Alternative Headwater Channel and Outfall Crediting Protocol

MARYLAND DEPARTMENT OF TRANSPORTATION

STATE HIGHWAY ADMINISTRATION

January 2018

Revised February 2018

Revised March 2018

Revised July 2018

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EXECUTIVE SUMMARY

This report outlines the Alternative Headwater Channel and Outfall crediting protocol developed to more accurately predict TMDL credit for Headwater and Outfall restoration projects. The specific application of this report is to provide an alternative to *Protocol 1: Credit for Prevented Sediment during Storm Flow* as described in the Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects (Schueler and Stack, 2014). This alternative protocol is intended to apply to headwater channels where vertical incision (progressive bed-lowering) is a dominant mechanism for erosion of the system. For the purposes of this protocol, headwater systems will be defined as zero (channel segments actively forming from erosion) or first order channels using the Strahler (1957) modified Horton (1945) method. Channel incision is a natural process and part of denudation, but is accelerated to produce a large proportion of total sediment yield in a drainage network in disturbed systems with excess amounts of fluvial energy relative to sediment load (Simon and Rinaldi, 2006). Smith, Belmont, and Wilcock (2011) found that a majority of material eroded from first order streams is not stored in the valley bottoms of second- to fifth-order streams. This indicates that the majority of sediment from headwater channels in the Chesapeake Bay watershed is transported into the Bay. Currently the expert panel guidance Protocol 1 focuses on sediment and nutrient inputs created by lateral erosion exclusively, therefore this additional method is proposed to account for erosion produced by vertical incision.

To quantify the amount of material that is available to erode at a headwater site, methods provided in Stream Restoration Design NRCS 2007 for finding equilibrium bank and bed slope are used in conjunction with field data for base level control and equilibrium bottom width. Together these data provide an approximate equilibrium condition which accounts for vertical and lateral erosion associated with headwater systems. Comparison between equilibrium and existing conditions provides a volume of material expected to be eroded and transported out of the headwater channel. This entire volume of material is adjusted by the bulk density and measured nutrient concentrations to determine the total potential reduction of TMDL pollutants provided by the headwater restoration project. In that natural, stable, stream systems still experience sediment transport, a conservative 56% efficiency factor is applied to the total potential reduction to determine the TMDL pollutant reduction. The Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects (Schueler and Stack, 2014) allows for a verification approach through site monitoring to determine if additional credit may be gained or the pollutant reduction percentage may be modified. A 30-year timeframe was used to annualize the total reduction based on literature search and engineering judgement of channel realignment. This annualized credit would be carried in perpetuity as long as inspection and maintenance protocols are followed. Annual load reductions are then compared to reforestation reductions as provided by Maryland Department of the Environment (MDE) 2014 to determine representative impervious acres treated. Using the impervious acres equivalence a metric of impervious acres treated per linear foot is developed for planning purposes and to compare to stream restoration credit as provided in MDE 2014.

As a case study, the I-97 SB Outfall Stabilization project is described. This project was initiated by Maryland Department of Transportation State Highway Administration (MDOT SHA) Office of Environmental Design (OED) for TMDL crediting as part of their Capital Improvements projects. The I-97 Outfall channel drains a 30 acre, 55% impervious watershed and contains variable bank heights up to 21 ft. consisting of primarily sand. This project aims to stabilize a headwater stream system historically impacted by roadway development, pond construction, and subsequent base level lowering and channel incision, representative of disturbed headwater systems. Comparison between existing and equilibrium conditions indicates that 5,226 tons of

material are expected to be eroded before the channel reaches equilibrium. TMDL pollutant reductions using the alternative method are compared to the methods provided in Schueler and Stack (2014) and the alternative method predicts two (2) to three (3) times higher pollutant reduction on average than Protocol 1, assuming a 30 year timeframe. The TMDL pollutant reductions for the I-97 SB Outfall Stabilization project indicate an equivalency of 0.026 impervious acres treated per linear foot of headwater stabilization.

This document recommends that individual site investigation is conducted to determine the comparability of sites before values provided in this report are used for planning purposes. Complete TMDL crediting using this method requires site specific calculations following the methodology as presented in the I-97 SB Outfall Stabilization project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 BACKGROUND

To address Total Maximum Daily Load (TMDL) reduction goals in compliance with the NPDES MS4 permit process, the Maryland Department of Transportation State Highway Administration (MDOT SHA) Office of Environmental Design (OED) is implementing best management practices (BMPs) to manage pollutant load reductions from impervious surfaces. Capital Improvement projects have been initiated by MDOT SHA-OED to remediate erosion and sedimentation problems caused by uncontrolled or inadequately controlled stormwater runoff, including installation of new water quality best management practices, rehabilitation of old storm drains, installation and retrofitting of storm water management ponds, and implementation of stream stabilization projects. For the purposes of this assessment, headwater channels are defined as stream segments connected to open or closed channel segments within zero to first order channels where water first originates in a stream system. These channels can be ephemeral, intermittent, or perennial and often adjust to storm flows through gully and rill formation and therefore can produce significant vertical and lateral rates of erosion. For the purposes of this protocol, headwater systems will be defined as zero (channel segments actively forming from erosion) or first order channels using the Strahler (1957) modified Horton (1945) method. Waterway outfall channels in headwater systems are critical elements in roadway design and management that present MDOT SHA with continued maintenance and stabilization challenges along state roads. Outfalls are often located at headwater stream systems or are direct connections to closed storm drain networks.

Methods are available for calculating pollutant load reductions for stream restoration and stabilization projects (e.g., Chesapeake Bay Program [CBP], 2014). However, the available methods may not provide the most accurate estimates of pollutant load reductions along headwater channels due to the unique and fundamental erosion processes that occur in these channels. As such, MDOT SHA-OED has developed a protocol to be used for crediting headwater stabilization projects by developing a method to calculate nutrient and sediment reductions. The intent of this report is to document the headwater crediting methods developed by MDOT SHA-OED and compare them with existing crediting methods documented in CBP (2014).

In compliance with MDOT SHA's NPDES MS4 Discharge Permit issued by MDE on October 9, 2015, MDOT SHA is required to treat 20% of the impervious surfaces currently without adequate stormwater controls in MS4 Phase I areas. In addition to stormwater management BMPs, *Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated: Guidance for National Pollutant Discharge Elimination System Stormwater Permits* (MDE, 2014) indicates that alternative BMPs including: reforestation, stream restoration, pavement removal and operational practices are also identified as suitable practices for treating impervious surfaces. As suitable BMPs are identified, MDOT SHA weighs a number of factors including: cost-effectiveness, pollutant removal efficiency, impervious surface treatment and maximizing available funds.

This report is not intended to promote specific methods for stabilizing headwater channels or limit pollutant load reduction credits for the methods described in this report. If determined feasible, MDOT SHA-OED anticipates additional credit could be requested if a headwater stabilization process also includes measures to directly treat runoff, such as a Regenerative Stormwater Conveyance System or another infiltration based water quality measure. Those crediting procedures are presented in Schueler and Stack (2014) and Schueler and Lane (2012).

1.2 IMPORTANCE OF HEADWATER CHANNELS IN POLLUTANT LOAD REDUCTION

Alexander, Boyer, Smith, Schwarz, and Moore (2007) and Freeman, Pringle, and Jackson (2007) identify headwater streams as direct connections between the upland and riparian landscape with the rest of the stream ecosystem and the important influence they have on the supply, transport, and fate of water and solutes in watersheds. Headwater streams provide a direct connection between the upland watershed and downstream receiving waters directly connected to the downstream ecosystem, including the Chesapeake Bay. Studies by Alexander et al. (2007) indicate that first-order headwaters—defined as first-order perennial streams that include input from smaller, intermittent and ephemeral streams—contribute approximately 70% of the mean-annual water volume and 65% of the nitrogen flux to second-order streams. When considering fourth-and higher-order rivers, Alexander et al. (2007) found that headwaters contribute about 55% and 40% of the mean-annual water volume and nitrogen flux, respectively. As direct conduits between the upland watershed and downstream receiving waters, headwater channels act similarly in contributing to the supply of water, sediment and nutrients from first order streams described by Alexander et al. (2007). Similarly, Freeman et al. (2007) underscore the importance of the linkage between headwaters and the downstream ecosystem by indicating the influence of headwater channel condition on the eutrophication and hypoxia in coastal waters.

In addition, stream bed and bank erosion has been shown to contribute substantial proportions of total fine sediment loads and associated nutrients (nitrogen and phosphorus) transported and stored within stream networks (Schueler and Stack, 2014; Devereux, Prestegaard, Needelman, and Gellis, 2010; Smith et al., 2011). Managing sediment and associated nutrients eroded from headwater channels is important as these pollutants impact downstream water resources and are regulated.

First order channels have been observed to provide larger amounts of fine sediment to downstream water resources than upland sources within the watershed (Smith et al., 2011). Smith et al. (2011) found that roughly 37% of material eroded from first order (or headwater) channels and associated uplands was subsequently stored along the valley bottoms of second- to fifth-order streams. This finding has important implications since a majority (greater than 60%) of material eroded from first order (or headwater) channels and associated uplands is transported, eventually to the Chesapeake Bay (Smith et al., 2011).

As indicated by the above summary, stabilizing headwater channels has the potential to positively influence the condition of downstream receiving waters by reducing the downstream supply of sediment and nutrients and represents an important management practice with benefit to the Chesapeake Bay.

1.3 METHODS FOR DEFINING POLLUTANT REMOVAL RATES

The most recent methods for determining pollutant removal rates for individual stream restoration projects are provided in CBP (2014). This document includes pollutant removal protocols for preventing sediment erosion, instream and floodplain nutrient processing, floodplain reconnection, and treatment of upland stormwater runoff. Each of the protocols recommended in CBP (2014) have been accepted by CBP's Urban Stormwater Workgroup, Watershed Technical Workgroup, and Water Quality Goal Implementation Team. The four protocols include:

- *Protocol 1: Credit for Preventing Sediment during Storm Flow*
- *Protocol 2: Credit for Instream and Riparian Nutrient Processing during Base Flow*
- *Protocol 3: Credit for Floodplain Reconnection Volume*
- *Protocol 4: Credit for Dry Channel Regenerative Stormwater Conveyance (RSC) as an Upland Stormwater Retrofit*

The four protocols listed above expand upon the CBP approved rates for urban stream restoration (Schueler and Stack, 2014).

Considering that headwaters are typically located in steep, first-order channels with limited baseflow and floodplain connection, it is likely that pollutant load reduction at stormwater headwaters is primarily associated with stabilizing existing eroding channel beds and banks and preventing the downstream supply of sediment and nutrients. Therefore, *Protocol 1: Credit for Preventing Sediment during Storm Flow* is the most applicable protocol for channel bed and bank stabilization credit generation at headwater channels. The specific application of this report is to provide an alternative to *Protocol 1: Credit for Prevented Sediment during Storm Flow* as described in the Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects (Schueler and Stack, 2014). This alternative protocol is intended to apply to headwater channels where vertical incision (progressive bed-lowering) is a dominant mechanism for erosion of the system. Currently the expert panel guidance Protocol 1 focuses on sediment and nutrient inputs created by lateral erosion exclusively, therefore this additional method is proposed to account for erosion produced by vertical incision.

If determined feasible, MDOT SHA-OED anticipates additional credit could be requested if a headwater stabilization process also includes measures to directly treat runoff at an outfall, such as a Regenerative Stormwater Conveyance System or another infiltration based water quality measure.

CBP (2014) provides basic Qualifying Conditions (Section 4.2 in CBP 2014) for determining if proposed actions of a stream project qualify it as acceptable for credit under the Stream Restoration crediting procedures defined in the document. MDOT SHA-OED contends that headwater stabilization efforts (Regenerative Stormwater Conveyance (RSC), step-pool morphology, plunge pools, channel stabilization using cascades or other natural analogs, wetland creation or other naturalized approaches to headwater stabilization) will all reduce erosion in low order stream channels. Furthermore, MDOT SHA-OED recommends any sustainable stabilization approach of headwaters at any length of treatment qualify for credit under the Alternative Protocol 1 Procedure described within this document.

An important distinction for this alternative protocol will be the clear delineation between areas applying for the current Protocol 1 for Prevented Sediment Credit and the Headwater Channel Alternative. MDOT SHA-OED proposes to identify this distinction in credit methodology through the identification of a base level control within a confined and incising zero or first order channel segment. The point must be clearly identified and delineate for all crediting request. The base level control points are discussed in Section 2.4 of this report and are further supported by the MDOT SHA Long-Term Bed Degradation in Maryland Stream Research Reports (Parola, Oberholtzer, and Altland, 2017). To define the total length of a project reach and its credit potential the following equation will be used: Total Site Length = Headwater Channel Length + Stream Length.

Protocol 1: Credit for Preventing Sediment during Storm Flow provides a means to calculate annual mass reduction credits for total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS). This credit is for stream restoration practices that prevent mobilization of sediment from channel or bank erosion which would otherwise be delivered downstream from an actively eroding stream (Schueler and Stack, 2014). Pollution reduction credits for Protocol 1 are determined based on the amount of TN, TP, and TSS reduced as a result of a proposed restoration project. Schueler and Stack (2014) identifies three steps for determining pollutant reduction credits:

- Estimate existing conditions sediment erosion rates and annual sediment loading along the project reach
- Convert sediment erosion rates to annual loading of TN and TP
- Estimate pollution reduction based on proposed restoration project

Protocol 1 guidelines allow three options for estimating stream sediment erosion rates, including (1) monitoring, (2) Bank Assessment for Non-point Source Consequences of Sediment (BANCS) method, and (3) alternative modeling approach. This report describes an alternative method for estimating annual sediment loading due to channel bed and bank erosion within incising headwater systems. The alternative method (Alternative Protocol 1 Procedure, presented in this document) focuses on estimating the following information to define an equilibrium ground surface wherein channel bed and bank slopes reach equilibrium with the hydrologic regime and erosion substantially decreases or ceases:

- Equilibrium slope
- Equilibrium bank angle
- Channel bottom width

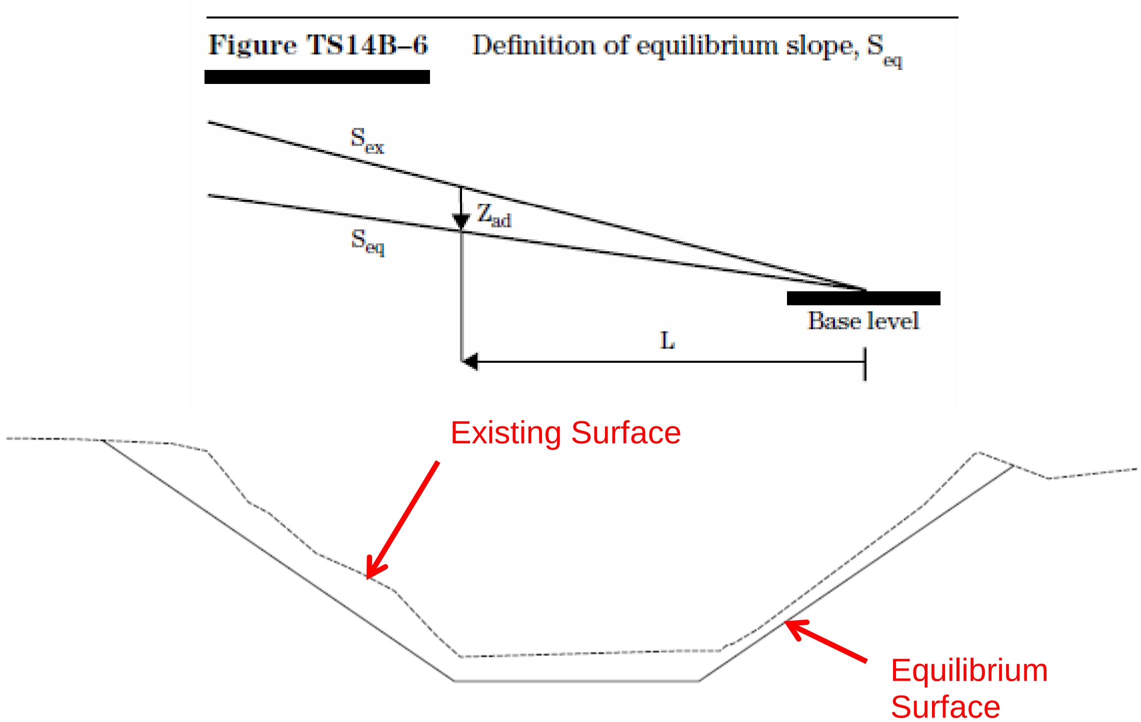
Methods for estimating these parameters, converting sediment erosion rates to annual TN and TP loading, and estimating pollution reduction are discussed below in ***Section 2.0***. See Schueler and Stack (2014) for more information about estimating erosion rates through monitoring or the BANCS method. A case study is also provided where the alternative method for estimating sediment erosion is applied to an MDOT SHA project (***Section 3.0***).

2.0 ALTERNATIVE METHOD FOR DETERMINING POLLUTANT REDUCTIONS

In addition to monitoring and the BANCS methods for estimating erosion rates and annual sediment loading, the Schueler and Stack (2014) provides an option for alternative modeling approaches to be used. A specific list of acceptable alternative modeling approaches is not provided. The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) is mentioned as an example alternative method for estimating erosion rates. It is stated that alternative modeling approaches should be calibrated to measured erosion rates in order to be acceptable.

This report discusses an alternative method for estimating erosion rates based on published methods for estimating equilibrium channel slope and bank angles. This method is based on the assumption that channel bed and bank incision will cease once the channel reaches equilibrium slope and bank angle, an equilibrium based on physical characteristics of the soil (bank) material. Other parameters such as hydrology, pore pressure, freeze thaw cycles, and vegetation also influence channel stability and are not directly considered in this protocol but could be considered under other protocol methods. The authors focused this protocol on the equilibrium slope and bank materials as the drivers for the final equilibrium state. The values calculated for these parameters are combined with channel bottom width to estimate cross-section dimensions at the future point when equilibrium slope and bank conditions are reached. The difference between current and future channel conditions represents the amount of material and pollutants with the potential to be supplied to downstream waters and the Chesapeake Bay. An important part of this method is assigning a downstream control point (base level) from which the new equilibrium slope is extended upstream. See ***Figure 1*** for a depiction of existing and equilibrium channel bed profiles and cross-section view or existing and equilibrium surfaces.

Figure 1: Equilibrium Bed Profile and Cross Section View of Equilibrium Surface



The amount of material having potential to be eroded and supply pollutants to downstream water resources and the Chesapeake Bay is then converted to an annual time scale, annual loading of TN and TP are determined, and pollution reduction is estimated.

2.1 EQUILIBRIUM SLOPE ANALYSIS

The equilibrium slope analysis is based on methods from Technical Supplement 14B (TS14B)—Scour Calculations—of Part 654 of the National Engineering Handbook—Stream Restoration Design (Natural Resource Conservation Service (NRCS), 2007). TS14B provides methods for estimating equilibrium slope for the following channel conditions related to headwater channels:

- Cohesive beds
- Sand and fine gravel—no bed-material sediment supplied from upstream
- Beds coarser than sand—no sediment supplied from upstream
    - also applicable for drastically reduced upstream sediment supply

TS14B provides other empirical or more complex methods incorporating sediment continuity for estimating equilibrium slope that include upstream sediment supply. Since this report focuses on headwater locations, it is anticipated that upstream sediment supply is limited (greatly reduced or absent) and that methods incorporating upstream sediment supply are not applicable. If it determined that an upstream sediment supply may be significant within a project reach, the additional methods accounting for the channel response to the equilibrium slope analysis may be required.

2.1.1 Cohesive Beds

TS14B acknowledges that cohesive beds typically erode as nickpoint migration and the associated difficulty with predicting nickpoint migration rates. The ultimate amount of degradation is presumed to be predictable by extending the thalweg profile of the equilibrium slope upstream from a fixed downstream point. TS14B provides the following relationship from Simon and Thomas (2002) for estimating equilibrium slope along cohesive beds:

$$S = 0.0028A^{-0.33}$$

where S is equilibrium slope (ft/ft or m/m) and A is drainage area (km^2). Considering that this relationship is based on observations of equilibrium slope within the Yalobusha River watershed in northern Mississippi, equilibrium slope values based on this relationship should be considered general and used with caution.

2.1.2 Sand and Fine Gravel—No Bed-material Sediment Supplied from Upstream

TS14B identifies Pemberton and Lara (1984) as suggesting the tractive force method from Lane (1952) as providing a means to estimate stable (equilibrium) slopes for non-cohesive channel bed material sizes in the range of 0.1 to 5 mm with no bed-material supplied from upstream. The following equation presented in TS14B to estimate equilibrium slope for sand and fine gravel with no bed material supplied from upstream:

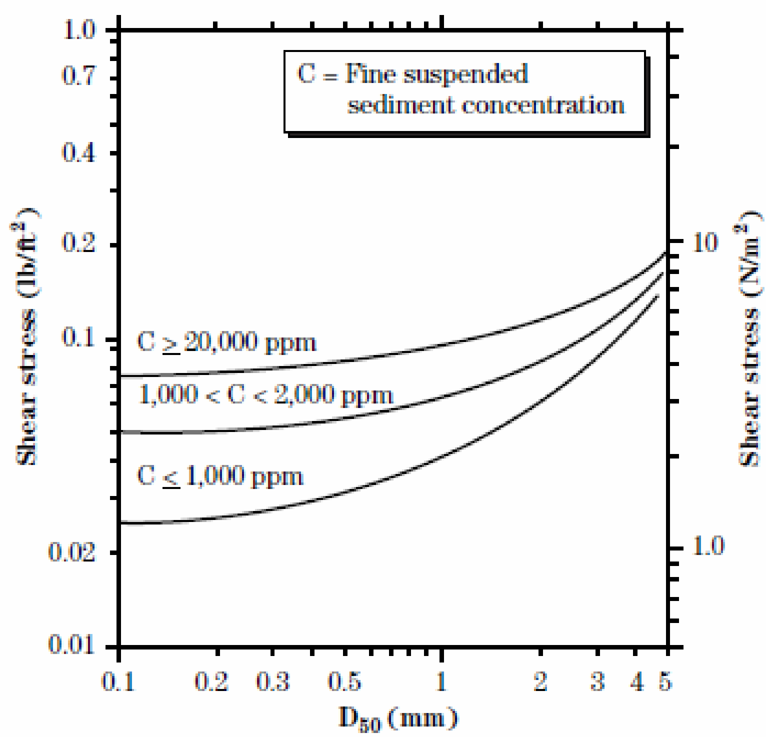
$$S_{eq} = \left(\frac{\tau_c}{\gamma_w y}\right)$$

where S_{eq} is equilibrium slope (ft/ft), τ_c is critical shear stress (lb/ft^2), γ_w is specific weight of water (lb/ft^3), and y is mean flow depth (ft). Both critical shear stress and mean flow depth require a design discharge to be specified. TS14B does not specify which design discharge should be used for this calculation. Lagasse, Zevenbergen, Spitz and Arneson (2012) indicate that the appropriate discharge for use in equilibrium slope equations is difficult to select. They acknowledge that a range of discharges are responsible for forming the channel and given long periods of time, extreme discharges would be responsible for forming the channel. Preliminary analyses evaluating results using the 1.5-, 10-, and 100-year recurrence interval discharges as the design discharge indicate that the 10-year recurrence interval discharge provide moderate estimates of equilibrium slope, neither underestimating nor overestimating equilibrium slope suggesting that the 10-year discharge is appropriate for use in equilibrium slope analyses.

Critical shear stress in the above equation is based on ***Figure 2*** (Figure TS14B-9 from TS14B). This method of estimating critical shear stress requires knowledge of the approximate fine suspended sediment concentration. Fine suspended sediment concentration should be estimated for an appropriate design discharge (10-year recurrence interval as discussed above). The procedure for estimating fine suspended sediment concentration is described below, however, an intermediate suspended sediment concentration (1,000 to 2,000 ppm) can be assumed, which would provide moderate estimates critical shear stress.

Figure 2: Source of Critical Shear Stress Value (from TS14B)

Figure TS14B–9 Critical shear stress for channels with boundaries of noncohesive material. Critical shear stress increases with increasing fine suspended sediment concentration.



Rough estimates of fine suspended sediment concentration can be completed using methods described in Wu, Wang and Jia (2000). Other methods for estimating suspended sediment should be used where appropriate. The Wu et al. (2000) suspended sediment transport relationship is discussed here due its versatility for analyzing multiple settings, relative ease of use, and ability to calibrate the relationship using suspended sediment transport samples. The Wu et al. (2000) relationship consists of:

$$q_{si} = \phi_{si} \, p_{bi} \sqrt{(\gamma_s / \gamma - 1) g d_i^{\,3}}$$

and

$$\phi_{si} = 0.0000262 \left[\left(\frac{\tau}{\tau_{ci}} - 1 \right) \frac{U}{\omega_i} \right]^{1.74}$$

where q_{si} is the fractional transport rate of the ith fraction of suspended sediment per unit width (m^2/s), Φ_{si} is the non-dimensional fractional suspended sediment transport rate, p_{bi} is the percent of the ith fraction of the bed material, γ_s is specific weight of sediment (kg/m^3), γ is specific weight of water (kg/m^3), g is gravitational acceleration (m/s^2), d_i is diameter of the ith fraction of sediment (mm), τ is shear stress on the entire section (Pa), τ_{ci} is critical shear stress (Pa) of ith grain fraction, *U* is average flow velocity (m/s), and ω_i is particle settling velocity (m/s) of the ith grain fraction.

Shear stress is calculated using the depth slope product:

$$\tau = \gamma R S$$

where τ is shear stress on the entire section (Pa), γ is specific weight of water (kg/m^3), *R* is hydraulic radius (m), and *S* is slope (m/m).

Particle settling velocity is calculated using the following relationship (Zhang and Xie 1993, as cited in Wu et al. 2000):

$$\omega_i = \sqrt{(13.95 \nu / d_i)^2 + 1.09 (\gamma_s / \gamma - 1) g d_i} - 13.95 \nu / d_i$$

where ω_i is particle settling velocity (m/s) of the ith grain fraction , ν is kinematic viscosity (m^2/s), d_i is diameter of the ith fraction of sediment (mm), γ_s is specific weight of sediment (kg/m^3), γ is specific weight of water (kg/m^3), and *g* is gravitational acceleration (m/s^2).

2.1.3 Beds Coarser than Sand—No Sediment Supplied from Upstream

Four relationships are described in NRCS (2007) for estimating equilibrium slope for channel bed material size greater than sand with no upstream sediment supply, including:

- simultaneously solving the Manning and Shields equations (for D_{50} greater than 6 mm):

$$S_{eq} = \left[\theta_C D_C \Delta S_g\right]^{10/7} \left(\frac{K}{qn}\right)^{6/7}$$

- Meyer-Peter and Muller transport relationship (for material coarser than sand)

$$S_{eq} = K \frac{(D_{50})^{\frac{10}{7}} n^{\frac{9}{7}}}{(D_{90})^{\frac{5}{14}} q^{\frac{6}{7}}}$$

- Schoklitsch equation (coarse sand or gravel)

$$S_{eq} = K \left(\frac{D_m}{q}\right)^{3/4}$$

- Henderson formula (material larger than 6 mm)

$$S_{eq} = K Q_d^{-0.46} D_{50}^{1.15}$$

where S_{eq} is equilibrium slope (ft/ft), θ_c is Shields parameter, D_c is critical bed material size (ft), ΔS_g is relative submerged density of sediment (1.65), K is a constant (1.486 for Manning and Shields; 60.1 for Meyer-Peter and Muller; 0.00174 for Schoklitsch; and 0.44 for Henderson), q is channel forming discharge per unit width (ft^2/s), n is Manning's roughness coefficient, D_m is mean grain size (mm), Q_d is design discharge (ft^3/s), D_{50} is median grain size (ft), and D_{90} is sediment size for which 90% of the bed material is finer (ft). Note that Lagasse et al. (2012) indicate that D_c in the Manning and Shields relationship should be represented by the D_{90} bed material size.

TS14B indicates that an equilibrium slope may be selected as the average of the four equations or those relations most applicable to the study reach. It is recommended that the results be evaluated and those relationships most applicable to the study reach be used to estimate the equilibrium slope. See ***Section 3.0*** for an example of how these relationships were used in the case study.

2.2 EQUILIBRIUM BANK SLOPE ANALYSIS

The equilibrium bank slope analysis is based on methods from Technical Supplement 14A (TS14A)—Soil Properties and Special Geotechnical Problems Related to Stream Stabilization Projects—of Part 654 of the National Engineering Handbook—Stream Restoration Design (NRCS 2007).

TS14A provides information for evaluating bank stability for highly plastic clays and low plasticity sands and silts and indicates that reliable analytical methods are not available for predicting stable slopes for highly plastic clays. Rather, empirical examination of nearby stable natural slopes may provide the most reliable evaluation method. TS14A recognizes soil plasticity as an important determinant of stable bank slopes. In addition, conservative evaluations of plastic soils consider the blocky structured soils to be zero and are based on a fully relaxed phi (or friction) angle, which is the measure of shear strength of soils due to friction (Liu 2014). Based on these conditions, TS14A identifies soils with plasticity values of 30 to 40 as being stable on slopes of 3H:1V (Horizontal:Vertical), and soils with plasticity values greater than approximately 80 as being stable on slopes of 6.5H:1V. More research is necessary to evaluate quantitative and semi-quantitative methods for estimating bank stability of plastic and/or cohesive soils.

TS14A describes three equations for quantitatively evaluating slope stability for the following seepage conditions:

- No seepage
  - for evaluating slope stability above the water table
- Seepage flowing generally parallel to slope
  - for soils with minimal layering
- Seepage generally flowing along horizontal flow paths
  - for soils with layered alluvial deposits

TS14A indicates that slope (bank) height is not a factor in evaluating stability since soils are assumed to have zero cohesion. In addition, a safety factor of 1.1 is considered appropriate for estimating these slopes. See ***Section 3.0*** for example calculations of the *No Seepage* relationship used in the case study.

2.2.1 No Seepage

The equation presented in TS14A for conditions without seepage is:

$$FS = m \times \tan \emptyset'$$

where FS is factor of safety, m is slope cotangent—mH:1V, and ϕ' is internal friction angle of cohesionless slope soil (radians). Assuming a safety factor of 1.1 and solving for the slope cotangent—m—yields the following relationship:

$$m = {}^{1.1}\!/_{\tan \emptyset'}$$

Typical values of internal friction angles of sand (from Table TS14A-3 in Technical Supplement 14A of NRCS 2007) and silt (Liu 2014) include: (1) 28 degrees (0.4887 radians) for loose sand, (2) 32 degrees (0.5585 radians) for medium dense sand, (3) 38 degrees (0.6632 radians) for dense sand, and (4) 30 degrees (0.5236 radians) for silt. Values of slope cotangent (m) based on a factor of safety of 1.1 and the four typical internal friction angle values include:

- 2.07 for loose sand
- 1.76 for medium dense sand
- 1.41 for dense sand
- 1.91 for silt

The results indicate that equilibrium bank slopes are in the range of 1.4:1 to 2.1:1 for banks comprised of sand and 1.9:1 for silt in the absence of influence of seepage.

2.2.2 Seepage Flowing Generally Parallel to Slope

TS14A identifies the following equation as applicable to evaluating slope stability with seepage flowing parallel to the slope:

$$FS = m \times \frac{\gamma_b}{\gamma_{sat}} \times \tan(\emptyset')$$

where m is slope cotangent (cot [θ]), θ is slope angle, γ_b is buoyant unit weight (lb/ft^3), γ_{sat} is saturated unit weight (lb/ft^3), and ϕ' is effective friction angle (radians). Assuming a safety factor of 1.1 and solving for the slope cotangent—m—yields the following relationship:

$$m = \frac{FS \times \gamma_{sat}}{\gamma_b \times tan\emptyset'}$$

Typical values for internal friction angles for sand and silt are provided above in the discussion for bank stability calculations where seepage is not present. Typical values for buoyant (γ_b) and saturated (γ_{sat}) unit weights are provided in ***Table 1***. Typical values of saturated and buoyant unit weights of sand were obtained from Table TS14A and silt in Mathalino (2014).

Table 1: Saturated and Buoyant Unit Weight Values

Soil Type	γ_{sat} (lb/ft^3)	γ_b (lb/ft^3)
Loose Sand	125	62.6
Medium Dense Sand	130	67.6
Dense Sand	135	72.6
Silt	121	58.6

Values of slope cotangent (m) based on a factor of safety of 1.1 and the four typical internal friction angle values include:

- 4.1 for loose sand
- 3.4 for medium dense sand
- 2.6 for dense sand
- 3.9 for silt

The results indicate that stable bank slopes are in the range of 2.6:1 to 4.1:1 for banks comprised of sand and 3.9:1 for silt with seepage occurring parallel to the slope.

2.2.3 Seepage Generally Flowing along Horizontal Flow Paths

TS14A identifies the following equation as applicable to evaluating slope stability with seepage flowing along horizontal flow paths:

$$FS = \frac{(\gamma_b \times m^2 - \gamma_w) \times \tan(\emptyset')}{m \times \gamma_{sat}}$$

where γ_w is unit weight of water (lb/ft^3) and the remaining variables are as defined above in ***Section 2.2.2***.

Values of slope cotangent (m) based on a factor of safety of 1.1 and the four typical internal friction angle values include:

- 4.4 for loose sand
- 3.7 for medium dense sand
- 2.9 for dense sand
- 4.2 for silt

The results indicate that stable bank slopes are in the range of 2.9:1 to 4.4:1 for banks comprised of sand and 4.2:1 for silt with seepage generally flowing horizontal to the slope.

2.2.4 Applying Bank Slope to Erosion Calculations

Utilizing a constant bank slope is likely to be the best approach and is consistent with recent modeling efforts for bed and bank evolution for channel incision (e.g, Cantelli, Wong, Parker, and Paola, 2007). Cantelli et al. (2007) developed a numerical model of bed and bank evolution of channel incision following dam removal. Channel bed incision is based on continuity of sediment transport and the sidewall (bank) region is held to a constant slope.

2.3 BOTTOM WIDTH

Bottom width, in addition to equilibrium slope and bank angle, is necessary to develop a future ground surface and estimate sediment erosion from the study site. Unlike the methods discussed above for equilibrium slope and bank angle, numerical and/or empirical relationships for approximating future bottom width of the equilibrium channel are sparse.

For headwater channels, the most appropriate predictor of future bottom width of the equilibrium channel is likely to be within the study reach itself. The study reach is assumed to extend from the groundwater origin or outfall location to the selected base level control feature, as described in ***Section 2.4***. Rather than basing equilibrium bottom width on a singular reference condition, three reference cross sections should be taken and averaged. Three cross sections is expected to be sufficient to determine average conditions due to the relatively short length of most headwater projects. It is recommended that these cross sections be selected to reflect average site conditions, therefore areas such as scour holes directly downstream of outfalls should not be included in the average. See ***Section 3.0*** (case study) for an example of how channel bottom width along the existing study reach was used to approximate future bottom width.

2.4 BASE LEVEL CONTROL

Determination of base level control is a critical element for this protocol as well as for the stability of the headwater project. Base level control can take several different forms depending on site conditions but in this report are characterized into three general categories hard point control, confluence, and equilibrium slope. Each of these represent channel conditions which are expected to be stable in existing conditions and are described in more detail below

2.4.1 Hard Point Control

This is the most permanent base level control and represents a channel condition which has the strength to withstand any expected channel conditions within any project lifespan. Examples of hard point control are bedrock and existing infrastructure.

2.4.2 Confluence

Where the headwater channel meets a larger receiving stream will dictate base level control as this provides a fixed elevation beyond which the headwater channel cannot erode. Care should be taken when using this method to ensure that the receiving stream is expected to remain stable, for example, receiving streams with significant headcuts downstream should not be considered stable unless restoration work is also proposed on the receiving channel.

2.4.3 Equilibrium Slope

Most degraded headwaters are expected to be controlled by either hard point control or a confluence, but in some instances the headwater channel may have reached a stable condition downstream. In this case the existing downstream conditions should be evaluated for equilibrium slope to determine if any additional channel adjustment is expected. If existing slope is within 5% of the equilibrium slope calculated for existing conditions, this portion of the channel can be considered stable base level control. As with the confluence, downstream of the intended base level control should be evaluated for any instabilities which may jeopardize the stability of the base level control location.

2.5 UPSTREAM LIMITS OF EROSION

In most cases, the upstream limits of erosion will be set by a pipe outfall. A method to determine upstream limits of erosion is necessary where a pipe outfall or other defining infrastructure is not present. Zero order channels along a hillslope (with no upstream infrastructure) represent an example where the upstream limits of erosion need to be determined. Estimating the upstream limits of erosion in the absence of a pipe outfall or other defining infrastructure is based on the following equation from Leopold et al. (1964):

$$L_{max} = 153A_d^{0.6}$$

where L_{max} is the maximum upstream channel length (feet) form a point of interest and A_d is drainage area (acres).

This relationship is used in the Annualized Agricultural Non-Point Source model (AnnAGNPS) model to calculate upstream limits of gully erosion. Based on this, it is considered a valid method for estimating the upstream limits of erosion for headwater channels and outfalls in the absence of upstream infrastructure.

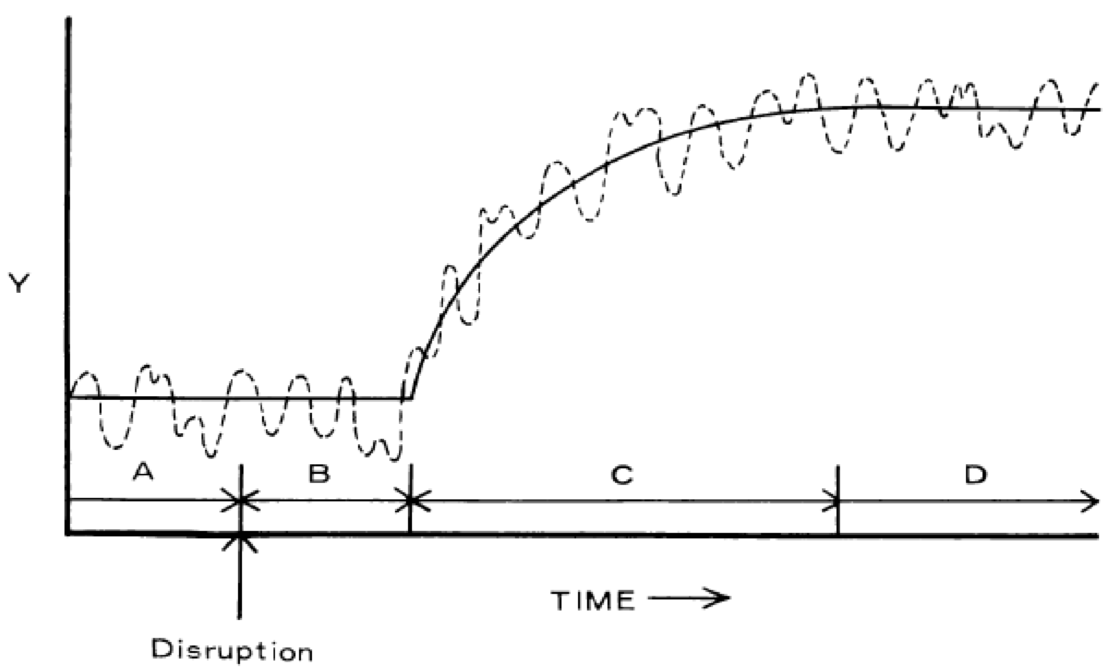
2.6 CONVERTING EROSION TO ANNUAL TIMESCALE

Combining the equilibrium slope, bank angle, and bottom width provides a surface that can be contrasted to the existing ground surface in order to estimate the amount of sediment having potential to be eroded and supply pollutants to the downstream river network. This method provides a total mass of sediment having potential to be eroded. This mass needs to be converted to an annual timescale of tons of sediment eroded per year in order to have the same units that TMDL credits for pollutant load reductions are determined.

One method would be to monitor bank erosion of the study reach and approximate annual bank erosion based on the results. It would be difficult to acquire accurate results considering that project timelines are typically shorter than the amount of time necessary for monitoring to provide reliable results. For example, Pizzuto, O'Neal, and Stotts (2010) indicate that approximately four years of monitoring are necessary to provide annual erosion rates within accuracy of 10%.

In addition, it is unlikely that channel bed and bank erosion will continue indefinitely at the estimated annual rate. Rather, it is anticipated that bed and bank erosion along headwater channels is likely to occur over a finite period until the channel bed and banks reach equilibrium slopes. The expectation that disturbed headwater channels will reach a future steady (or equilibrium) state is similar to the processes described by channel evolution models (e.g., Schumm, Harvey, and Watson, 1984, Simon 1989). Graf (1977) discusses channel adjustment to disturbance over time and the establishment of a new steady state (***Figure 3***). ***Figure 3*** shows time intervals partitioned as (A) steady state prior to disruption, (B) reaction time where change does not occur immediately following disruption, (C) relaxation time where the system adjusts to the disruption, and (D) new steady state.

Figure 3: Geomorphic Response to Disturbance (Graf 1977)



Time required for eroding systems to reach a new steady state is variable. Data from Ireland, Sharpe, and Eargle (1939), Graf (1977), Simon (1989), Burkard and Kostachuk (1995), and Nachtergaele, Poeson, Wijdenes, and Vanderkerckhove, (2002) indicate that the majority of gully or stream erosion occurs between 10 and 51 years with subsequent stabilization occurring between 50 and 100 years. Based on this, a period of 30 years is recommended to normalize erosion on an annual time scale. The annual rate generated by dividing the predicted load by a 30 year time frame will be utilized as the annual load reduction of the BMP, in perpetuity, as long as the project is functioning as designed and inspected accordingly.

2.7 CONVERT SEDIMENT EROSION RATES TO ANNUAL LOADING OF TN AND TP

Pollutant load reduction credits are awarded based on the amount of pollutant—TN, TP, and sediment—reduction estimated to occur as a result of the proposed project. The amount of TN and TP present along a project reach is determined by applying TN and TP concentrations to the annual sediment loading rate. Schueler and Stack (2014) provides two methods for determining TN and TP concentrations:

- Use default values provided in by the Expert Panel
- Directly measure TN and TP concentrations along the project reach

Default TN and TP concentrations provided by the expert panel are based on values from Walter et al. 2007:

- 2.28 pounds TN/ton sediment
- 1.05 pounds TP/ton sediment

Individual localities have been encouraged to develop their own methods and rates of bank nutrient data, and should be investigated prior to using the generalized rates. Merritts, Walter, and Rahnis (2010) outlines methods used to directly measure the nutrient content of bed and bank material. This method involves the collection of soil samples representative of all unique bank strata and laboratory testing following EPA 3051 Method for total phosphorus, and elemental combustion analysis for total nitrogen.

2.8 ESTIMATE POLLUTION REDUCTION

Schueler and Stack (2014) states "mass load reductions should be discounted to account for the fact that projects will not be 100% effective in preventing stream bank erosion" and further states that Stream Restoration projects are 50% effective at removing TP, 37.5% for TN, and 80% for TSS. The average of these values is 56% effectiveness. To be conservative and consistent with other crediting methods, MDOT SHA-OED recommends 56% effectiveness factor be applied to headwater stabilization projects utilizing the alternative crediting strategy described in this document. As headwaters are located in low order stream channels that are ephemeral or intermittent, the resulting channels will be producers of sediment, similar to a point source. These channels are often formed as a result of the combination of concentrated upland flow and base level modifications and often lack the "natural" erosion rates indicative of higher order channel evolution processes (Schumm, et al., 1984).

2.9 IMPERVIOUS SURFACE TREATMENT

Guidance for determining credits for projects that apply toward meeting the impervious surface treatment requirements outlined in MDOT SHA's Draft Permit is provided in MDE (2014). MDE (2014) provides descriptions of alternative practices, practices other than those considered acceptable water quality treatment BMPs that provide water quality benefits and are approved to be applied toward the criteria for restoring 20% of the impervious area and stormwater wasteload allocations. MDE (2014) refers to the alternative practices as "alternative BMPs" and provides methods for relating the pollutant load reductions from these practices into an equivalent impervious acre.

MDE (2014) allows outfall stabilization projects to take credit toward impervious area restoration at a rate of 1 acre per 100 linear feet of the project length, up to a maximum of 2 acres. The impervious area restoration rate of 1 acre per 100 linear feet is the same as the credit provided for stream restoration projects. The impervious area restoration rate for stream restoration projects is based on nitrogen, phosphorus and sediment pollutant load reduction data from the Spring Branch stream restoration project. Impervious area restoration rate for the Spring Branch stream restoration project appears to be calculated based on (1) MDE pollutant load values from impervious surfaces, (2) MDE pollutant load values from forest land use as a background pollutant load, and (3) average pollutant load for the Spring Branch stream restoration project, provided in post construction monitoring data. Considering a drainage area of 481 acres and project length of 10,000 linear feet, the apparent Spring Branch impervious area restoration calculations are summarized in ***Table 2***.

Table 2: Summary of Spring Branch Impervious Acre Treatment Calculations

Parameter	MDE Impervious (lbs/acre/yr)	MDE Forest (lbs/acre/yr)	Delta of Impervious Surface and Forest (lbs/acre/yr)	Average Pollutant Load Reduction (lbs/acre/yr)	Impervious Acre Conversion Factor (AC/AC)
TN	10.85	3.16	7.69	4.2	0.55
TP	2.04	0.13	1.91	0.215	0.11
TSS (tons)	0.46	0.03	0.43	0.037	0.09
Average for Nutrients and Sediment:					**0.25**
Average Acres of treatment for Nutrients and Sediment per LF:					**0.01**
Average Acres of treatment for Nutrients and Sediment per 100 LF:					**1**

The impervious acre conversion factor in ***Table 2*** is calculated by dividing the average pollutant load reduction by the delta of impervious surface and forest. The impervious acre conversion factor for TN, TP, and TSS are averaged together. The average impervious acre conversion factor is multiplied by the ratio of drainage area (in acres) divided by project length (in linear feet) in order to calculate the average acres of treatment for nutrients and sediment per linear foot of project. As indicated in MDE (2014), insufficient data are available regarding allowable nutrient and sediment removal rates for outfall stabilization projects. While MDE will allow outfall stabilization projects to receive impervious area treatment credit at a rate of 1 acre per 100 linear feet, the credit is capped at a maximum of 2 acres per project. If an outfall channel evaluated for a BMP meets the criteria of a headwater channel, MDOT SHA-OED proposes the Alternative Headwater Channel Prevented Sediment Credit Protocol is appropriate and the calculated credit at each site following this method should apply.

The 481 acre drainage area used to calculate the impervious area restoration for the Spring Branch project represents the total drainage area of the 10,000 linear foot Spring Branch project reach. This indicates that the average pollutant load reduction listed above in ***Table 2*** is averaged over the entire watershed rather than being related specifically to urban (impervious and pervious) land use. Using either the total drainage area or the urban land use drainage area is not specifically important for calculating impervious area restoration because both provide the same result. First, the average pollutant load reduction is calculated by dividing the annual pollutant load by drainage area. Average acres of treatment for nutrients and sediment per linear foot are then calculated by multiplying the impervious acre conversion factor by the drainage area divided by the project reach length. The effect of dividing by and then multiplying by drainage area effectively cancels any influence of drainage area on the final calculation. In order to be consistent with the Spring Branch calculations, it is recommended that total drainage area be used to calculate impervious acre treatment. The process of calculating impervious area restoration is further illustrated in ***Section 3.5***.

A method to calculate impervious acre equivalent is proposed here that follows the methods described in MDE (2014) and the Spring Branch stream restoration study as shown in ***Table 2*** with the pollutant load reduction based on estimated sediment erosion and nutrient loading described in ***Section 2*** of this document due to the unique and fundamental erosion processes that occur along headwater channels. The methods described above in ***Section 2*** provide an approach to estimate total sediment erosion and associated nutrient loading having potential to occur along a given headwater channel if stabilization is not completed. An example calculation following this method is provided below in ***Section 3***.

Erosion from headwater channels represents a direct source of sediment and nutrients into the tributaries of the Chesapeake Bay, and, as outlined in ***Section 1.2***, first order channels have been observed to provide larger amounts of fine sediment to downstream water resources than upland sources within the watershed (Smith et al., 2011). Sediment delivery factors (SDF) as defined in Schueler and Stack 2014 account for losses of eroded sediments due to deposition, resuspension, sedimentation, and transport processes within the stream. As the Bay models are updated and SDF are modified, the appropriate SDF values will be selected and applied to the credit calculations.

In addition to the sediment and nutrient source reduction due to headwater stabilization, additional impervious area treatment is possible for stormwater management BMP-type components at a stormwater outfall location. For example, the case study in ***Section 3*** has step-pool and infiltration components that attenuate flow and function similarly to a regenerative stormwater conveyance (RSC) system. Pollutant load reduction due to the RSC-type component of the project are based on Protocol 4: Credit for Dry Channel Regenerative Stormwater Conveyance (RSC) as an Upland Stormwater Retrofit described in Schueler and Stack (2014).

Impervious area treatment credit is anticipated to include a combination of source reduction due to erosion stabilization and pollutant removal from stormwater-type BMPs (e.g., RSC systems) where appropriate. In addition, the annual impervious area treatment credit is based on the source reduction from channel stabilization occurs over finite time of 30 years, long term inspection and associated maintenance will be continued for the duration the credit is claimed. The interim credit will be capped at the amount of impervious acres in the watershed.

3.0 CASE STUDY

This case study provides an example application of the alternative method for determining pollutant reductions for individual stream restoration projects where future equilibrium slope, bank angle, and channel bottom width are combined to estimate cross-section dimensions at the future point when equilibrium conditions are reached. The difference between current and future channel conditions represents the amount of material having potential to be eroded and supply pollutants to downstream waters and the Chesapeake Bay. This method is also compared with the *Protocol 1: Credit for Prevented Sediment during Storm Flow* as recommended by Schueler and Stack (2014) to define removal rates for individual stream restoration projects for calculating pollutant load reduction and TMDL credit associated with stream restoration projects.

MDOT SHA-OED identified the I-97 Southbound Outfall Stabilization project reach for stream stabilization efforts in pursuit of TMDL credit. Within the project reach, the channel exhibits highly erodible banks, reduced in-stream habitat, and the potential for further bed and bank instabilities. Proposed project reach length is approximately 450 feet, existing slope ranges from 0.3 to 13%, existing bank height ranges from 6 to 21 feet, and bottom width ranges from 4 to 40 feet.

There are generally three distinct zones of channel bed material along the project reach including Class III riprap (35 linear feet), Class I riprap (81 linear feet), and primarily sand (355 linear feet). Channel bed and bank material along non riprap bank portions of the channel is primarily sand (91%) with approximately 7% silt and clay and 2% gravel. A soil boring completed in the vicinity of the project reach yielded an average of 71% sand, 18% silt, 9% clay, and 2% gravel.

Recommended solutions for improving in-stream condition and reducing lateral erosion within the project reach focus on modifying channel planform, altering bank geometry to reduce availability of sediment, and improving the resistance of boundary conditions to transition and minimize energy flux in the system. Stabilization will focus on preventing downstream sedimentation and providing increased riparian habitat, with instream habitat creation where possible. The proposed design approach consists of in-stream structures, bank stabilization grading, and channel bed fill, such that the grade loss from the existing I-97 outfall to the existing bed will transition in a hydraulically stable manner. Proposed in-stream structures include a plunge pool/infiltration treatment forebay, step pools, and a cobble riffle.

Land use within the 30-acre I-97 project watershed includes 16.5 acres of impervious surface, 7.2 acres of predominantly grass or herbaceous vegetation, and 6.3 acres of forest.

3.1 BASE LEVEL CONTROL

Base level at the I-97 project was based on a confluence with a downstream receiving channel. This channel was evaluated in the field is expected to be stable and provide an unchanging base level control.

3.2 BOTTOM WIDTH DETERMINATION

The bottom width value is based on the average of three surveyed cross sections which gives a value of 17 ft.

3.3 EQUILIBRIUM SLOPE ANALYSIS

The equilibrium slope analysis is based on methods from Technical Supplement 14B—Scour Calculations—of Part 654 of the National Engineering Handbook—Stream Restoration Design (NRCS 2007). Channel bed conditions along the existing channel alignment include:

- Class III Riprap between approximate stations 10+00 and 10+35
- Class I Riprap between approximate stations 10+35 and 11+16
- Sand between approximate stations 11+16 and 14+71

The analysis assumed that the Class III Riprap (stations 10+00 to 10+35) remained stable and was not subject to channel bed erosion or elevation change. Two separate analyses were conducted for the Class I Riprap (stations 10+35 to 11+16) and sand (stations 11+16 to 14+71) areas due to the different grain sizes observed.

The following equation presented in NRCS (2007) was used to estimate equilibrium slope for the sand-bed area (stations 11+16 to 14+71):

$$S_{eq} = \left(\frac{\tau_c}{\gamma_w y}\right)$$

where S_{eq} is equilibrium slope (ft/ft), τ_c is critical shear stress (lb/ft^2), γ_w is specific weight of water (lb/ft^3), and y is mean flow depth (ft). Specific weight of water is 62.4 lb/ft^3 at 10 degrees C.

Critical shear stress in the above equation is based on ***Figure 2.2*** (Figure TS14B-9 from Technical Supplement 14B of NRCS 2007). The reach-averaged median grain size—0.6 mm—was used to determine representative critical shear stress. Critical shear stress based on a 0.6 mm median grain size and the curve for fine suspended sediment concentration between 1,000 and 2,000 ppm is 0.055 lb/ft^2 (2.63 N/m^2 [Pa]). A rough analysis of suspended sediment transport along the project reach using methods in Wu et al. (2000) indicates that use of the 1,000 to 2,000 ppm suspended sediment curve is appropriate for this analysis.

The I-97 SB Outfall Stabilization project reach equilibrium slope analysis examined a range of discharges to evaluate the influence of input values on equilibrium slope calculations and provide a coarse evaluation of uncertainty associated with the calculations. Equilibrium slope was calculated for each of the three cross sections collected during the geomorphic assessment based on mean flow depth for the 1.5-, 10-, and 100-year discharges. Values of the recurrence interval discharges are 55, 120, and 236 cfs, respectively. Roughness of 0.025 was used to calculate mean flow depth, assuming that flow conditions were in the range of lower to transitional flow regimes (Lagasse et al. 2012). This assumption is valid for XS-1 and XS-3, but XS-2 is likely to be in the range of transitional to upper flow regime under existing conditions. However, conditions are likely to be in the lower flow regime for all cross sections once slope declines toward the equilibrium value. Slope values, based on the existing conditions geomorphic assessment, used in the calculations include 0.28, 1.12, and 0.82 percent for XS-1, XS-2, and XS-3. Results of the equilibrium slope analysis along the sand-bed area (stations 11+16 to 14+71), including average, minimum, and maximum values, are summarized in ***Table 3***.

Table 3: Summary of Equilibrium Slope Calculations for Stations 11+16 to 14+71

Discharge (cfs)	Recurrence Interval	Equilibrium Slope (%)					
		XS-1	XS-2	XS-3	Average	Min	Max
55	1.5-YR	0.0588	0.1100	0.1260	0.0983	0.0588	0.1260
120	10-YR	0.0518	0.0801	0.0880	0.0733	0.0518	0.0880
236	100-YR	0.0326	0.0550	0.0734	0.0537	0.0326	0.0734

Results indicate that equilibrium slope ranges from 0.0326 to 0.126 percent. The range of potential equilibrium slope values reveals the uncertainty in the calculations and the importance on choosing appropriate input values. There is, however, less variability in the range of average equilibrium slope values—0.0537 to 0.0983 percent. Based on this, it appears appropriate to use the average equilibrium slope for the 10-year recurrence interval discharge—0.0733 percent—as the representative value for the analysis along the sand-bed reach (stations 11+16 to 14+71).

Equilibrium slope along the Class I Riprap area (stations 10+35 to 11+16) was evaluated using four relationships identified by NRCS (2007) for estimating equilibrium slope for channel bed material size greater than sand with no upstream sediment supply, including: (1) simultaneously solving the Manning and Shields equations, (2) Meyer-Peter and Muller transport relationship, (3) Schoklitsch equation, and (4) Henderson formula. Two of the relationship were used for this analysis—the combined Manning and Shields equations and the Schoklitsch relationship. The Meyer-Peter and Muller relationship yielded inconsistent values compared to the Manning and Shields and Schoklitsch relationships. While the Henderson formula resulted in a value consistent with the Manning and Shields and Schoklitsch relationships, it did not allow comparison between varying channel geometry as discharge is the flow variable input rather than unit discharge or channel depth. The Henderson formula is, however, valuable as a check to evaluating the whether or not the equilibrium slope value based on the Manning and Shields and Schoklitsch relationships is appropriate. The Manning and Shields, Schoklitsch, and Henderson relationships are shown below:

- Manning and Shields:

$$S_{eq} = \left[\theta_C D_C \Delta S_g\right]^{10/7} \left(\frac{K}{qn}\right)^{6/7}$$

- Schoklitsch

$$S_{eq} = K\left(\frac{D_m}{q}\right)^{3/4}$$

- Henderson

$$S_{eq} = KQ_d^{-0.46} D_{50}^{1.15}$$

where S_{eq} is equilibrium slope (ft/ft), θ_c is Shields parameter, D_c is critical bed material size (ft), ΔS_g is relative submerged density of sediment (1.65), K is a constant (1.486 for Manning and Shields; 0.00174 for Schoklitsch; and 0.44 for Henderson), q is channel forming discharge per unit width (ft^2/s), n is Manning's roughness coefficient, D_m is mean grain size (mm), Q_d is design discharge (ft^3/s), and D_{50} is median grain size (ft).

Results of the equilibrium slope analysis along the Class I Riprap area (stations 10+35 to 11+16), including average, minimum, and maximum values, for the 10-year recurrence interval discharge are summarized in ***Table 4***. This analysis focused on the 10-year discharge to be consistent with the equilibrium slope analysis conducted for the sand-bed area (stations 11+16 to 14+71). Results indicate that equilibrium slope along the Class I Riprap area range from 0.73 to 4.81 percent. The average value for the Manning and Shields and Schoklitsch relationships is 2.4 percent. This value is consistent with the equilibrium slope estimated using the Henderson relationship (3.1 percent). It appears that using 2.4 percent is an appropriate equilibrium slope for this analysis.

Table 4: Summary of Equilibrium Slope Calculations for Stations 10+35 to 11+16

Discharge (cfs)	Recurrence Interval	Equilibrium Slope (%)					
		XS-1	XS-2	XS-3	Average	Min	Max
Manning and Shields							
120	10-YR	0.84	2.74	4.81	2.80	0.84	4.81
Shoklitsch							
120	10-YR	0.73	2.07	3.37	2.06	0.73	3.37
Henderson							
120	10-YR	3.1			NA	NA	NA

Results of the equilibrium slope analysis indicate the following:

- Class III Riprap between approximate stations 10+00 and 10+35
  - no change to existing conditions is anticipated/assumed for this analysis
- Class I Riprap between approximate stations 10+35 and 11+16
  - equilibrium slope of 2.4 percent is anticipated/assumed for this analysis
- Sand between approximate stations 11+16 and 14+71
  - equilibrium slope of 0.0733 percent is anticipated/assumed for this analysis

3.4 EQUILIBRIUM BANK SLOPE ANALYSIS

The equilibrium bank slope analysis is based on methods from Technical Supplement 14A —Soil Properties and Special Geotechnical Problems Related to Stream Stabilization Projects— of Part 654 of the National Engineering Handbook—Stream Restoration Design (NRCS 2007).

The following equation estimates the factor of safety for slope stability for low plasticity sands and silts with no seepage (p. TS14A-30):

$$FS = m \times \tan \emptyset'$$

where FS is factor of safety, m is slope cotangent—mH:1V, and ϕ' is internal friction angle of cohesionless slope soil (radians). According to Technical Supplement 14A, a factor of safety of 1.1 is commonly regarded as acceptable for low plasticity sands and silts with no seepage. Solving form, considering a factor of safety value of 1.1, yields:

$$m = {}^{1.1}/_{\tan \emptyset'}$$

Bank material was assumed to be similar to the channel bed material with a median grain size of 0.6 mm. Typical values of internal friction angle of sand material (from Table TS14A-3 in Technical Supplement 14A of NRCS 2007) include: (1) 28 degrees (0.4887 radians) for loose sand, (2) 32 degrees (0.5585 radians) for medium dense sand, and (3) 38 degrees (0.6632 radians) for dense sand. Values of slope cotangent (m) based on a factor of safety of 1.1 and the three typical internal friction angle values include:

- 2.07 for loose sand
- 1.76 for medium dense sand
- 1.41 for dense sand

The results indicate that stable bank slopes are in the range of 1.4:1 to 2.1:1 for banks comprised of sand in the absence of influence of seepage. Utilizing the value of 1.76 for medium dense sand is likely an appropriate representative value for this analysis. Utilizing the value for medium dense sand is likely to provide conservatively low results without overestimating equilibrium bank angle, which would result in greater values of erosion.

3.5 RESULTS OF EROSION ESTIMATE BASED ON ALTERNATIVE ANALYSIS

The representative values calculated for equilibrium slope and stable bank angle are combined with bottom width in order to estimate cross-section dimensions at the future point when equilibrium slope conditions are reached. A constant bottom width of 17 feet was utilized for the erosion analysis as discussed in ***Section 3.2***. The difference between current and future channel conditions represents the amount of material having potential to be eroded and subsequently supply pollutants to downstream waters and the Chesapeake Bay. In addition, both channel bed and bank erosion were included in the erosion estimate since the channel bed and bank materials consist of sand. Results of the erosion estimate based on equilibrium slope, bank stability, and representative bottom width indicate that 139,929 cubic feet (5,182 cubic yards) of sediment would erode from the project reach before equilibrium conditions were achieved.

Nutrient content was directly measured for the project reach by the methods presented in Merritts et al 2010. This method involves the collection of soil samples representative of all unique bank strata and laboratory testing following EPA 3051 Method for total phosphorus, and elemental combustion analysis for total nitrogen. Bank nutrient content was measured at two elevations along both banks at each cross section. The nutrient content varied from 0.01% to 0.05% TN and 0.003% to 0.023% TP, by weight. These values correspond with average nutrient concentrations of 0.25 pounds of TP per ton of sediment and 0.70 pounds of TN per ton of sediment.

Utilizing a 100% efficiency factor, removal rates include (1) 5,226 tons for sediment load reduction, (2) 1,307 pounds for phosphorus load reduction, and (3) 3,658 pounds for nitrogen load reduction. Note that these values include total tons or pounds, rather than tons per year and pounds per year.

Applying the 56% efficiency factor recommended by Schueler and Stack (2014), removal rates include (1) 2,927 tons for sediment load reduction, (2) 732 pounds for phosphorus load reduction, and (3) 2,048 pounds for nitrogen load reduction. Note that these values include total tons or pounds, rather than tons per year and pounds per year.

The total load conversion factors provided in MDE (2014) for street sweeping of 70% dry mass of material and 30% TSS reduction rates were not applied to the load reductions for I-97. These reduction factors were specific to street sweeping and are designed to take into consideration the mass of material which is available for transport in the stream. In the methodology presented in this document the mass of material available for transport is accounted for by applying bulk density and nutrient concentrations to the predicted evacuated material.

Converting total load reduction calculated in the alternative method is completed using an assumed fixed project life of 30 years. The 30 year duration is expected to be a rough estimate of the probable time of channel readjustment based on engineering judgment. This method assumes that the credit can be applied on a linear basis.

Utilizing a 100% efficiency factor, over the 30 year time period the yearly reductions are (1) 174 tons per year for sediment load reduction, (2) 44 pounds per year for phosphorus load reduction, and (3) 122 pounds per year for nitrogen load reduction (***Table 5***).

Utilizing a 56% efficiency factor, over the 30 year time period the yearly reductions are (1) 97 tons per year for sediment load reduction, (2) 25 pounds per year for phosphorus load reduction, and (3) 68 pounds per year for nitrogen load reduction (***Table 5***).

Table 5: TMDL Credit through Alternative Method

Pollutant	***Alternative Method***	
	100 % Efficiency	***56% Efficiency***
TN (lbs/yr)	122	68
TP (lbs/yr)	44	25
TSS (tons/yr)	174	97

3.6 TMDL CREDIT BASED ON PROTOCOL 1

TMDL credit was also calculated using methods described in Schueler and Stack (2014) for *Protocol 1: Credit for Preventing Sediment during Storm Flow*. For this effort, the BANCS process was used in conjunction with regional curves and measured bulk density to determine the total sediment load. Estimates of bank material nutrient is based on the measured values listed in ***Section 2.3***.

The nutrient concentration multiplied by the total sediment annual sediment loading provides an estimate of the existing sediment loading. In Schueler and Stack (2014) it is determined that a removal efficiency of 56% will be assumed for all stream restoration projects. An efficiency value of 100% is also included for comparison purposes. Existing conditions bank erosion potential for *Protocol 1: Credit for Preventing Sediment during Storm Flow* was calculated along:

- Station 10+07 to 10+48, Left
- Station 10+35 to 10+48, Right
- Station 10+48 to 14+54, Left and Right
- Station 300+26 to 300+79, Left

Average cross section nutrient content values were then applied to similar reaches along the entire channel.

Estimated pollutant removal rates for the I-97 SB Outfall Stabilization project reach based on *Protocol 1: Credit for Preventing Sediment during Storm Flow* are summarized in ***Table 6***.

Table 6: TMDL Credit through Protocol 1

Pollutant	***Protocol 1***	
	100% Efficiency	***56% Efficiency***
TN (lbs/yr)	42	24
TP (lbs/yr)	16	9
TSS (tons/yr)	70	39

Table 7 lists the results of both the alternative method and *Protocol 1: Credit for Preventing Sediment during Storm Flow* method for determining annual TMDL credit. Annual removal for the alternative method is two (2) to three (3) times greater for each of the pollutants. ***Table 7*** assumes both credits *(Alternative and Protocol 1)* would be applied in perpetuity.

Table 7: Comparison of TMDL Credit for Alternative Method and Protocol 1

Efficiency	*Method*	*Annual Removal Potential*		
		TSS (tons/yr)	**TP (lbs/yr)**	**TN (lbs/yr)**
100%	Alternative	174	44	122
	Protocol 1	70	16	42
56%	Alternative	97	25	68
	Protocol 1	39	9	24

3.7 RESULTS OF IMPERVIOUS AREA TREATMENT CALCULATIONS

Impervious area treatment was calculated for the I-97 project following methods described in MDE (2014) and methods for estimating pollutant load reduction described in ***Section 2*** and discussed in ***Sections 3.3***, ***3.4*** and ***3.5***. Converting total load reduction calculated in ***Sections 3.3***, ***3.4*** and ***3.5*** for evaluating impervious area treatment is based on a fixed timeframe of 30 years. The 30-year duration is a rough estimate of the probable timeframe of channel readjustment based on engineering judgment and published research discussed in ***Section 2.4***.

The total load reduction for the I-97 stream restoration project, as stated in ***Section 3.5*** is 5,226 tons TSS, 1,307 lbs TP, and 3,658 lbs TN. This total load is annualized by the 30-year probable time frame to give a total annual pollutant load reduction of 174 tons/year TSS, 44 lbs/year TP and 122 lbs/year TN. This is converted to an average pollutant load reduction by dividing by the watershed acres, 30 acres for the I-97 SB Outfall Stabilization project. Total drainage area (30 acres for the I-97 SB Outfall Stabilization project) is used here to be consistent with impervious area treatment calculations completed for the Spring Branch stream restoration project, as discussed above in ***Section 2.0***. As shown in the equations presented below, the effect of drainage area in the impervious area treatment is canceled, and the same result will be calculated regardless of drainage area used, since the average pollutant load reduction is divided by drainage area (***Column 6***) and then the impervious acre conversion factor is multiplied by drainage area divided by project length (***Row 6***).

The following equations demonstrate the impervious area treatment calculation process:

Column 5

$$Total\ annual\ pollutant\ load\ reduction\left(\frac{lbs}{yr}\ or\ \frac{tons}{yr}\right) = \frac{Total\ pollutant\ load\ reduction\ (lbs\ or\ tons)}{Probable\ timeframe\ (yr)}$$

Column 6

$$Average\ pollutant\ load\ reduction\ \left(\frac{lbs\ or\ tons}{AC\ yr}\right) = \frac{Total\ annual\ pollutant\ load\ reduction\left(\frac{lbs}{yr}\ or\ \frac{tons}{yr}\right)}{Project\ drainage\ area\ (AC)}$$

Column 7

$$Impervious\ acre\ conversion\ factor\ \left(\frac{AC}{AC}\right) = \frac{Average\ pollutant\ load\ reduction\ \left(\frac{lbs}{acre\ yr}\right)}{Delta\ of\ impervious\ surface\ and\ forest\ \left(\frac{lbs}{acre\ yr}\right)}$$

Row 6

$$Average\ acres\ of\ treatment\ for\ nutrients\ and\ sediment\ per\ LF\ \left(\frac{AC}{LF}\right) = Impervious\ acre\ conversion\ factor\ \left(\frac{AC}{AC}\right) * \frac{Drainage\ area\ (AC)}{Project\ length\ (LF)}$$

Results of the impervious area treatment calculations associated with the I-97 project are included in ***Table 8*** with the annual pollutant load reduction based on a 30-year timeframe.

Table 8 does not include using the 70% dry mass of material and 30% TSS reduction used in MDE (2014) for street sweeping. These conversions do not apply to the mass loading associated with headwater restoration or stabilization projects where bulk density and nutrient concentration of the soil are field verified since the measured values provide an accurate representation of mass per volume of the soil and the associated nutrient concentrations.

Table 8: Impervious Area Treatment Summary based on a 30-year Timeframe

Parameter	MDE Impervious (lbs/acre/yr)	MDE Forest (lbs/acre/yr)	Delta of Impervious Surface and Forest (lbs/acre/yr)	Total Annual Pollutant Load Reduction (56%) (lbs/yr)	Total Annual Pollutant Load Reduction (w/SDF) (lbs/yr)	Average Pollutant Load Reduction (lbs/acre/yr)	Impervious Acre Conversion Factor (AC/AC)
TN	10.85	3.16	7.69	68	68	2.3	0.30
TP	2.04	0.13	1.91	24	24	0.8	0.43
TSS (tons)	0.46	0.03	0.43	98	6	0.2	0.46
	Average for Nutrients and Sediment:						**0.39**
	Average Acres of treatment for Nutrients and Sediment per LF:						**0.026**
	Average Acres of treatment for Nutrients and Sediment per 100 LF:						**2.6**

Results in ***Table 8*** indicates that the amount of pollutant load reduction associated with stabilizing the existing eroding channel along the I-97 project results in impervious area treatment values of 0.026 acres per linear foot based on a 30-year timeframe.

In addition to pollutant load reduction due to stabilizing and preventing erosion along the headwater channel, the proposed I-97 project includes step-pool features and infiltration components that attenuate flow and function similarly to a regenerative stormwater conveyance (RSC) system. Pollutant load reduction due to the RSC-type component of the project are based on Protocol 4: Credit for Dry Channel Regenerative Stormwater Conveyance (RSC) as an Upland Stormwater Retrofit described in Schueler and Stack (2014).

Runoff storage volume for Protocol 4 is based on above-grade pool volume and the subgrade sand filter. Above-grade pool volume is based on the step-pool pool dimensions at a 1.5-foot depth (the pool depth based on the elevation of the downstream crest). The volume of storage available within the subgrade sand filter assumed the following:

- Fill Conditions
  - a 1.5-foot depth below the cobble layer within the pool up to a maximum elevation at the channel bed surface
  - in addition to sand filter material used as fill material to meet existing grade below the material within the 1.5-foot depth zone described above
  - areas below the pool bed surface elevation and extending laterally from the pool location where sand filter material is proposed as fill to meet existing grade were also considered
- Cut Conditions
  - a 1.5-foot depth below the cobble layer within the pool up to a maximum elevation at the channel bed surface
  - it is anticipated that the existing material beneath the proposed channel will consist primarily of sand and will function in a similar manner to the sand filter material

The I-97 SB Outfall Stabilization project reach will provide an estimated removal of 23 lbs/yr TN, 5 lbs/yr TP, 1 ton/yr TSS based on Protocol 4. Following methods in MDE (2014), impervious area treated due to the step-pool and infiltration (RSC-type) components along the I-97 project reach are summarized in ***Table 9***.

Table 9: Impervious Area Treatment Summary Step-pool and Infiltration

Parameter	MDE Impervious (lbs/acre/yr)	MDE Forest (lbs/acre/yr)	Delta of Impervious Surface and Forest (lbs/acre/yr)	Average Pollutant Load Reduction (lbs/acre/yr)	Impervious Acre Conversion Factor (AC/AC)
TN	10.85	3.16	7.69	0.77	0.10
TP	2.04	0.13	1.91	0.17	0.087
TSS (tons)	0.46	0.03	0.43	0.03	0.078
Average for Nutrients and Sediment:					**0.088**
Average Acres of treatment for Nutrients and Sediment per LF:					**0.006**
Average Acres of treatment for Nutrients and Sediment per 100 LF:					**0.6**

Results in ***Table 9*** indicate that the amount of pollutant load reduction associated with the step-pool and infiltration (RSC-type) components along the I-97 project reach is 0.006 acres per linear foot.

Table 10 summarizes the impervious area treatment for stabilizing erosion along the I-97 project reach, based on a 30-year timeframe, and the step-pool and infiltration (RSC-type) components.

Table 10: Impervious Area Treatment Summary for the I-97 Project Reach

Parameter	Channel Stabilization based on 30-yr Timeframe	RSC-type Components
Average Acres of treatment for Nutrients and Sediment per LF	0.026	0.006
Average Acres of treatment for Nutrients and Sediment per 100 LF	2.6	0.6
Total Acres of treatment for Nutrients and Sediment for the I-97 Project	11.8	2.6

The values in ***Table 10*** indicate that the channel stabilization associated with the I-97 project is equivalent to treating 11.8 impervious acres over a 30-year timeframe. In addition, the step-pool and infiltration (RSC-type) components are equivalent to treating 2.6 acres of impervious surface. The total impervious acre equivalency credit eligible at I-97 would be 10.1 acres.

MDE (2014) provides impervious area treatment credit for outfall stabilization at a rate of 0.01 acres per linear foot (or 1 acre per 100) linear feet, with the maximum credit capped at 2 acres. These values are based on monitoring data from the Spring Branch stream restoration project. The higher values associated with the I-97 outfall stabilization project are likely due to the site-specific sediment and nutrient loading and relatively smaller drainage area. As summarized in ***Section 3.0***, existing conditions along the I-97 project reach include highly erodible banks with heights ranging from 6 to 21 feet and bottom width ranging from 4 to 40 feet. These conditions result in a sediment and nutrient loading source that has a higher supply rate per liner foot of project length or per acre of drainage area.

Erosion from headwater channels represents a direct source of sediment and nutrients into the tributaries of the Chesapeake Bay, and, as outlined in ***Section 1.2***, first order channels have been observed to provide larger amounts of fine sediment to downstream water resources than upland sources within the watershed (Smith et al. 2011).

Based on the results of the impervious area treatment calculations for the I-97 project reach, including impervious area treatment of 11.8 acres (based on the I-97 source loading) plus 2.6 acres for the step-pool and infiltration (RSC-type) components, it appears that capping impervious area treatment credit at 2 acres is too low. As 14.4 acres of credit is less than the current impervious surface watershed area of 16.5 acres, the site would be eligible for the entire calculated credit in perpetuity.

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