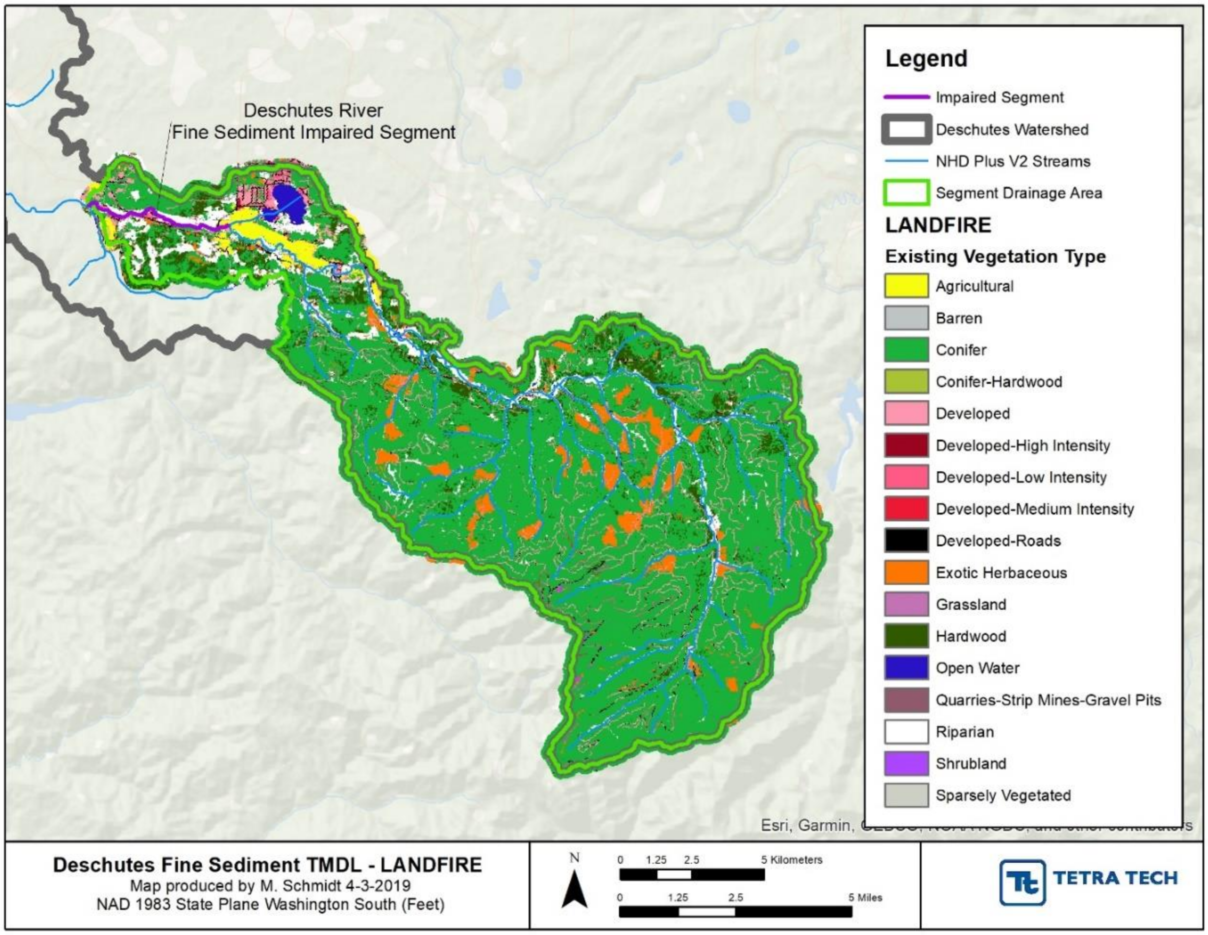

Figure 5. LANDFIRE Existing Vegetation Type.

Table 3. C Factors by Land Cover.

Land Cover in Study Area	Percent of Study Area	C factor
Agricultural	1.65%	0.5
Barren	0.02%	1
Conifer	70.82%	0.002
Conifer-Hardwood	0.19%	0.001
Developed	6.05%	0.003
Developed-High Intensity	0.02%	0.002
Developed-Low Intensity	0.89%	0.003
Developed-Medium Intensity	0.06%	0.002
Developed-Roads	1.10%	0
Exotic Herbaceous	4.53%	0.2
Grassland	0.05%	0.012
Hardwood	6.91%	0.001
Open Water	0.61%	0
Riparian	6.95%	0.001
Shrubland	0.15%	0.029
Sparsely Vegetated	0.01%	0.2

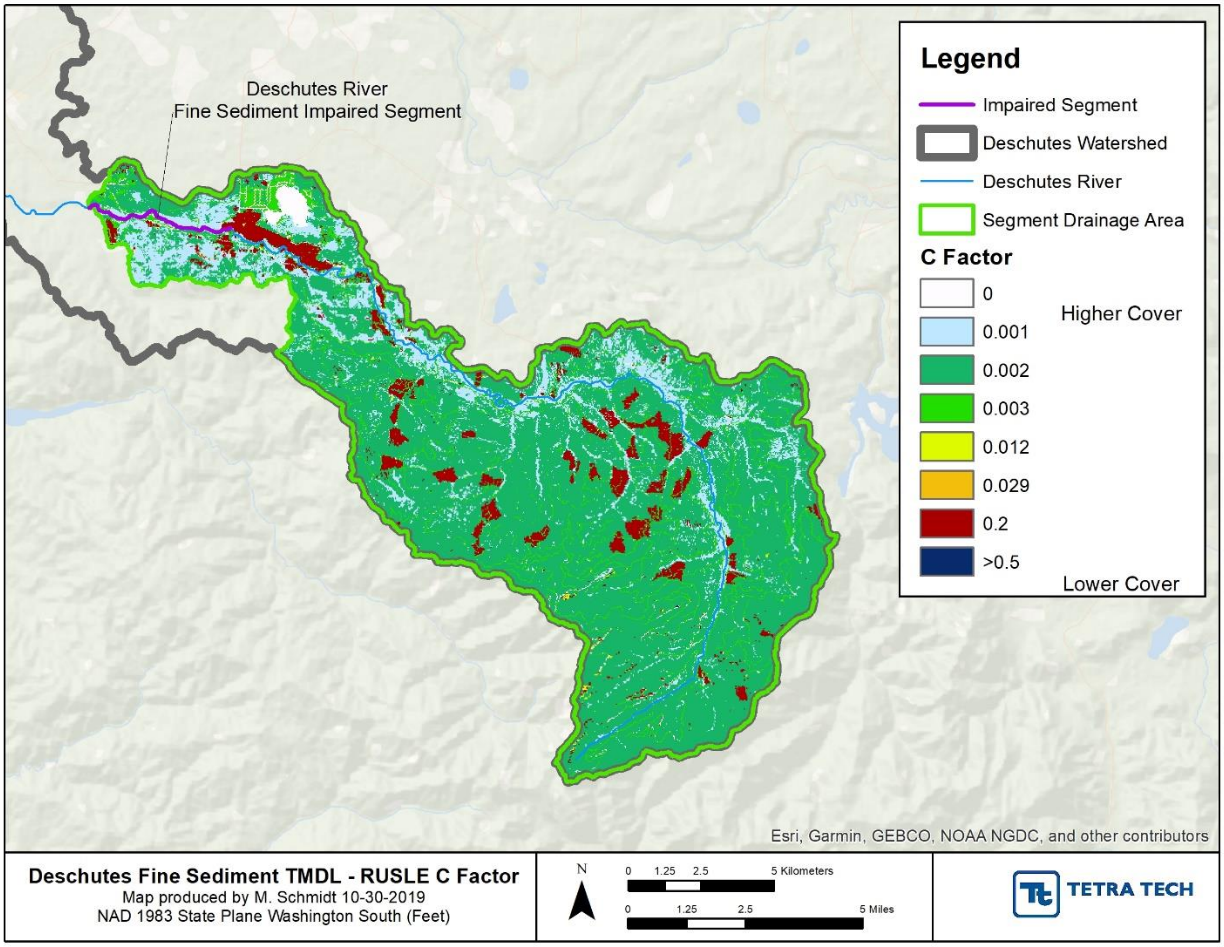

Figure 6. RUSLE C Factor.

2.2.5 Support Practice Factor (P)

The Practice Support Factor (P) reflects the impact of support practices associated with reducing erosion on cropland (e.g. crop contouring, terracing). A P Factor of one is typically assumed for non-agricultural lands. A higher P Factor (on a scale of zero to one) indicates less protective support practices and higher erosion rates. These practices tend to vary at a scale that is finer than practical for using in TMDL development and information regarding application of these practices in the watershed is uncertain, therefore, the practice (P) factor was set uniformly to one (i.e., neutral impact on soil loss).

2.2.6 Sediment Delivery Ratio

RUSLE provides an estimate of soil loss but does not directly estimate downstream delivery of upland sediment, much of which may be trapped near the source. It is common practice to apply a sediment delivery ratio (SDR) to RUSLE soil loss to estimate sediment yield to the river. Advanced GIS techniques for determining sediment and flow connectivity on landscapes have been developed to approximate *SDR*s for grid-based applications of RUSLE (Borselli et al., 2008; Vigiak et al., 2012). This provides an effective means of converting the RUSLE analysis to an estimate of delivered sediment yield from upland sources.

To provide a site-specific estimate of *SDR* for each grid cell in the study area, the methods of Borselli et al. (2008) were used to establish flow path connectivity. This method calculates an Index of Connectivity (*IC*) that, for each point, depends on both upslope and downslope components (*D_{up}, D_{dn}*) relative to a receiving point of interest, the stream network for purposes of this study defined using the National Hydrography Dataset (NHD Plus Version 2).

IC is defined for a cell k as the common logarithm of the ratio of upstream and downstream characteristics:

$$IC_k = \log_{10}\left(\frac{D_{up,k}}{D_{dn,k}}\right) = \log_{10}\left(\frac{\overline{W_k}\,\overline{S_k}\,\sqrt{A_k}}{\sum_{i=k,n_k} {d_i}/{(W_i S_i)}}\right)$$

for the ith cell, W_k is the average weighting factor for the upslope contributing area, S_i is the slope of the ith cell, $\overline{S_k}$ is the average slope of the contributing area, A_k is the upstream contributing area, and d_i is the length of the ith cell along the downslope path ending at cell n_k. The dimensionless weighting factors are typically computed from RUSLE C factors or surface roughness measures (Vigiak et al., 2012; Cavalli et al., 2013, 2014).

The Connectivity Index ToolBox in Environmental Systems Research Institute's geographic information system ArcGIS (Cavalli et al., 2013, 2014) uses inputs of high-resolution elevation data to estimate an IC grid. Elevation data at a 10 m resolution (National Elevation Dataset) retrieved from the USDA Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/) was used for this study and the C factor grid (Section 2.2.4) was applied as the surface roughness weighting factor. The SDR grid was then derived such that SDR for a cell $\boldsymbol{i}$ was estimated using a sigmoid model of delivery that takes the following form:

$$SDR_i = SDR_{max,i} \times \left[1 + exp\left(\frac{IC_o - IC_i}{k}\right)\right]^{-1}$$

In this equation, IC_o and k are calibration parameters, IC_i is the Index of Connectivity for the ith cell, and $SDR_{max,i}$ is the maximum possible delivery ratio for the ith cell, usually defined on the basis of particle size. Vigiak et al. (2012) defined the maximum SDR based on topsoil particles finer than coarse sand – thus indicating that the approach estimates delivery primarily of fine sediment with diameters less than 2 mm (very coarse sand).

Vigiak et al. calibrated the approach to sediment data at the mouth of the Avon-Richardson catchment in southeast Australia. The best fit was obtained with IC_o set to 0.5, which is the same value found in previous studies in Italy (Borselli et al., 2008), and Vigiak suggests that this factor may be landscape-independent. This leaves k as the primary calibration factor, for which Vigiak et al. obtained a best fit with k = 2. For application to the catchment of the impaired segment, IC_o was set to 0.5 and k was set to 2. SDR_{max} was derived using the mean soil particle diameter in the top 50 cm of soil from gSSURGO for the ith cell, d_i, and Wentworth grain size classifications (representative particle diameters were selected from the middle range of diameters for clay, silt, and sand and equaled 2 µm for clay, 27 µm for silt, and 262.5 µm for sand). SDR_{max} was computed from the following equation from Vigiak et al. (2012):

$$SDR_{max,i} = 0.92 - 0.00093 d_i$$

The previous two equations were combined to derive the *SDR* grid for the catchment, which is shown in Figure 7. *SDR* varies from a minimum of 0.000 to a maximum of 0.519, with the mean *SDR* being 0.018, which is less than the catchment-wide *SDR* derived using the watershed area approach presented in Bicknell et al. (2001), which estimates a spatially uniform *SDR* of 0.105.

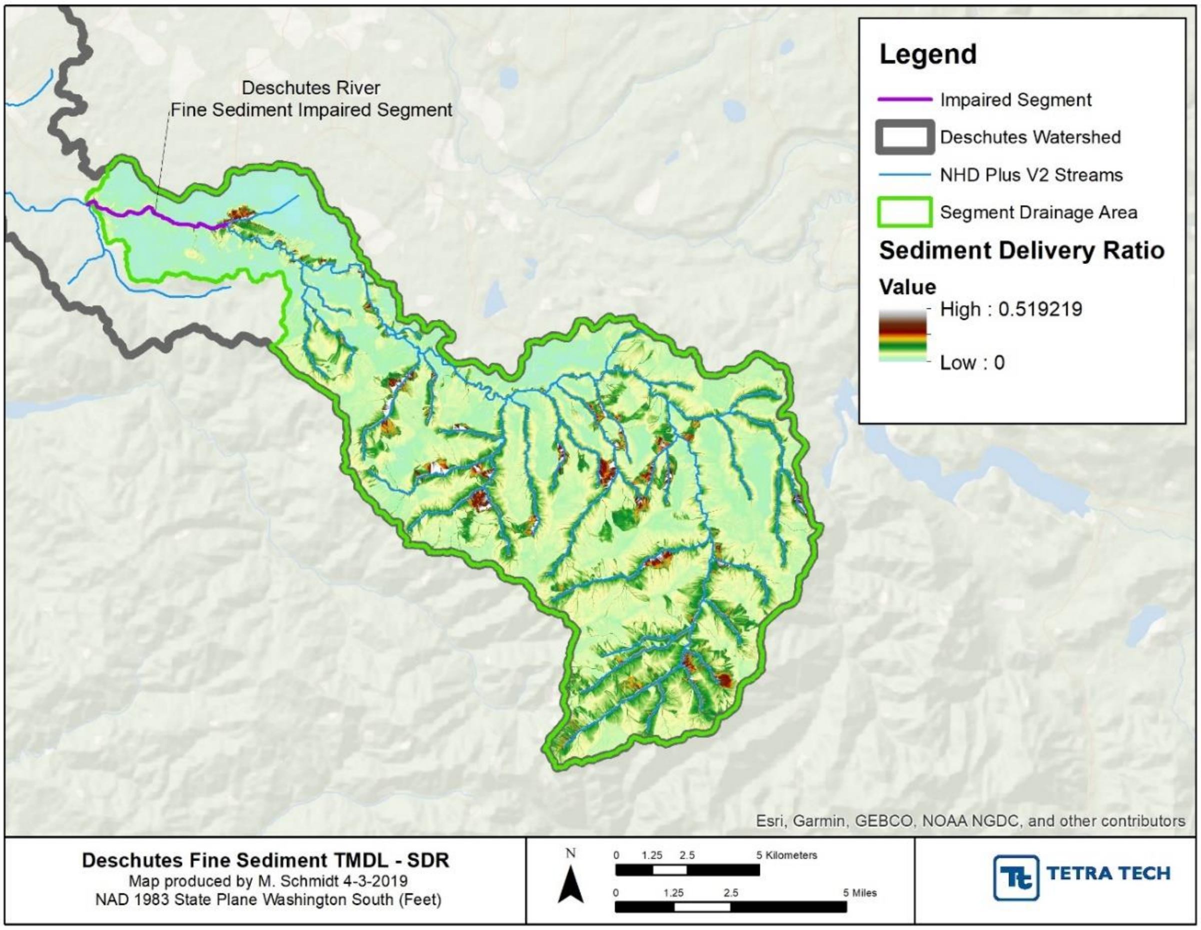

Figure 7. Sediment Delivery Ratio (*SDR*).

2.2.7 Upland Sediment Load

The existing average annual upland sediment load to the Deschutes River fine sediment impaired segment are tabulated by land use in Table 4. Unit area (tons/ac/yr) sediment loads are shown for the study area in Figure 8. The average annual upland sediment yield delivered to the impaired reach totals 1,494 tons/yr. This is primarily fine sediment because particles sizes of 262.5 µm or less (< 0.2625 mm) were applied in the development of the *SDR* grid. A representative bulk density of 1.07 g/cm^3 (0.90 tons/yd^3) from gSSURGO (dbovendry_r; USDA, 2016) was used to translate from sediment mass to volume for a total of 1,660 yd^3/yr from sources of upland erosion.

Less than 6 percent of the total upland load is attributed to agriculture, developed land, and grassland/shrubland. However, as Figure 5 shows, the majority of agricultural land is in close proximity to the mainstem, directly upstream of the impaired segment. Sediment eroded from this surrounding agricultural land, and other areas surrounding the stream network, has a relatively short landscape transport distance, which reduces the likelihood of eroded sediment in runoff being redeposited on land, and reincorporated into the sediment matrix, prior to reaching the river. More than 75 percent of the land draining to the fine sediment impaired segment is classified as forest, primarily coniferous forest. This land cover class includes areas where timber harvest is conducted following Washington's Forest Practices Habitat Conservation Plan. Forests contribute only 11 percent of the total upland load (189 yd^3/yr) due to protective vegetative cover that limits erosion. Upland sediment is highest from barren and sparsely vegetated areas where soils are exposed and susceptible to rainfall impact (e.g., heavily harvested forests, old landslides, or burned areas typically classified as exotic herbaceous by LANDFIRE; Figure 5). These areas tend to be concentrated on relatively steep slopes near the stream network. The estimated average annual sheet and rill erosion load from barren and sparsely vegetated areas in the drainage area is 1,374 yd^3/yr; most of this load originates from exotic herbaceous land, which covers nearly 5 percent of the drainage area. This estimate partially represents surface erosion of old landslide areas. Direct delivery of sediment to the stream network at the time of landslide events is quantified separately in Section 2.1.2.

Table 4. Average Annual Upland Fine Sediment Yield Delivered to the Fine Sediment Impaired Segment.

Land Cover	Average Annual Upland Fine Sediment Yield	
	tons/yr	yd^3/yr
Agriculture	41	45
Barren/sparse/exotic herbaceous vegetation (including clearcut forests)	1,237	1,374
Developed (low, medium, and high density)	28	32
Forest (hardwood and conifer)	170	189
Grassland/shrubland/riparian	18	19
Total	1,494	1,660

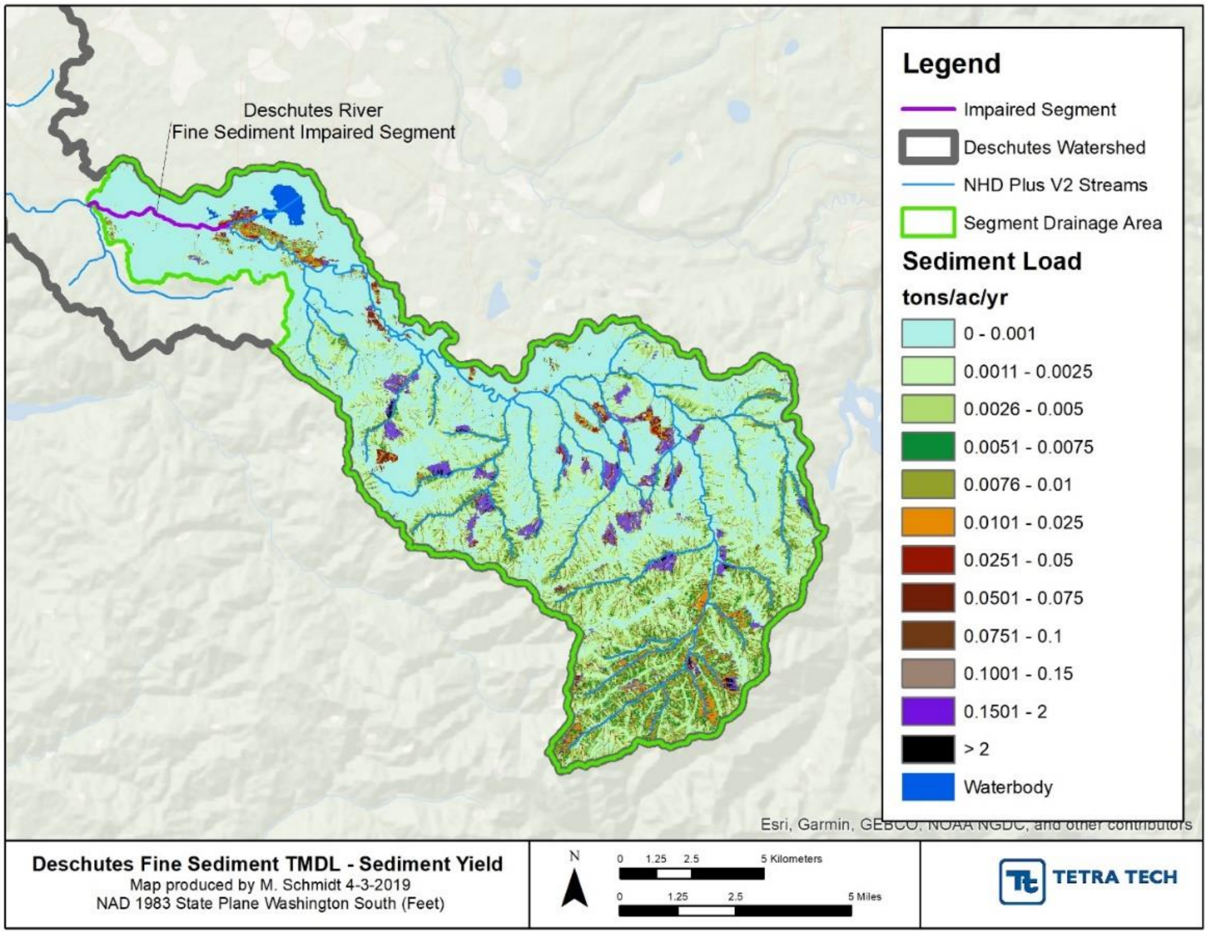

Figure 8. Upland Sediment Yields (tons/ac/yr).

2.3 SUMMARY OF EXISTING LOADS

The existing average annual sediment load from upland sheet and rill erosion, bank erosion, unpaved roads, and landslides is summarized in Table 5. Historical dredging data and bathymetric surveys were used to estimate the annual average sediment load of 36,000 yd^3/yr to Capitol Lake for Ecology’s 2015 TMDL submittal. Ecology’s *Technical Report* for the *2015 Deschutes TMDLs* (Roberts et al., 2012) indicated approximately 76 percent of the loads estimated by Raines (2007) from bank erosion, landslides, and unpaved roads consisted of fine sediment. Assuming that same percentage applies to the 36,000 yd^3 of sediment Ecology estimated goes into Capitol Lake annually from the watershed, then 27,315 yd^3 of that load is fine sediment.

Forty six percent of the Deschutes River watershed is upstream of the fine sediment impaired segment. If the annual average sediment load contributed to the lake from the watershed upstream of the impaired segment of the river corresponded to its percent of the total watershed, the load would be 12,565 yd^3/yr (i.e., 46 percent of 27,315 yd^3/yr). However, given that sources of sediment in the lower watershed, such as construction activities, agriculture, and urban development, are in closer proximity to the lake, they likely have a greater relative contribution to the total sediment load compared to sources in the upper watershed that partially deposit along the stream bed and banks prior to reaching the lake.

Table 5. Existing Average Annual Sediment Loads to the Fine Sediment Impaired Segment.

Sediment Source	Fine Sediment Volume (yd^3/yr)	Fine Sediment Load (tons/yr)[1]	Relative Load Contribution (%)
Upland sheet and rill erosion	1,660	1,494	14.4%
Bank erosion	1,200	1,080	10.4%
Unpaved roads	3,000	3,780	36.3%
Landslides	4,500	4,050	38.9%
Total	10,360	10,404	100%

[1] A representative bulk density from gSSURGO of 0.9 tons/yd^3 was applied to translate sediment volume loads to mass loads for upland sheet and rill erosion, bank erosion, and landslides. A representative bulk density of 1.26 tons/yd^3 from Raines (2007) was applied similarly for unpaved roads.

3.0 NATURAL CONDITIONS SEDIMENT SOURCE ASSESSMENT

The average annual sediment load to the impaired segment that would occur under natural, or pre-anthropogenic, conditions in the watershed was also estimated. This was done to for two purposes: 1) To evaluate loading reductions that could be achieved under natural conditions to see how that compares to the reduction needed in percent embeddedness; and 2) To support the calculation of the background Total Suspended Solids (TSS) concentration and the associated turbidity, which is the baseline for the turbidity water quality standard.

3.1 NATURAL LOADING BASED ON THE *2015 DESCHUTES TMDLS*

The *2015 Deschutes TMDLs* classified sediment attributed to unpaved roads and associated landslides (as indicated in the Weyerhaeuser Company landslide inventory) as anthropogenic. The natural sources of loading were identified as bank erosion due to fluvial geomorphology, which assumes that human activities have not significantly altered the flow regime in the upper watershed, and landslides that were not associated with roads. However, the Raines (2007) report indicates that landslides not associated with roads tend to be attributed to timber harvest. For the revised TMDL, EPA has reclassified the full sediment load from landslides to the non-natural sediment loading category.

3.2 NATURAL LOADING FROM UPLAND SHEET AND RILL EROSION

EPA estimated natural levels of upland sheet and rill erosion using RUSLE following the methods discussed in Section 2.2 and applying an approximation of natural land cover instead of existing land cover. Vegetation on the landscape prior to Euro-American settlement and disturbance is characterized by LANDFIRE’s Biophysical Settings (BPS) coverage (https://www.landfire.gov/bps.php). Natural land cover for the impaired catchment consisted mainly of coniferous forest, with patches of hardwood forest and riparian vegetation, as shown in Figure 9.

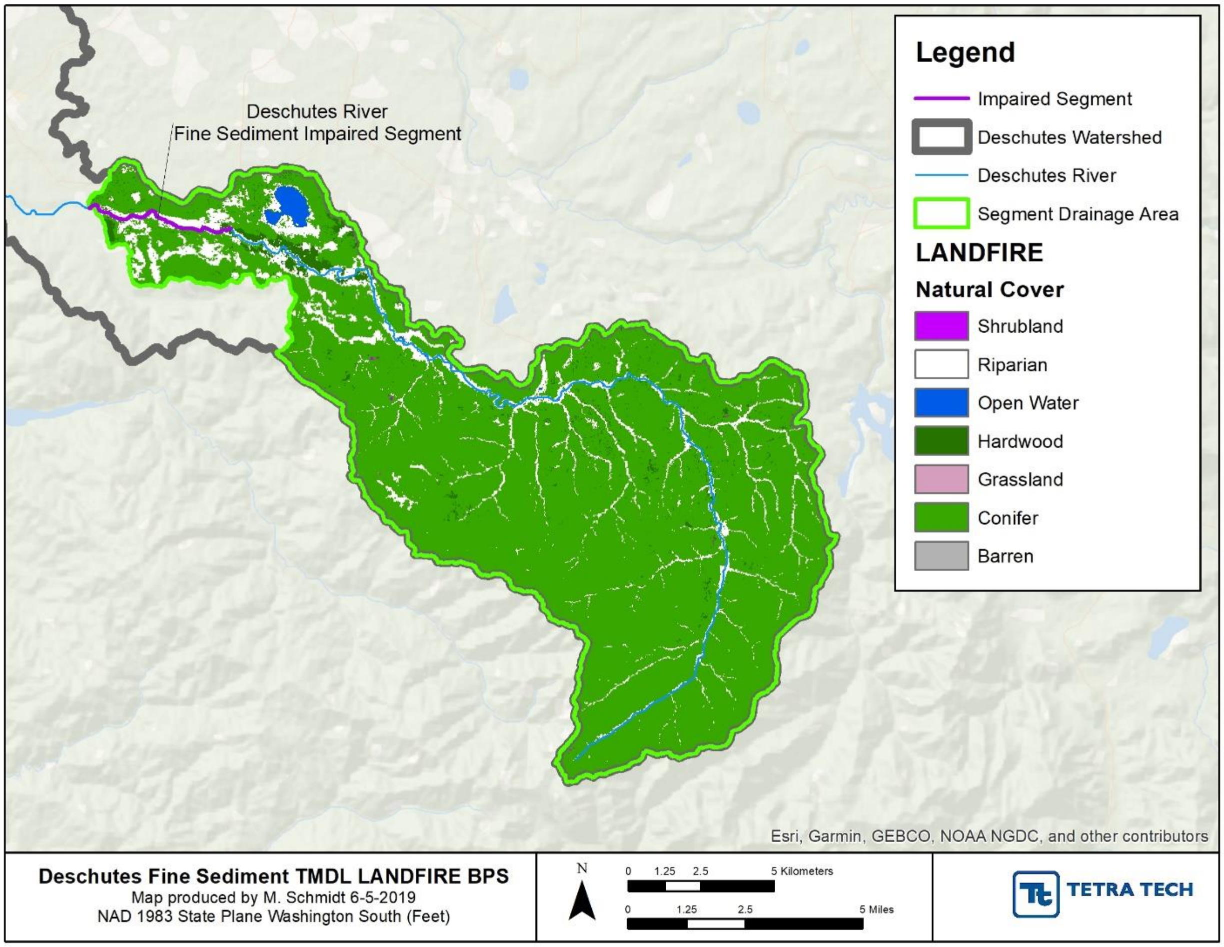

Figure 9. LANDFIRE Biophysical Settings Natural Land Cover.

A natural coverage factor grid was derived for RUSLE based on the BPS coverage and the representative C Factor values (from Table 3), as shown in Figure 10. In addition, a natural SDR grid was developed using the methods discussed in Section 2.2.6 and by applying the natural cover grid as the weighting factor in the development of the IC grid for SDR approximation (Figure 11). All other RUSLE inputs, including the rainfall-runoff erosivity, soil erodibility, slope length and steepness, and practice factors, were kept the same for the natural condition assessment as in the existing conditions assessment. Natural upland loads from sheet and rill erosion are presented in Figure 12. The average annual natural conditions load from upland erosion is 132 tons/yr, which is about 9 percent of the upland erosion load for existing land cover.

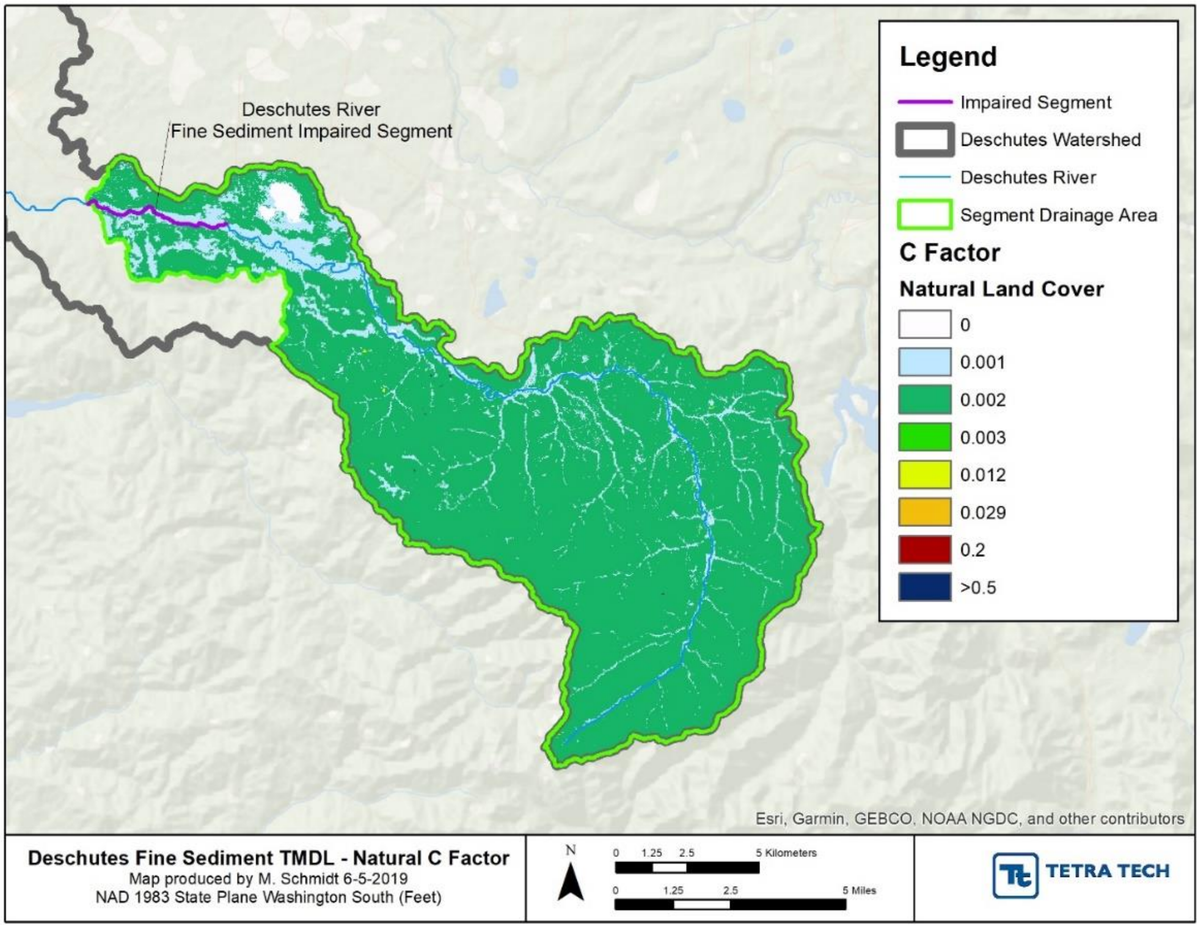

Figure 10. RUSLE C Factor for Natural Land Cover.

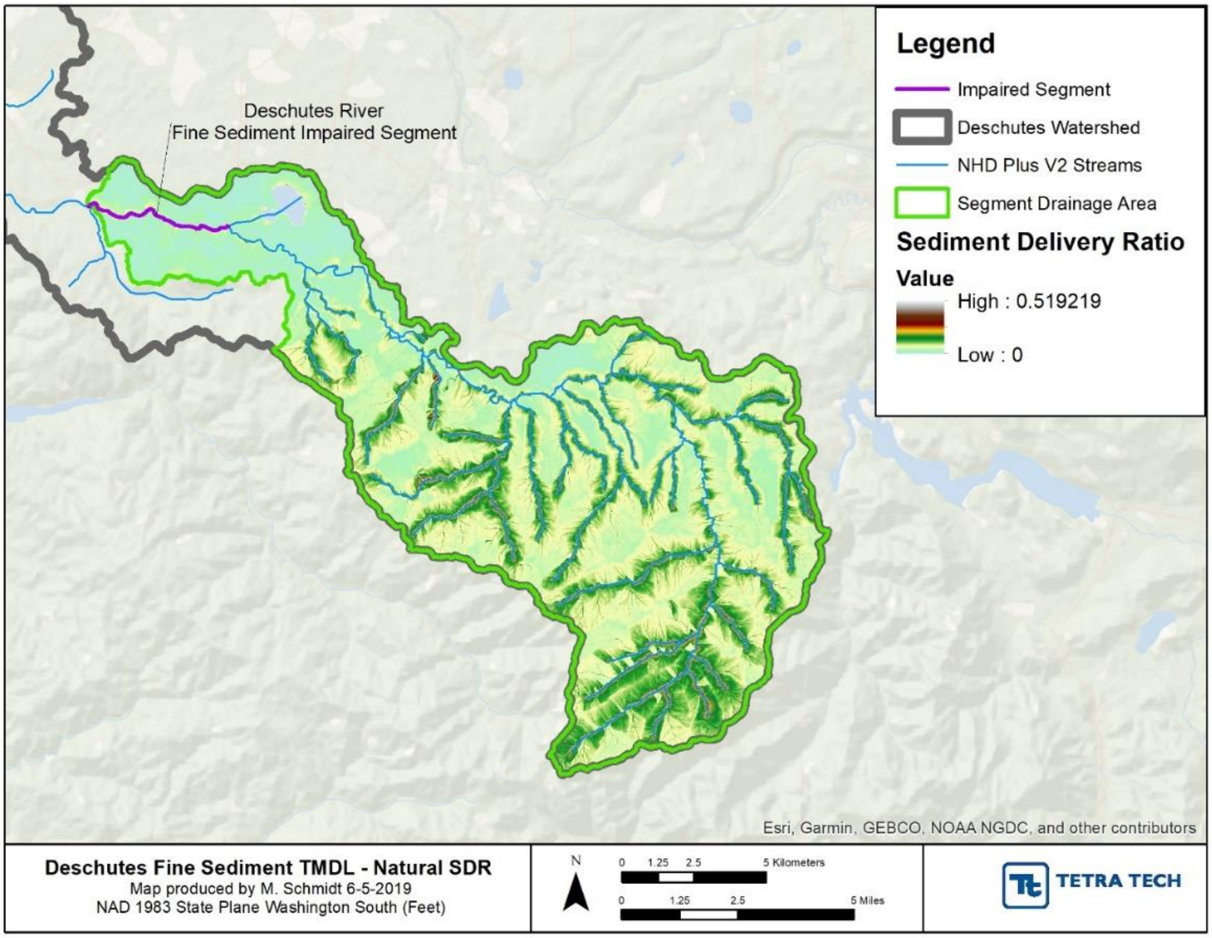

Figure 11. Natural Sediment Delivery Ratio.

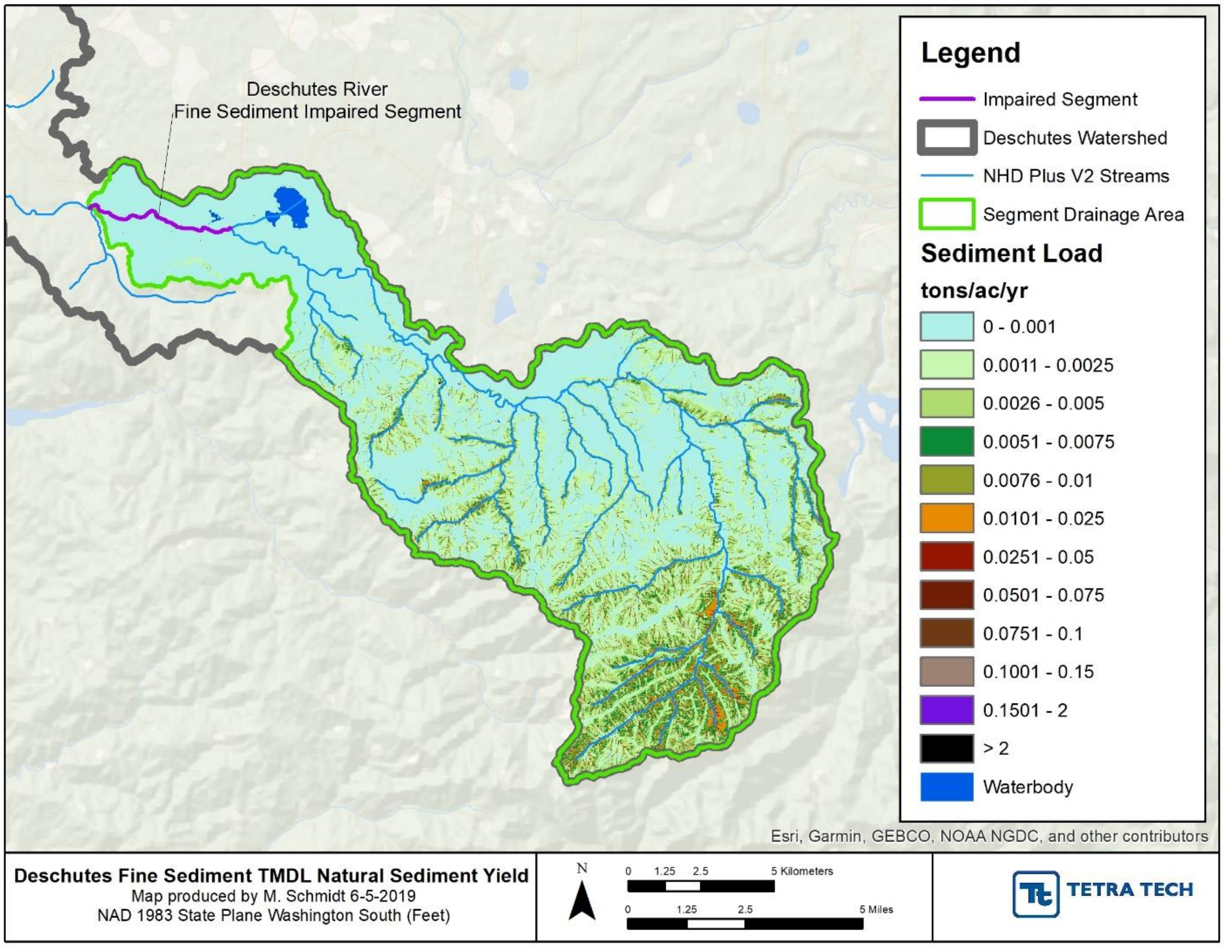

Figure 12. Natural Conditions Scenario Upland Sediment Yields (tons/ac/yr).

3.3 SUMMARY OF NATURAL LOADS RELATIVE TO EXISTING LOADS

Estimated average annual natural fine sediment loads for the impaired river segment are provided in Table 6. The natural sediment load is about 88 percent less than the existing sediment load as shown in Figure 13.

Table 6. Natural Condition Average Annual Sediment Loads.

Sediment Source	Technical Assessment Source	Natural Fine Sediment Load (tons/yr)[1]	Relative Contribution (%)
Upland sheet and rill erosion	RUSLE model	132	10.9%
Bank erosion	Anthropogenic and natural components from Roberts et al., 2012, based on Raines (2007) with landslides reclassified.	1,080	89.1%
Unpaved roads		0	0%
Landslides		0	0%
Total		1,212	100%

[1] A representative bulk density from gSSURGO of 0.9 tons/yd^3 was applied to translate sediment volume loads to mass loads for upland sheet and rill erosion, bank erosion, and landslides. A representative bulk density of 1.26 tons/yd^3 from Raines (2007) was applied similarly for unpaved roads.

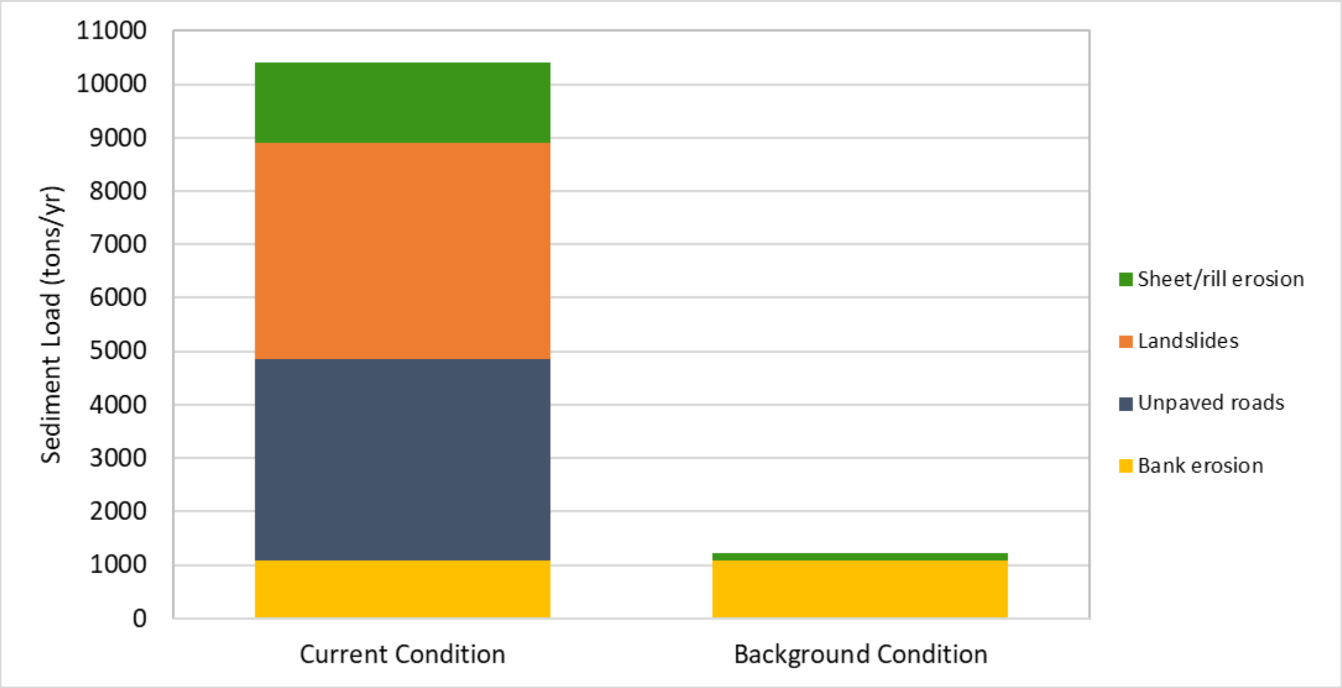

Figure 13. Current and Natural Condition Average Annual Sediment Loads to the Impaired Segment.

4.0 TSS-TURBIDITY REGRESSION

A TSS-turbidity regression was developed so that the TSS concentration associated with natural background and the TMDL for the impaired segment of the Deschutes River could be evaluated within the context of the turbidity standard, which restricts human-induced increases to 5 nephelometric turbidity units (NTU) over background (when background is <50 NTU). This was done to ensure the TMDL is dually protective of the water quality standards for embedded fines and turbidity.

Turbidity is a measure of the attenuation or scattering of a light beam in a water sample. This optical property is affected by color and dissolved organic solids, as well as the shape, size, and mineral composition of particles; however, it is strongly correlated with TSS concentration, especially at higher concentrations. Packman et al. (1999) determined that turbidity provided a good surrogate for TSS in urbanizing streams in the Puget Lowlands. They collected 113 paired samples of TSS (mg/L) and turbidity in NTU for this purpose and performed a linear regression on log-transformed data, resulting in the following model:

$$ln(TSS) = 1.32\, ln(NTU) + 0.15$$

with an explained variance of $R^2 = 0.96$. (They fit a variant model with the same slope but a different intercept for Rutherford Creek).

Packman's results suggest there is a strong correlation between turbidity and TSS. However, the need is to predict turbidity from TSS, not TSS from turbidity. It is not possible to invert the regression equation and solve for NTU because the regression also includes an error term. The regression coefficients that minimize the squared difference between observed and predicted TSS are not the same as those that would minimize the squared difference between observed and predicted NTU (unless TSS and turbidity are perfectly colinear) by virtue of the Cauchy-Schwarz inequality (Mukhopadhyay, 2000).

The original data from Packman et al (1999) were not available, so a reverse regression of NTU on TSS could not be performed with that data set. The Deschutes River also does not have enough paired TSS and turbidity data. However, there are large amounts of paired data from the Deschutes watershed, which is part of what Washington calls Water Resource Inventory Area (WRIA) 13. This is a representative dataset for the study area because it includes streams in the Deschutes River watershed as well as nearby direct drainage to Budd Inlet, east Eld Inlet, and Henderson Inlet.

First, all freshwater surface water samples for turbidity as NTU (1,349 samples) and TSS (1,492 samples) were retrieved. True paired data were identified as samples with the same sample location, sample date, and sample time. Samples for which a collection time was not provided were omitted as they may have been collected hours apart. A number of samples, primarily for TSS, were reported as below detection limits (most commonly 1 mg/L for TSS and 1 NTU for turbidity). These samples were also omitted from the analysis. The final set consisted of 1,062 pairs with dates ranging from 1979 to 2019.

A plot of the raw, untransformed data shows a strong linear relationship, but the strength of this apparent relationship is due to a small number of high TSS – high turbidity samples (Figure 14). Most of the samples had TSS less than 50 mg/L and turbidity less than 40 NTU and the linear relationship is much weaker in this range (Figure 15). A natural logarithm transformation results in a more even spread of the data (Figure 16) and maintains a reasonably high squared correlation coefficient (R^2) of 0.72 for samples below 50 NTU (Figure 17). Much of the residual uncertainty is due to low precision in TSS measurements below 10 mg/L, which are typically reported to the nearest integer value.

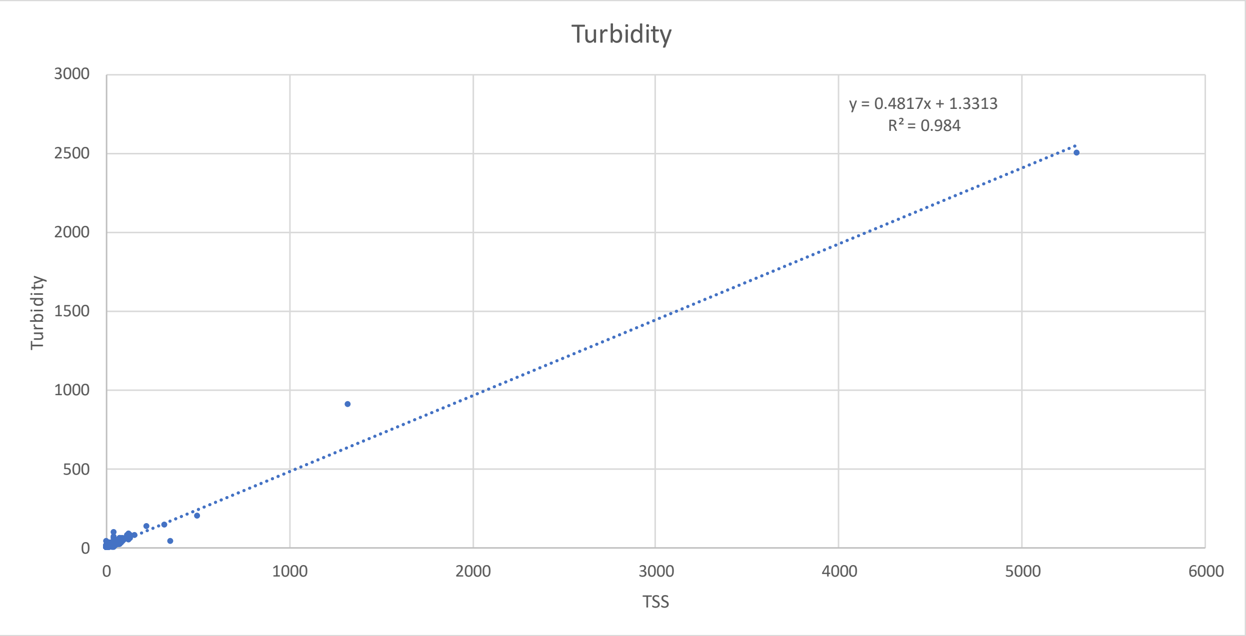

Figure 14. Linear Relationship between Turbidity (NTU) and TSS (mg/L), Full Data Set.

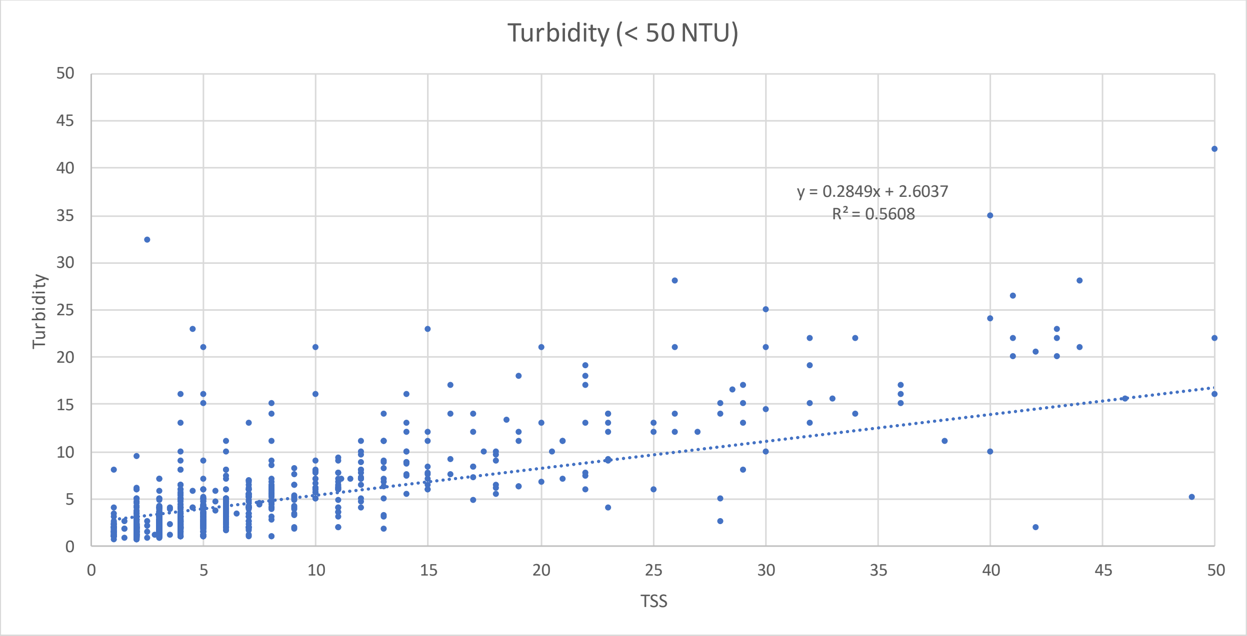

Figure 15. Linear Relationship between Turbidity (NTU) and TSS (mg/L), Samples with Turbidity < 50 NTU.

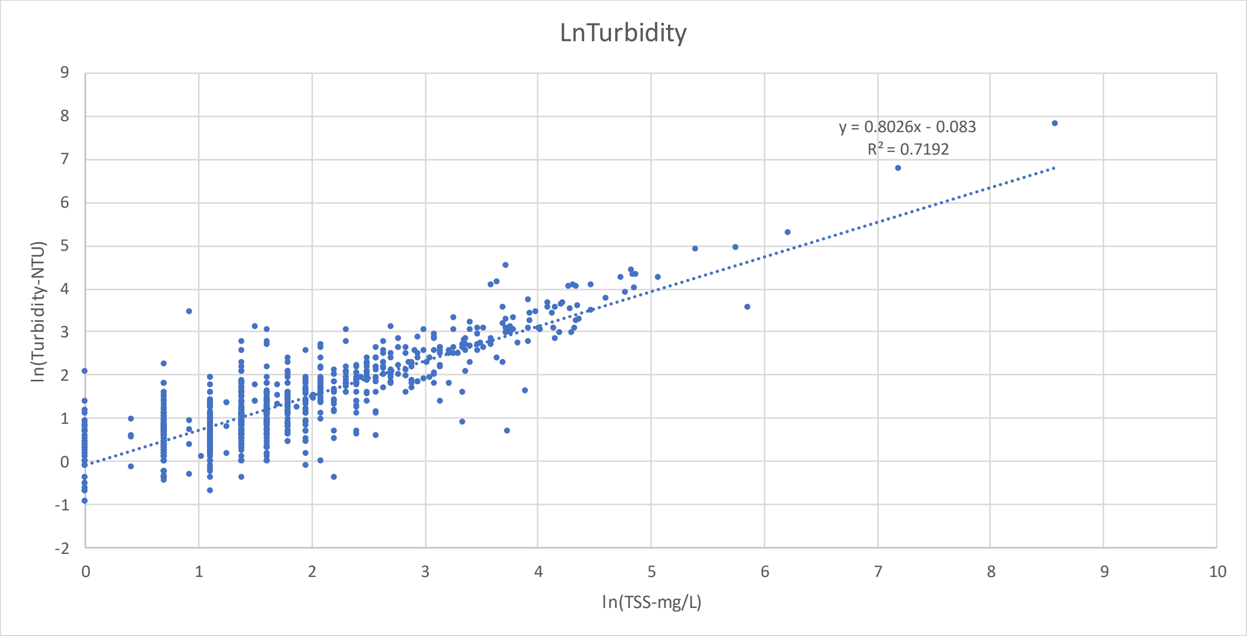

Figure 16. Linear Relationship between Ln(Turbidity) and Ln(TSS).

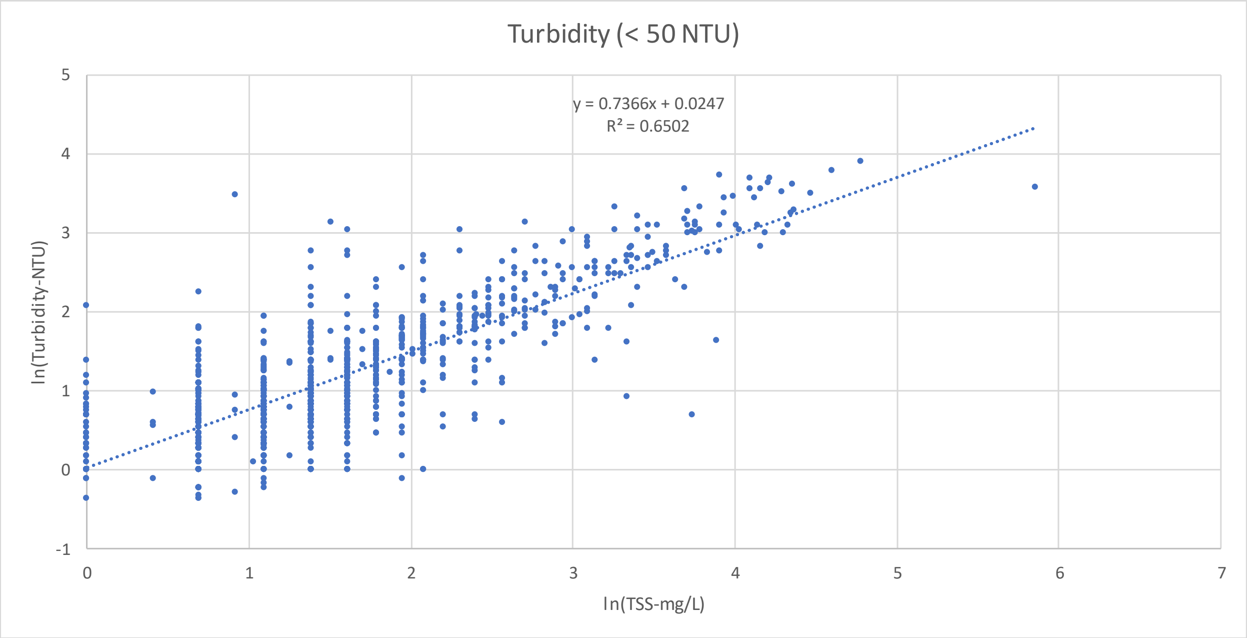

Figure 17. Linear Relationship between Ln(Turbidity) and Ln(TSS), Samples with Turbidity < 50 NTU.

The resulting regression model for the full data set is:

$$ln(NTU) = 0.8026\, ln(TSS) - 0.083$$

Both coefficients are significantly different from zero at a 99 percent confidence level and the standard error of the model is 0.516 NTU.

Confidence intervals about the regression line can be calculated for both the mean (conditional on $ln(TSS)$) and on individual predictions. 95 percent confidence intervals are calculated as the regression prediction ± 1.96 *s*, where *s* is the relevant sample standard deviation. For predicting the mean conditional on $x_0 = ln(TSS)$ this is given by

$$s^2_{\mu_y|x_0} = s^2_{y|x}\left[\frac{1}{n} + \frac{(x_0 - \overline{x})^2}{\sum(x_i - \overline{x})^2}\right],$$

and, for individual predictions,

$$s^2_{y|x_0} = s^2_{y|x}\left[\frac{1}{n} + \frac{(x_0 - \overline{x})^2}{\sum(x_i - \overline{x})^2} + 1\right].$$

Here, *n* is the sample size and $s^2_{y|x}$ is the variance of the sample model residuals or standard error of the estimate, which for this model is 0.2663. Because there is a large sample size and a relatively strong linear model, the confidence interval on individual predictions is much larger than the confidence interval on the mean prediction. These confidence intervals, back-transformed to arithmetic space, are shown in Figure 18.

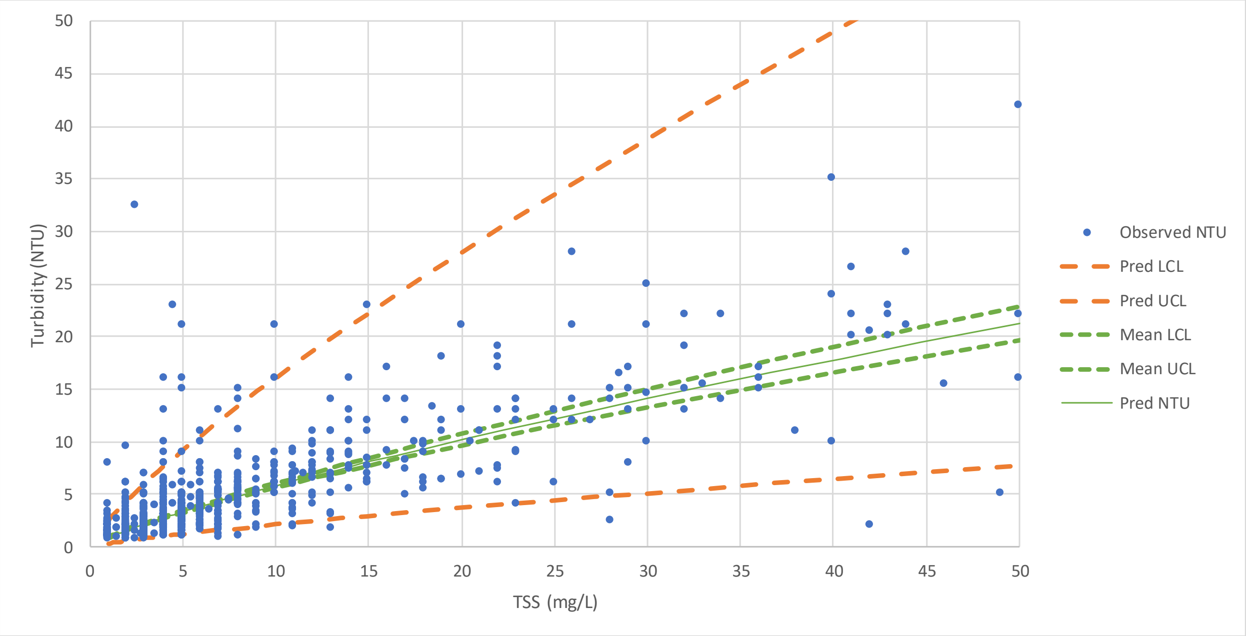

Figure 18. 95% Confidence Intervals for Log-Log Linear Model of Turbidity as a Function of TSS.

The regression can be applied to estimate the turbidity that would result from a specified TSS load required for the TMDL. Because a complete time series of TSS or turbidity is not being developed for the TMDL, it is appropriate to make the comparison based on the mean prediction and its confidence limits. For example, if the hypothetical average background TSS was 5 mg/L and the TMDL average TSS was 15 mg/L, average turbidity would be predicted to increase from 3.5 to 8.5 NTU for an increase of 5 NTU – using the upper confidence limit values which produce a slightly larger range.

5.0 TMDL AND REQUIRED REDUCTIONS

5.1 ENSURING REDUCTIONS MEET THE TARGETS

EPA's *Protocol for Developing Sediment TMDLs* provides several potential options for linking water quality targets to sources of sediment (U.S. Environmental Protection Agency (USEPA), 1999) to determine the TMDL and required reductions. One option is the use of process-based or mechanistic models, which can be used to identify the change in erosion and sedimentation processes needed to restore water quality. However, development, calibration, and validation of a mechanistic model for the Deschutes River watershed was determined to be too time intensive and complex for the needs of this TMDL (i.e. addressing only one sediment impaired reach of the Deschutes River). The usage of an empirical linkage model was considered but ruled out because it is more suitable for suspended sediment TMDLs where source loads can be paired with flows to derive instream concentrations. Available water column sediment data (e.g., total suspended sediment) is insufficient to apply this approach for the impaired segment, and a linkage between water column sediment and fines in gravel would remain uncertain. Another recommendation is to link multiple source assessment methods and targets, which EPA selected for this TMDL.

EPA is applying the target of less than 12 percent embedded fine sediment, which was used in the *2015 Deschutes TMDLs* as a translation of its narrative criteria based on that level supporting salmonid fry emergence in Washington streams (Washington Forest Practices Board, 1997; Jensen et al., 2009). The primary target is embeddedness, but EPA is also establishing a target for turbidity because Washington has a numeric water quality standard for turbidity, which as discussed in Section 4.0, is a reasonable proxy for fine sediment in the water column (i.e., TSS). As described in below, the turbidity target is 8.3 NTU.

EPA is basing the TMDL on the greatest reduction needed to meet both water quality targets, which is presented in this section. Although the embeddedness target does not directly correlate to upland and in-channel sources of loading, EPA expects a reduction in fine sediment loading will result in a decrease in fine sediment embeddedness within the Deschutes River, as research by Cover et al. (2008) observed a correlation between sediment supply and instream measurements of fine sediment. Because the turbidity target is directly linked to the TSS concentration derived from the source assessment, meeting the required loading reduction identified below will ensure attainment of the turbidity target and support of water quality standards.

5.1.1 Identifying the Most Stringent Reduction

Based on data collected by the Squaxin Island Tribe in 2004 (Konovsky and Puhn, 2005) and presented in the *2015 Deschutes TMDLs*, a reduction of up to 41 percent is required in the impaired segment to meet the embeddedness target.

The reduction necessary to meet the turbidity target requires the use of the TSS-turbidity regression from Section 4.0 and then the existing and natural background loads estimated by the source assessment as summarized in Section 3.3. The estimated current conditions average annual sediment load was paired with the mean flow at Deschutes River near Rainier (USGS 12079000; 255 cfs for 1950-2018) to approximate the TSS concentration associated with average flow, 41.5 mg/L. Similarly, the background TSS concentration associated with average flow was derived from the estimated natural sediment load (Section 3.3) as 4.8 mg/L. These were computed as follows:

$$C = \frac{L}{f * \alpha} * \beta$$

where C is the TSS concentration in units of mg/L; L is the average annual sediment load in units of tons/yr, f is mean flow at Deschutes River in units of cfs; α is a factor to convert from cfs to L/yr (893,610,248); and β is a factor to convert from tons to mg (907,200,000).

Average turbidity was estimated for the current conditions (19.6 NTU) and natural conditions (3.3 NTU) based on approximated TSS concentrations and through application of the TSS-turbidity regression and is based on the upper confidence limit. The turbidity water quality standard allows for an anthropogenic-based increase of 5 NTU over background, which means the applicable standard and turbidity water quality target is 8.3 NTU for the impaired segment of the Deschutes River (3.3 NTU + 5 NTU). This turbidity level is associated with a mean TSS concentration of 14.8 mg/L (based on the more conservative/protective upper confidence limit of the regression). This TSS concentration (which corresponds to the turbidity target) is conservatively assumed to be 100 percent fine sediment because fine particles will more slowly settle through the water column. Thus, the reduction needed to achieve the turbidity target is 64 percent [(41.5 – 14.8)/41.5 x 100].

It is important to consider the implications of retransformation bias regarding the TSS-turbidity regression in the context of the TMDL. It is well known that there is a retransformation bias when going from a log-based regression to an untransformed estimate based on that regression (Cohn et al., 1989) as the arithmetic mean depends on both the mean and variance in log space. If the logarithmic regression takes the form $x = \alpha + \beta y$, where x and y are log-transformed variables, then a maximum likelihood estimator of the antilog of x is given by $exp(\alpha + \beta y)\ x\ exp(\frac{s^2}{2})$, where s^2 is the estimated error variance of the regression, $s^2 = \sum_{i=1}^{N} \frac{(Y_i - \hat{Y})^2}{N-k}$, for a regression based on N data points with k variables. In the case of the predictive regression for $\ln(NTU)$, $s^2 =$

0.2663 and $exp(\frac{s^2}{2})$ = 1.1424. This solution assumes that s^2 is an accurate estimate of the true error variance of the regression and more complex adjustments (without a closed form solution) can be applied to obtain a minimum variance estimator that accounts for bias introduced by uncertainty in the estimation of s^2. Given the large sample size for the regression (N = 1062), this additional adjustment is not necessary to obtain a reasonable approximation.

Applying the maximum likelihood estimator to the retransformed upper confidence limit on the log-space regression to predict turbidity from TSS yields an estimate for the natural background condition with TSS = 4.8 mg/L of 3.3 x 1.1424 = 3.8 NTU. Allowing a 5 NTU increase yields 8.8 NTU. The TSS concentration that results in 8.8 NTU (after multiplying by 1.1424) is 13.8 mg/L. This suggests the need for a reduction in TSS of about 67 percent [(41.5 – 13.8)/41.5 x 100].

Given the high level of uncertainty in the retransformation bias analysis, the distinction between the reduction required without the bias correction (64 percent) or with the bias correction (67 percent) is insignificant, and 64 percent is considered an appropriate reduction to meet the turbidity target. Since this value is greater than the 41 percent reduction needed to meet the embedded fines target, the loading reduction necessary to meet both targets is 64 percent.

5.2 TMDL

An average annual load of 3,745 tons/yr, which is based on a reduction of 64 percent from current loading, is dually protective of embedded fines and turbidity (Table 7). Because substrate embeddedness is a cumulative, long-term process, the average annual load is the most relevant expression of the TMDL. However, as daily loads are required for TMDLs, a maximum daily load is also presented in Table 7.

The expression of the daily maximum load is calculated based on the 95th percentile flow (flow equaled or exceeded five percent of the time), as follows:

$$TMDL = Q_{95th} \times C \times \alpha$$

where $TMDL$ is the maximum daily load in units of tons per day, Q_{95th} is the 95th percentile flow at Deschutes River near Rainier, WA (USGS 12079000) for the period of 1950-2018 (906 cfs), C is the TSS concentration corresponding to the NTU target (14.8 mg/L – discussed in Section 5.1.1), and α is a multiplicative factor (0.002697) to convert the load to units of tons per day. The maximum daily load for the TMDL is 36.2 tons per day. Because it is calculated based on a 95th percentile flow value, it represents a load that should not be met or exceeded more than five percent of the time.

Table 7. Required Reduction in Fine Sediment Load and TMDL.

Total Current Fine Sediment Load (tons/yr)	Required Percent Reduction in Fine Sediment	Average Annual Load	Maximum Daily Load
		tons/yr	tons/day
10,404	64%	3,745	36.2

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