Appendix F

BMP Clogging Risk Assessment Tool

User Guide and Technical Documentation

This appendix contains a User's Guide and Technical Documentation for the BMP Clogging Risk Assessment Tool. The User Tool can be downloaded from the TRB website (www.trb.org); search for "*NCHRP Research Report 922*".

Appendix F

BMP Clogging Risk Assessment Tool
User Guide and Technical Documentation

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1. Introduction

Clogging of infiltration and filtration best management practices (BMPs) with sediment is a common failure mechanism and is a major factor in the lifespan, maintenance requirements, and long-term performance of these systems. Clogging occurs over time as fines accumulate at or near the surface of the soil and/or media. This progressively reduces the permeability of the soil or filter media. An understanding of the potential for premature clogging and risk factors related to clogging can aid practitioners in selecting appropriate BMPs and supporting design decisions intended to extend the lifespan of implemented practices.

The BMP Clogging Risk Assessment Tool (tool) was developed to provide an interactive semi-quantitative framework to assess the clogging susceptibility of a proposed infiltration or filtration BMP system. The tool is based on a relationship, developed as part of this project, that describes the estimated decline in permeability as a function of the accumulated sediment load. This function was developed based on a review of data from several studies (Clark & Pitt, 1999; Le Coustumer et al., 2012; Limouzin et al., 2011; Pitt & Clark, 2010). Figure 1 provides an outline of the technical framework of the tool.

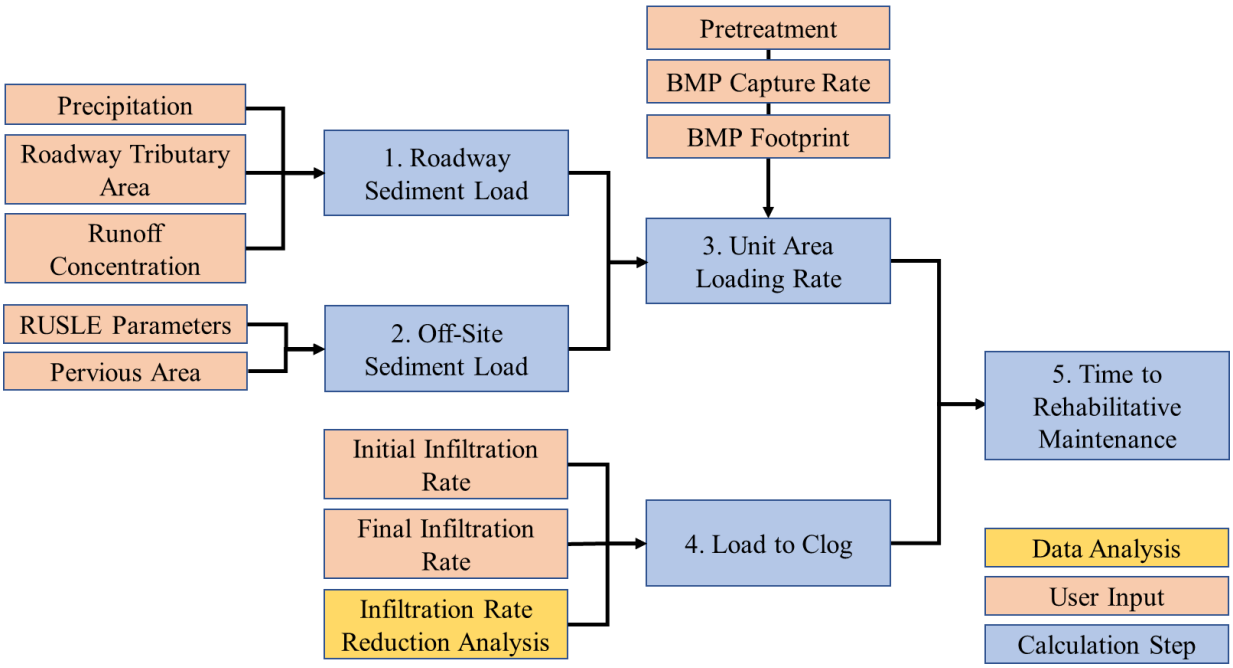


Figure 1. Roadside BMP Clogging Risk Assessment Tool calculation flowchart

The tool calculates the site-specific loading rate per unit area of infiltrating or filtering surface within the BMP based on user inputs describing the location, tributary area characteristics, and BMP system design parameters. The BMP system is inclusive of any pre-treatment provided. User inputs are also used to define the initial permeability and the acceptable lower range of permeability before maintenance is needed. Based

on these inputs and built-in algorithms, the tool provides several outputs, including an estimated time range until the practice will require rehabilitative maintenance and a quantification of risk factors to alert the user of specific design aspects that may lead to a reduced lifespan. The tool is designed to estimate the rate of decline in permeability as a function of clogging at a single limiting interface. If two potential interfaces are susceptible to clogging (i.e., media and underlying soil) each can be assessed independently, and the pre-treatment provided by the overlying media layer can be accounted for in the calculations of clogging of the underlying soil.

The purpose of the tool is to provide input on how clogging risk would be affected by site conditions and design decisions, such as average precipitation, average traffic volume, tributary area size, presence of erodible areas in the watershed (as well design decisions to isolate or stabilize these areas), type of pretreatment provided (if any), BMP footprint and depth, and other factors. While certain estimates are quantitative, the interpretation of these estimates is inherently semi-quantitative due to the uncertainty and variability in environmental processes associated with clogging.

The tool contains guidance embedded within its interface. The following sections supplement the guidance provided within the tool to guide the user in selecting appropriate parameters. This appendix also provides technical documentation of Tool calculations.

2. General Use of Tool

2.1 System Requirements

- The tool is intended to run in Microsoft Excel 2010 to 2016; macros must be enabled for the tool to run properly.
- The tool has been tested in a Windows 10 environment; user experience may differ in other operating system environments.
- The tool involves no traditional “installation”, therefore should generally not require administrator privileges to use. For users operating within strict security settings, administrator privileges may be required to enable macros within Excel.

2.2 Starting a New Project (Evaluation)

To start a new project, follow these steps:

- Open the original Tool spreadsheet by double-clicking the .xlsm file extracted from the Zip Folder.
- When the tool opens, it is necessary to enable macros. The process of enabling macros varies depending on local security settings in place. If macros are not enabled, the user should consult Excel support for guidance in enabling macros.
- Save the project to a directory of the user’s choice by using the “Save As” command in Excel. The file must be saved as a macro-enabled workbook (.xlsm) file.
- The tool will open to the Project Location Worksheet. The header provides space to enter project information (Figure 2).

- Once the project information is entered on the Project Location Worksheet, the remaining headings on subsequent worksheets will be updated to match.

These steps can be followed for each project/scenario being analyzed with the tool.

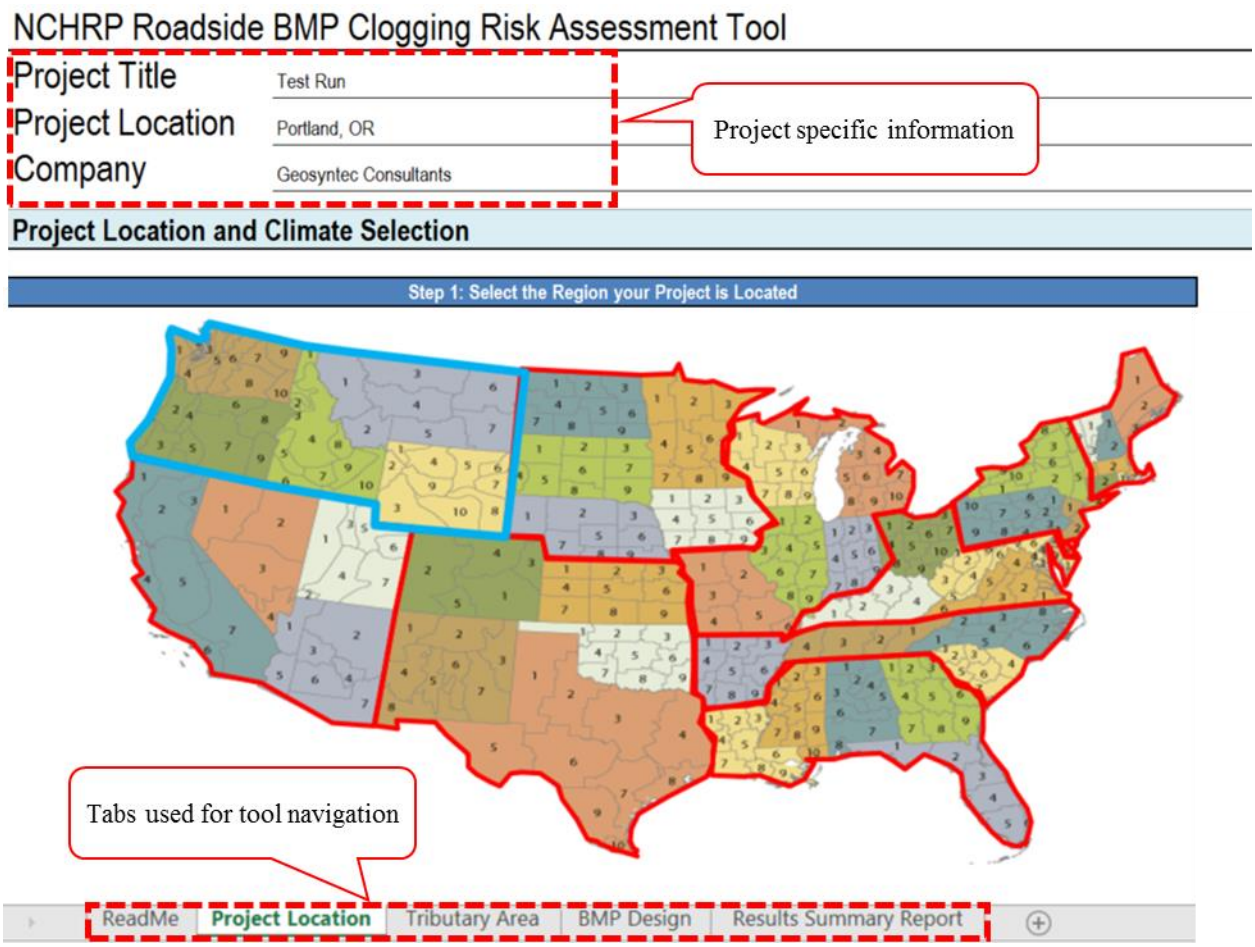


Figure 2. Project information and tool navigation

2.3 Organization and Navigation of the tool

The tool is divided into various input forms that reside on separate worksheets. The user navigates the tool by selecting the worksheet tabs located at the bottom of the spreadsheet (Figure 2). The tool is set up sequentially to define project attributes and then view a summary of results. Inputs are defined on three worksheet tabs: (1) Project Location, (2) Tributary Area, and (3) BMP Design (

Table 1). On these tabs, inputs are defined by the user and are then applied to calculate the Results Summary Report parameters. The tool is designed to operate sequentially with all inputs defined on a worksheet before progressing to the next as certain inputs are used to calculate intermediate values and suggest default values in later cells.

The tool is password protected to inhibit accidental adjustment of cells that will affect clogging calculations. The worksheet may be unprotected using the password "NCHRP". Calculation cells are normally hidden to the right of user input cells on each worksheet. Two additional tabs, graph parameters and rain gage summary, include supporting data and are hidden unless specified by the user.

Table 1. Overview of user actions on each worksheet tab

Worksheet Name	Summary of User Inputs and Results
Project Location	Specify project rain gage View default precipitation parameters Override default precipitation parameters as needed
Tributary Area	View/edit roadway TSS runoff concentrations Specify roadway tributary area parameters Specify tributary area parameters for open space areas, including Revised Universal Soil Loss Equation (RUSLE)[1] inputs
BMP Design	Specify practice type and media/soil infiltration parameters Specify BMP sizing and configuration parameters This tab includes pre-treatment options as an element of overall BMP system design
Results Summary Report	View summary of system parameters View warnings on clogging risk View clogging results and risk factors in tabular and graphical format

Each worksheet contains stepwise instructions and a key for identifying the user tasks for each cell. The following cell color coding is present on each input worksheet:

Key

User Steps	Default data; editing allowed with rationale
User Entered Data	Guidance
Reference Data; do not edit cells	Reference Links

- **User Steps:** The Project Location, Tributary Area, and BMP Design tabs each include user steps, displayed as headings in white text in the worksheet. These steps are intended to be completed sequentially and are organized into input groupings based on the tasks identified in Table 1.
- **User Entered Data:** The user is expected to enter data for all cells with a light blue background with black text. Input values will either be a dropdown list or a user specified value. Each user entered data cell is accompanied by an adjacent **Guidance Cell**, with a white background and

[1] The RUSLE equation was used because of its simplicity and the ability to apply this method in the spreadsheet environment. A more detailed version of this equation (RUSLE2) can be applied to improve estimates. This typically requires a software program to perform calculations. https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/rusle2/revised-universal-soil-loss-equation-2-overview-of-rusle2/

lighter blue text of instructions on the range of acceptable values, guidance on value selection, and information on how the tool uses the value. The user should read the guidance cell prior to selecting each input and ensure that values are reasonable.

- **Reference Data:** The light green cells with dark green text display calculated values that may not be edited by the user. These cells are used to display results in the results summary report or provide intermediate calculations on the input worksheets to aid the user in reviewing there already entered/selected parameters, selecting additional parameters and understanding tool calculations.
- **Default Data:** The yellow orange cells with dark orange text can be used to override default inputs calculated by the tool. If data is not entered in these cells the tool uses the presented default values.
- **Guidance and Reference Links:** User entered data, reference data, and default data cells are accompanied by an adjacent guidance cell to aid the user in understanding inputs and interpreting results. The guidance cells provide instructions, valid ranges, and where applicable, reference links to web references for further information or sources of data are provide in the white cells with dark blue text.

Analyzing Multiple Scenarios

Each instance of the tool (i.e., each individual .xlsm file) represents a single scenario. Multiple scenarios can be run using the following general steps:

1. Open a new instance of the tool
2. Enter inputs to define the first scenario
3. Save this scenario with a distinct file name (e.g., “File” ➔ “Save As” ➔ “ScenarioA1.xlsm”)
4. Edit inputs in the appropriate worksheet(s) to define a new scenario
5. Save this scenario with a distinct file name (e.g., “File” ➔ “Save As” ➔ “ScenarioA2.xlsm”)
6. And so on for as many scenarios as desired. Files can be organized into directories to help distinguish different analysis scenarios. After scenarios are generated, any of the instances of the tool can be reopened by double-clicking on the selected .xlsm file to view the scenario inputs and results.

Printing Summary Results

Any sheet within the worksheet can be printed using native Excel print functions. The user can use Excel menus to specify the paper size, printer preferences, and print ranges. By selecting multiple worksheet tables, multiple worksheets can be printed at the same time. Please consult Excel documentation and help files for guidance on printing from Excel.

3. Project Location Worksheet

The first step in developing a project scenario is to select the appropriate precipitation gage for the project. A precipitation gage must be selected, or a user-entered average annual rainfall must be entered for values to appear in the Results Summary Report. The tool is pre-loaded with average annual precipitation for 343 National Climatic Data Center (NCDC) Cooperative Observer Program (COOP) stations covering

all major climate regions in the contiguous United States. The average annual precipitation depth is the primary factor associated with climate that is used in the tool calculations.

To select a project precipitation gauge, complete the following steps (Figure 3):

1. Select the project region by clicking on the map.
2. Select the project state by using the drop-down menu under "States within Selected Region."
3. Select the precipitation gage that best represents the project precipitation by using the drop-down menu under "Rain Gages Available in State." Generally, the precipitation gage closest to the project location should be used. However, in some cases it might be appropriate to use another. For example, if the nearest gage is at lower or higher elevation than the site or on the other side of a mountainous area, it might be appropriate to select another nearby gage that better represents the site.
4. If project specific precipitation data is available override the default average annual value.

Note, the 85th percentile, 24-hour event precipitation depth is not used directly in clogging calculations. This is only used as a reference value, as the 85th percentile, 24-hour storm (or similar) is a common BMP sizing standard in the US.

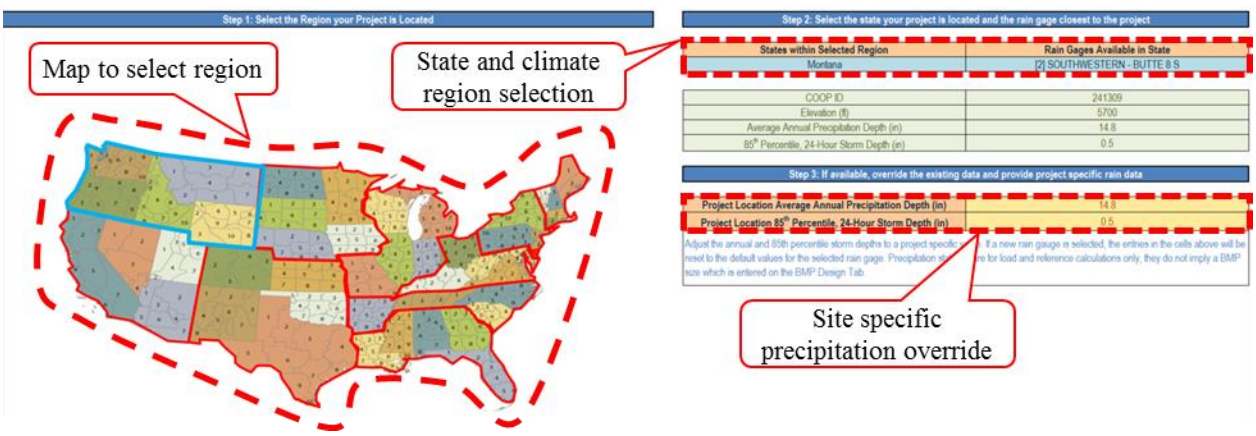


Figure 3. Project Location Worksheet layout

4. Tributary Area Worksheet

The Tributary Area Worksheet is used to define the parameters necessary to calculate the average annual influent suspended sediment load. Input parameters are entered to define the roadway tributary area and pervious non-roadway areas that drain to the practice. Roadway tributary area input parameters are used to determine the average annual sediment load based on the average runoff concentration and calculated annual runoff volume. The off-site drainage area uses a different method for estimating sediment load, based on the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). This method is relatively simple. The RUSLE 2 method is more detailed and can be used to improve inputs.

4.1 Roadway Tributary Area Inputs

The first two steps of the Tributary Area Worksheet are used to define the characteristics of the roadway drainage area (Figure 4) and the median/shoulder areas typically associated with roadway runoff. The

default roadway TSS concentration is defined based on the input for the roadway average annual daily traffic (AADT) volume. Selecting an AADT range from the dropdown menu will define a default roadway TSS concentration based on median values from the Highway Runoff Database (HRDB; Granato and Cazenas, 2009). The default roadway median TSS concentration may be replaced by a user-provided roadway TSS concentration, which is recommended if locally suitable data are available.

User adjustments to the default TSS loading may be needed in arid areas where airborne particles (i.e., dust) can add sediment loading beyond what would be typically associated with highway runoff. Additionally, where traction sand generates TSS-size particle fractions, users should adjust the default TSS concentration to account for the effect of traction sand. In both cases, the effects should be expressed as a user-defined average annual concentration calculated based on local data. This calculation should account for portions of the year when dust or sanding apply and portions of the year when these factors do not apply. The input to the tool should be the average annual concentration.

Step 2 of the Tributary Area Worksheet is used to define the roadway watershed parameters used in calculating the average annual runoff volume. The roadway drainage area and percent imperviousness are entered by the user. A runoff coefficient is calculated based on the impervious area input. The calculated runoff coefficient may be overridden by a user-provided value. This should reflect the area and imperviousness of typical roadway features such as pavement and stabilized median/shoulder areas. If there are substantial open space areas draining into the right-of-way, these areas should be included as part of the next step.

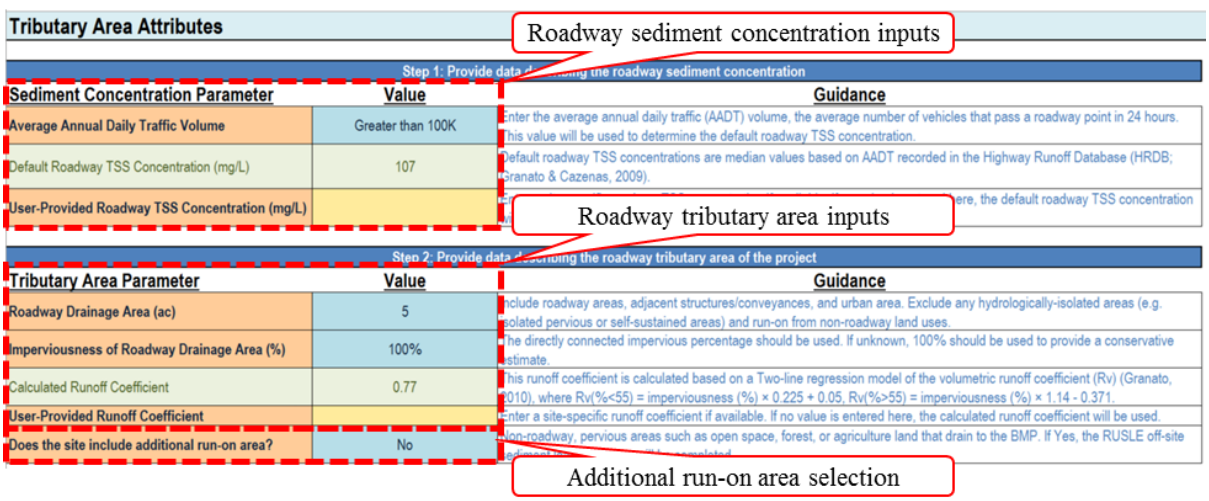


Figure 4. Tributary Area Worksheet – Roadway sediment concentration inputs

4.2 Additional Run-On Area Inputs

Selecting "Yes" on the additional run-on area selection cell (Figure 4) will bring up Step 3 of the Tributary Area Worksheet. This step defines tributary area parameters for pervious areas adjacent to the roadway that drain to the BMP to estimate suspended sediment loading from these areas. This should include substantial open space areas beyond what typically make up a highway right of way. For example,

normal medians and a short length of shoulder would be included in the previous step as runoff from this area is already accounted for in typical highway suspended sediment concentration data. But if the median and/or shoulders are unusually wide or are known to be erosive, then this area should be tabulated as part of this step.

The RUSLE method is used as a simple approximation. Parameters are defined to calculate the five RUSLE factors (Figure 5):

- **Rainfall-Runoff Erosivity (R):** This factor is defined based on project location to account for the effects of annual rainfall depth and intensity on erosion. R factor values can be determined using isoerodent maps (Renard et al., 1997, Chapter 2).
- **Soil Erodibility (K):** The soil erodibility factor accounts for the effect of soil type on erosion potential. The tool allows for two options for entering the soil erodibility factor:
    - **K Factor Known:** If the soil erodibility factor is known for the project site, the user may directly input the value. Depending on the site location, the K value may be determined using soil maps. The NRCS Web Soil Survey lists K values under the soil properties and qualities ratings (NRCS Soil Survey Staff, 2017).
    - **K Factor Unknown:** If the K factor is unknown, the tool includes a look-up table to determine an estimated K value based on the input soil texture class and organic matter content (Renard et al., 1997, Chapter 3).
- **Length-Slope (LS):** The length-slope factor is calculated based on inputs for the length and slope of overland flow (Renard et al., 1997, Chapter 4).
- **Cover Management (C):** The cover management factor is defined based on user input parameters defining the site vegetation, ground cover, and canopy cover. The user input values are used to define a C Factor based on values for pasture, range, and idle lands from Wischmeier & Smith (1978).
- **Practice Support (P):** The practice support factor accounts for on-site practices that reduce erosion. The default value of 1 is recommended under normal conditions. Refer to Renard et al. (1997), Chapter 6 for guidance on P value selection if erosion control measures are present onsite.

This module is organized into inputs relating to drainage area, climate, soil type, vegetation/cover, and practice management. The defined input parameters are used to calculate a value for each of the five RUSLE factors. Calculated factor values are shown in the RUSLE Calculation section (Figure 5). Inputs for calculating the RUSLE factors require specific inputs describing site conditions and care should be taken to define parameters that are representative of the project location and within acceptable ranges. When applicable, reference links are provided in the guidance descriptions to link the user to additional guidance documents or web-based tools for determining parameters.

This module allows for a rapid planning-level assessment of how erodible open space areas could influence lifespan of an infiltration or filtration BMP. However, in general, estimates of sediment yield from pervious areas are highly uncertain. These estimates could over-estimate or underestimate sediment yield by an order of magnitude or more depending on site-specific conditions. When open space areas have the potential to be erosive or experience land-sliding, the best practice is to bypass runoff from these areas

around BMPs (isolate this area from the BMP tributary area) so that it does not pose an elevated risk clogging to the BMP.

Using the results of alternative loading methods. For simplicity, the tool only supports the RUSLE method. However, the user could develop estimates using a different method (e.g., RUSLE2) and use these estimates to support RUSLE parameters. If the annual sediment load is estimated from a different method, the user can adjust the RUSLE parameters in the tool to yield the same estimate.

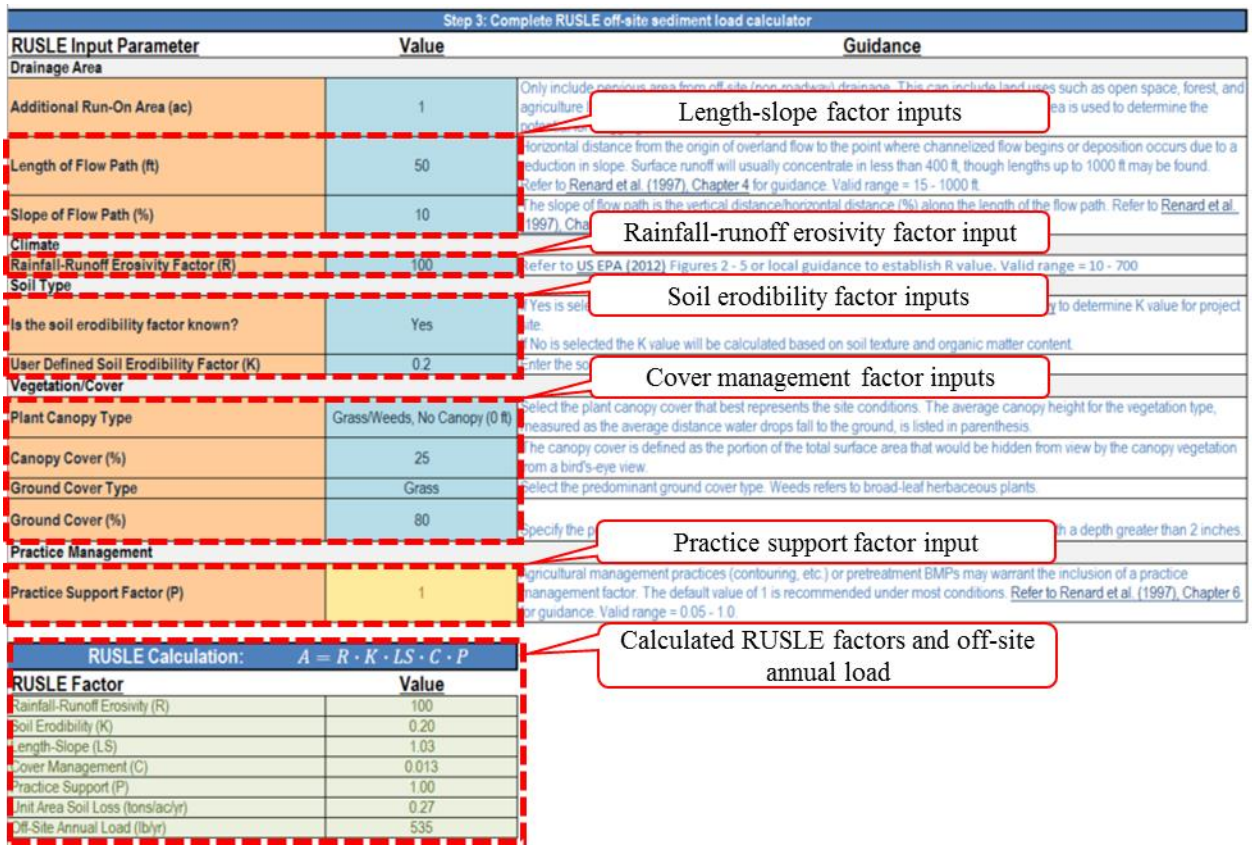


Figure 5. Tributary area worksheet – Off-site RUSLE sediment load inputs

5. BMP Design Worksheet

The BMP Design Worksheet is used to define parameters relating to soil or media characteristics and BMP size. The worksheet includes steps for defining media/soil parameters and BMP design characteristics. The worksheet is designed to be completed sequentially and depending on user inputs for certain cells additional inputs will be hidden or unhidden.

5.1 Media/Soil Parameter Inputs

In the first input, the user specifies the BMP as an infiltration or filtration BMP (Figure 6). Depending on this selection, the cells below will change to display inputs specific to the selected practice type. The limiting interface for media filtration is assumed to be the media surface. The limiting interface for infiltration is the underlying soil (if no sacrificial medial layer present) or the media surface (if there is a sacrificial media layer).

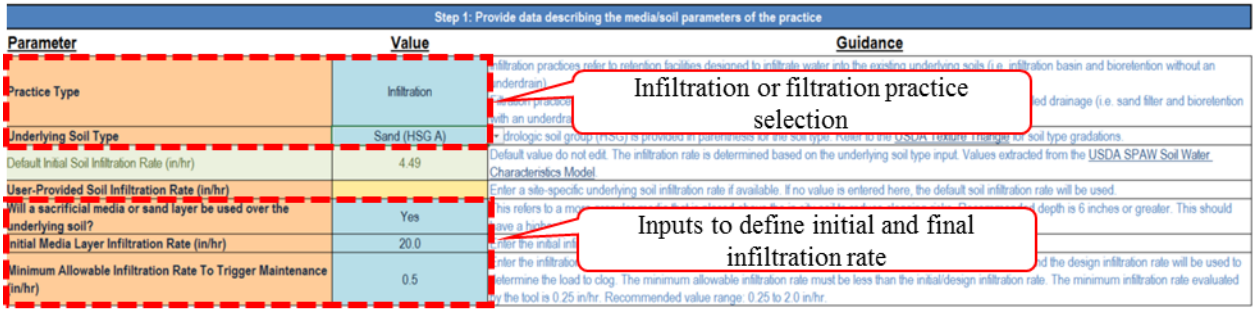
As part of Step 1, the user can define the initial design infiltration rate for the soil or media and the final system infiltration rate that would trigger rehabilitative maintenance. The tool uses this information to determine the change in infiltration rate that will result in system clogging. The final infiltration rate is the minimum allowable rate before rehabilitative maintenance is needed. The initial infiltration rate is defined based on the characteristics of the soil or media layer. For example, a BMP has an initial design soil infiltration rate of 5 inches per hour. The BMP could be designed with shallow ponding such that it would still function reliability at 1 inches per hour. In this case, the initial design infiltration rate would be 5 inches per hour and the final infiltration rate would be 1 inch per hour.

The infiltration practice type includes the option of using a sacrificial media layer (Figure 6) as pre-treatment for the underlying soil interface. If an infiltration practice with a media layer is specified, the initial infiltration rate with respect to clogging will be based on the media instead of the underlying soil type. If a filtration practice is used with hydraulic outlet control on the underdrain, the initial rate would be set at the maximum gravity infiltration rate of the media, while the actual flow through the system would be controlled to a lower rate via an underdrain.

The selection of initial and final infiltration rates in this section allows various design alternatives to be evaluated to estimate their effects on lifespan, including:

- Designs using a sacrificial media layer to prolong lifespan and protect the underlying soil layer that has lower permeability. The initial rate would be based on the sacrificial media rather than the underlying soil. The final rate would be based on when the permeability of the sacrificial layer drops below the underlying soil layer.
- Designs using a higher factor of safety in design, such that infiltration rate could drop further from its initial condition before clogging would result in required maintenance. Using a higher factor of safety tends to result in BMPs that are shallower, thus can operate effectively even at lower infiltration rates.
- Designs that involve a media filter with higher initial media permeability, but with an outlet on the underdrain to control flowrate. This configuration allows the use of more permeable media while also restricting the flow through the media to improve treatment. More permeable media can allow greater amount of sediment accumulation before clogging occurs. The initial rate would be based on the permeability of the media.

If a sacrificial media layer or media filter will be used over a less permeable soil, the tool assumes the media layer will experience clogging, but not the underlying soil. If clogging of the underlying soil is of interest, then a second scenario can be run without the media layer, but with a higher level of pre-treatment to account for the filtering effects of the media layer. This can be used to check whether the media will adequately prolong clogging of the underlying soil. A media layer will typically remove 80 to 90 percent of roadway sediment.



Step 1: Provide data describing the media/soil parameters of the practice		
Parameter	**Value**	**Guidance**
Practice Type	Infiltration	Infiltration practices refer to retention facilities designed to infiltrate water into the existing underlying soils (i.e. infiltration basin and bioretention without an underdrain). Filtration practices refer to retention facilities designed with an underdrain to provide drainage (i.e. sand filter and bioretention with an underdrain).
Underlying Soil Type	Sand (HSG A)	Hydrologic soil group (HSG) is provided in parenthesis for the soil type. Refer to the USDA Texture Triangle for soil type gradations.
Default Initial Soil Infiltration Rate (in/hr)	4.49	Default value do not edit. The infiltration rate is determined based on the underlying soil type input. Values extracted from the USDA SPAW Soil Water Characteristics Model.
User-Provided Soil Infiltration Rate (in/hr)		Enter a site-specific underlying soil infiltration rate if available. If no value is entered here, the default soil infiltration rate will be used.
Will a sacrificial media or sand layer be used over the underlying soil?	Yes	This refers to a more permeable layer of media placed over the underlying soil. Recommended depth is 6 inches or greater. This should have a higher infiltration rate than the underlying soil.
Initial Media Layer Infiltration Rate (in/hr)	20.0	Enter the initial infiltration rate of the media layer.
Minimum Allowable Infiltration Rate To Trigger Maintenance (in/hr)	0.5	Enter the infiltration rate at which maintenance is required. The design infiltration rate will be used to determine the load to clog. The minimum allowable infiltration rate must be less than the initial/design infiltration rate. The minimum infiltration rate evaluated by the tool is 0.25 in/hr. Recommended value range: 0.25 to 2.0 in/hr.

Figure 6. Practice drainage configuration and media/soil infiltration rate inputs

5.2 BMP Design Inputs

The BMP design and configuration step defines the practice size and sediment capture parameters used in the load to clog calculation. The following four input groups are defined based on user inputs (Figure 7):

1. **Practice Size:** The user entered values for the infiltrating footprint area and storage volume are used to determine the unit area sediment loading rate and practice drawdown time. The 85th percentile, 24-hour runoff volume is provided for reference purposes only and may be used to approximate a storage volume for planning level estimates.

2. **Flow Configuration:** The user can specify the practice flow configuration as either on-line or off-line. This selection will set default values for the average annual BMP sediment capture rate. The user may override the default data with project specific information. A more precise calculation of BMP sediment capture rate can be determined using the NCHRP 792, Long Term Performance and Life Cycle Costs of BMPs evaluation tools (Taylor et al., 2014)

3. **Pretreatment Design:** The selection of a pretreatment device will result in a default TSS removal efficiency. Washington State Department of Ecology (WSDOE) Testing Assessment Protocol (TAPE) General Use Level Designations (GULD) for Pretreatment and Basic Treatment are used to define default removal efficiencies. The user may reference the WSDOE list to determine an appropriate removal efficiency for the type of pretreatment present (WSDOE, 2017). The default values may be overridden with a user provided pretreatment removal efficiency. Lower removal efficiencies should be considered if influent concentrations are relatively low.

4. **Location and Vegetation:** The practice installation location can be specified as either at the surface or below grade and the vegetation type as either vegetated or unvegetated. This selection is used to inform qualitative assessments of clogging risk. Due to relatively small sample sizes and challenges in comparing data from multiple studies, the available data were not adequate to quantitatively distinguish the effects of vegetated systems versus unvegetated systems.

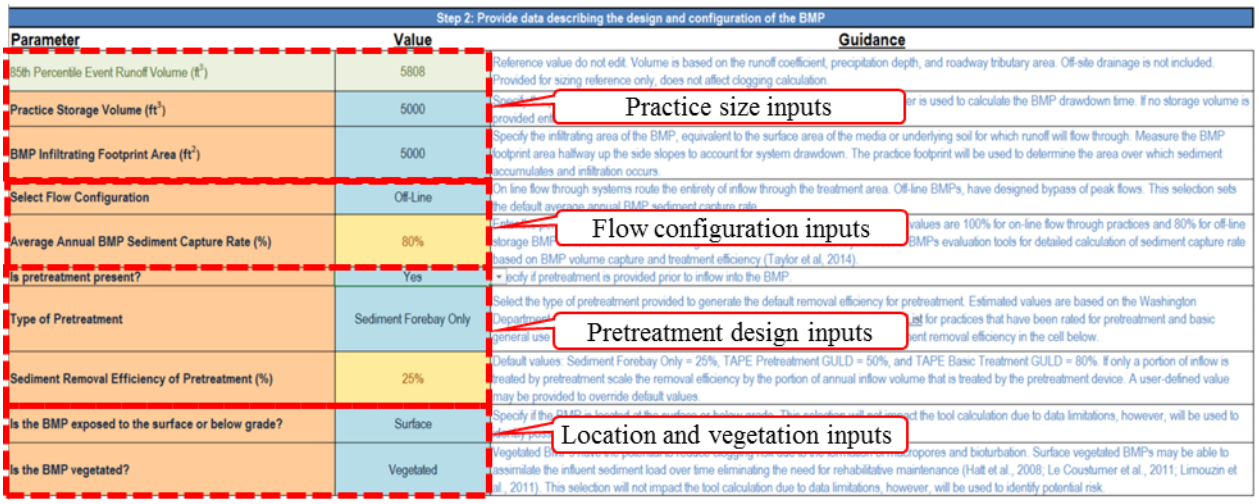


Figure 7. Practice design and configuration inputs

6. Results Summary Report

The Results Summary Report provides the user with a summary of the design scenario, load to clog calculation, and an assessment of risk factors. All values on the Results Summary Report are automatically updated if parameters are changed on the input tabs. The summary of modeled scenario section provides a description of the tributary area, precipitation, BMP design, and pretreatment inputs (Figure 8).

The design warnings section will display up to four critical design warnings to alert the user of a design that is either infeasible or at an elevated risk of clogging (Figure 8). Warnings are displayed relating to installing an infiltration practice in an area with poorly infiltrating soils, drawdown times that exceed recommended values, or a time to rehabilitative maintenance of less than 10 years. The user should review the design warnings and consider these issues in evaluating potential design modifications. All possible design warnings are shown in the example in Figure 8, if no design warnings are presented the tool will display "No fatal design warnings have been identified, view results below."

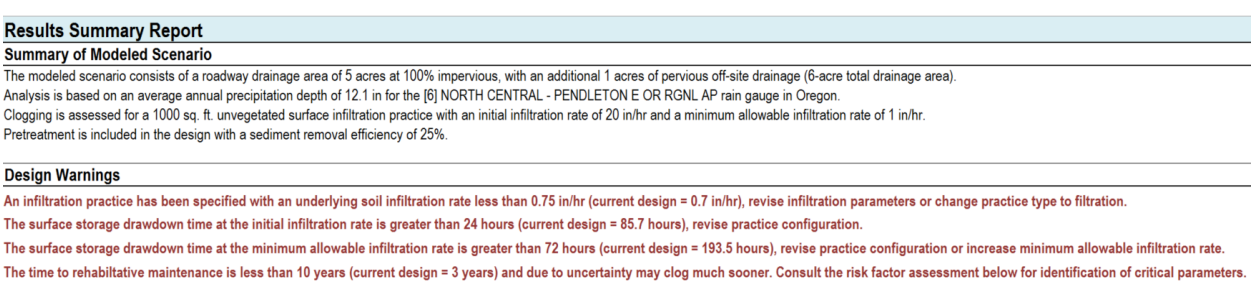


Figure 8. Example Results Summary Report – Model summary and design warnings (all warnings are shown in this example)

The time to rehabilitative maintenance is calculated based on the reduction in infiltration rate due to sediment loading. The Infiltration Rate Reduction Summary displays the load and time to reduce the design

(initial) infiltration rate to the minimum allowable (final) infiltration rate in both tabular and graphical format (Figure 9). A time to rehabilitative maintenance of less than 10 years will be flagged as a design that is susceptible to clogging and the user should review the Risk Factor Assessment (Figure 10) to determine if high risk design factors can be revised. The reduction in infiltration rate and applied load over time are graphed to illustrate how the tool calculates the time to rehabilitative maintenance (Figure 9).

The tool calculates the time to rehabilitative maintenance based on empirical data from laboratory assessments (Clark & Pitt, 1999; Le Coustumer et al., 2012; Limouzin et al., 2011; Pitt & Clark, 2010; Section 7.1). Due to limited data availability, the reported time to rehabilitative maintenance should be considered an estimate, and actual field observations may be highly variable and dependent on factors not accounted for in the tool.

he tool does not adjust estimates based on the presence of vegetation or installation location. Based on comparative studies and anecdotal evidence, subsurface and unvegetated practices are believed to be at a higher risk for clogging. However, data were not adequate to support quantification of this difference in the tool. Users should regard subsurface and unvegetated systems with greater uncertainty relative to maintenance intervals. Facilities put into service before tributary watersheds are stabilized (vegetation mature, etc.) can also result in elevated sediment loadings and early clogging.

Infiltration Rate Reduction Summary

Parameter	Value	Guidance
Load to Rehabilitative Maintenance (lb/ft^2)	2.46	The applied load to reduce the infiltration rate from the initial to minimum allowable value. The tool uses estimates for the infiltration rate of reduction per applied load for different infiltration rate zones based on laboratory experiments (Clark and Pitt, 2010; Le Coustumer et al., 2012; Limouzin et al., 2011). Refer to the technical report for method details.
BMP Captured Unit Area Sediment Load (lb/ft^2/yr)	0.20	The annual BMP sediment capture rate is normalized by practice footprint and calculated based on the runoff volume, roadway runoff concentration, and off-site sediment load determined by RUSLE. The sediment load that bypasses the practice or is removed by pretreatment is not included in the BMP capture rate. The load applied over time is graphed below.
Time to Rehabilitative Maintenance (yrs)	**12**	The time to rehabilitative maintenance is the duration for the initial infiltration rate to be reduced to the minimum allowable value due to sediment loading. If this value is less than acceptable for maintenance considerations consider the risk factors identified below to revise the system design. This value will be flagged for surface practices with a time to rehabilitative maintenance less than 10 years. The predicted infiltration rate reduction over time is graphed below.

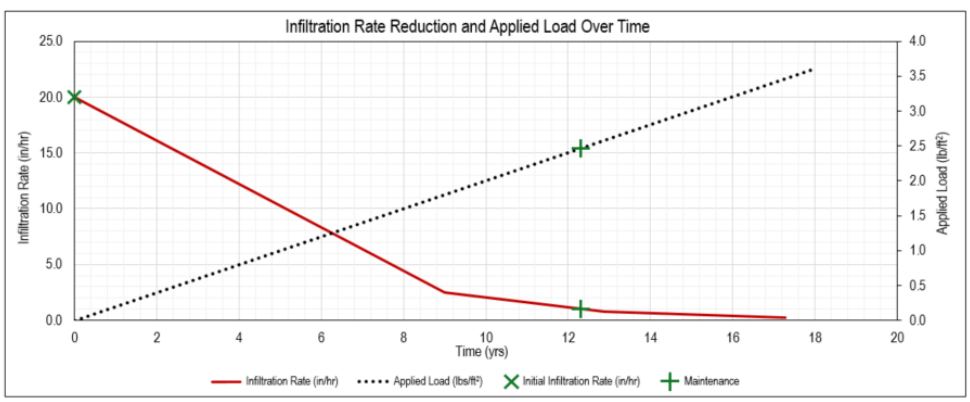


Figure 9. Example Results Summary Report – Infiltration rate reduction summary

The Risk Factor Assessment displays a table of defined parameters accompanied by risk factor ratings of low, moderate, or high (Figure 10). The table provides the user with the ability to identify what factors may contribute to a high clogging risk. Ranges used in defining the risk factor rating are provided in the Risk Factor Range Table (Table 2). The provided ranges are guideline values to assist with identification of clogging risk and are not associated with specific design recommendations.

Risk Factor Assessment

Parameter	Value	Risk	Guidance
Drawdown Rate	(see risk factor range table below for levels)		
Practice Footprint Area (% Watershed Area)	2.3%	Moderate	The drawdown rate risk factor is identified based on the drawdown time for the initial and minimum allowable infiltration rate inputs. The higher initial or final drawdown time risk is identified in the table. Extended drawdown times increase the risk for biofouling, reduce capture efficiency, and may lead to vector or human safety risks. Outlet control is encouraged for filtration practices using highly permeable media.
Drawdown Time at Initial Infiltration Rate (hr)	2.7		
Drawdown Time at Minimum Allowable Infiltration Rate (hr)	24.0		
Off-Site Drainage			
Annual Sediment Load from Roadway Area (lb/yr)	1023	High	Off-site drainage risk is identified based on the percentage of annual sediment load that is due to off-site drainage. Sediment loads are calculated based on tributary area and RUSLE inputs. Consider rerouting off-site drainage areas or providing additional pretreatment for scenarios with high off-site sediment loading.
Annual Sediment Load from Off-Site Area (lb/yr)	4937		
Off-Site Sediment Contribution (% of Total Load)	82.8%		
Reduction in Time to Maintenance due to Off-Site Drainage (yr)	20.3		
Media Conditions - Infiltration Practice			
Underlying Soil Type	Sand (HSG A)	Low	This risk factor is identified based on the infiltration rate of the underlying soil. Low infiltration rates of the underlying soil will lead to a lack of system drawdown and if a media layer is used poses a risk to clogging at the interface of the media layer and underlying soil.
Underlying Soil Infiltration Rate (in/hr)	4.49		
Pretreatment			
Type of Pretreatment	Sediment Forebay Only	Moderate	This risk factor is identified based on the removal efficiency of pretreatment. Providing additional pretreatment will reduce the BMP sediment load and reduce clogging risk.
Pretreatment Removal Efficiency (%)	25		
Vegetation and Location			
Is the practice installed at the surface or below grade?	Surface	Low	Below grade BMPs are increasingly susceptible to clogging due to confined area of infiltration and restricted maintenance access. Added caution with regards to clogging is recommended when implementing a below grade BMP.
Is the practice vegetated?	Vegetated		The presence of vegetation can reduce clogging risk due to the formation of macropores and bioturbation. When feasible surface vegetated BMPs are recommended.

Figure 10. Results Summary Report – Risk factor Assessment

Table 2. Risk Factor Range Table

Parameter	Risk Range		
	Low	Moderate	High
Drawdown Time at Initial Infiltration Rate (hr)	< 12	12 to 24	> 24
Drawdown Time at Minimum Allowable Infiltration Rate (hr)	< 24	24 to 72	> 72
Off-Site Sediment Contribution (% of Total Load)	< 5%	5 to 25%	> 25%
Infiltration Practice, Underlying Soil Infiltration Rate (in/hr)	> 2	0.75 to 2.0	< 0.75
Pretreatment Removal Efficiency (%)	> 50	20 to 50	< 20
Vegetation and Location	Surface Vegetated	Surface Unvegetated	Below Grade Unvegetated

6.1 Practical Interpretation of Lifespan Estimates

The tool is designed to compute one primary metric – length of time to time to rehabilitative maintenance. Due to limitations of available data, the tool is not able to explicitly account for processes that could allow for stabilization of infiltration rate decline. Processes such vegetation root growth, soil shrink/swell, assimilation of sediment into the soil structure, and other processes can result in stabilization of infiltration rate decline. In some respects, the progressively declining slope of the infiltration decay curve results in more stability at lower infiltration rates. However, the tool still associates decline in infiltration rate with each unit of sediment added.

Dr. Bob Pitt typically applies the following rule of thumb, derived from extensive experience, in interpreting the results of similar algorithms: *If the critical load to clogging occurs over a time greater than about 10 years, and systems are vegetated, it is more likely that systems will reach a new pseudo-steady-state condition. For systems that are above ground and vegetated, a result above 10 years suggests that rehabilitative maintenance could potentially not be required for a longer time than estimated by the tool. Sediment removal and plant management would still be needed.*

For subsurface systems, not exposed to plant growth or atmospheric weathering, there are fewer processes that could result in stabilization of infiltration rate decline. For these systems, the estimated time to maintenance of greater than 10 years may be desirable to reduce lifecycle costs.

7. Technical Approach

The tool combines site-specific calculations of sediment loading with an analysis of infiltration rate reduction values from literature studies to determine an approximate time to rehabilitative maintenance (see diagram in Figure 1, above). The literature review conducted as part of this project (Appendix D to the Project Summary Report) identified the accumulation of sediment load, normalized to load per unit area of infiltrating surface, as the most consistent parameter affecting infiltration rate reduction. A review of relevant research studies was conducted to create a database of measured infiltration rates and the incremental change on these infiltration rates in response to increments of applied sediment loads. A load to clog relationship was developed based on study evidence and integrated with sediment load calculations to develop an interactive tool.

7.1 Infiltration Rate Reduction Data Analysis

An infiltration rate reduction data analysis was performed based on a review of published studies assessing the impact of sediment loading on the permeability of filter media (Table 3). In this section, the term “infiltration rate” refers to the rate at which ponded columns were able to transmit water vertically.

Data were extracted from the studies to create a database of the starting infiltration rate, applied sediment load, decline in infiltration rate in response to the applied load, and a description of study parameters. Each study used in this assessment monitored the change in infiltration rate over time within a column run, based on applied sediment load, often involving measurements at multiple intermediate points of time. Studies varied in terms of media type, media depth, presence of vegetation, influent concentration, and loading frequency (Table 3).

For each study, the initial, final, and reported mid-study infiltration rates were recorded and paired with the applied load to each of the mid-study points and the final point. The Kandra et al. (2014a/b) studies were removed from the dataset due to starting infiltration rates (3000 in/hr) that were not representative of typical field conditions. The applied loads for Clark & Pitt (1999) and Pitt & Clark (2010) were multiplied by 5 to account for the effect of small, unvegetated column diameter on clogging rates per recommendations by the study authors (Clark & Pitt, 2009) which would account for no lateral movement, less spatial heterogeneity, less surface roughness, and less weathering than full-scale systems.

The relationship between infiltration rate and loading was often non-linear, typically represented by a more rapid decline associated with higher initial infiltration rates. Additionally, studies differed in how low the infiltration rate was allowed to become before column runs were discontinued. Therefore, a start-to-end “load to clog” could not be consistently extracted from the studies and would have been biased by the difference in study methods. Instead, the analysis focused on extracting adjacent (sequential) points on each infiltration degradation curve. For each set of adjacent (sequential) data points collected from an individual column, the infiltration rate reduction per applied load was determined. The rate of change was determined as the difference between initial and final infiltration rates divided by the applied load. This method maintains the correlation between adjacent (sequential) observations measured for an individual column,

but divides each column run into different segments rather than simply evaluating the starting and ending point of each column run.

A binned analysis was conducted to account for unequal distribution of data points within the monitored range and non-normal distribution of residuals when conducting a regression analysis. The data were grouped into four bins based on the average infiltration rate of the adjacent point pairs (initial infiltration rate + final infiltration rate/2). For each bin, the average infiltration rate was plotted in comparison to the infiltration reduction per applied load (Figure 11), and summary statistics calculated (Table 4)

Table 3. Summary of column studies used in infiltration rate reduction analysis

Reference	Infiltration Rate Range (in/hr)	Media Type	Column Diameter (in)	Vegetated	Mean Influent TSS Conc. (mg/L)	Number of Columns	Cataloged Rate of Reduction Data Points (sequential pairs)
(Clark & Pitt, 1999)	4.2 to 650	(1) sand, (2) 50% sand, 50% peat moss (3) 50% GAC, 50% sand	2	No	80 to 400	3	9
(Pitt & Clark, 2010)	4.2 to 104	(1) granulated activated carbon (GAC), (2) rhyolite sand, (3) site sand, (4) site zeolite, (5) surface modified zeolite, (6) rhyolite sand and surface modified zeolite	4	No	125 to 225	6	12
(Kandra et al., 2014a/b)	2 to 3000	rhyolite	4	No	25 to 400	10	Removed
(Le Coustumer et al., 2012)	0.01 to 2.4	(1) sandy loam, (2) sandy loam, vermiculite, perlite, (3) sandy loam, wood chips, compost	15	(1) unvegetated, (2) Carex appressa, (3) Dianella revoluta, (4) Microleana stipoides, (5) Leucophyta brownii, (6) Melaleuca ericifolia	115 to 200	12	43
(Limouzin et al., 2011)	1.2 to 48	(1) sand filter mix, (2) biofiltration mix, (3) masonry sand	18	(1) unvegetated, (2) Buffalo Grass, (3) Big Muhly	127	7	21

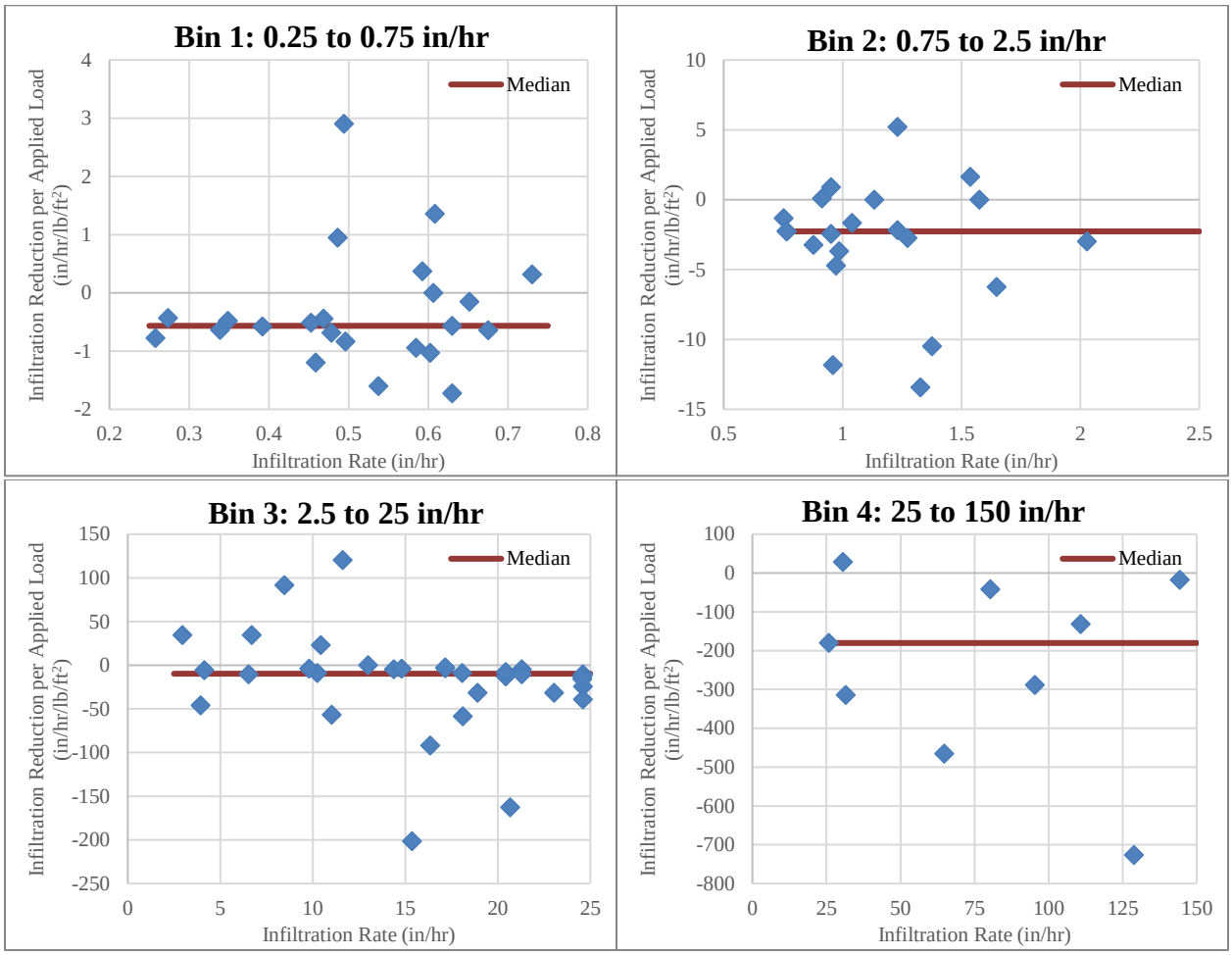


Figure 11. Infiltration rate of reduction binned analysis

Table 4. Infiltration rate of reduction binned analysis summary statistics

Bin	**1**	**2**	**3**	**4**
Infiltration Range (in/hr)	0.25 to 0.75	0.75 to 2.5	2.5 to 25	25 to 150
Count	23	17	32	9
	Rate of Reduction (in/hr/lb/ft^2)			
Mean	-0.32	-3.29	-17.74	-237.38
Median	-0.57	-2.27	-9.72	-180.27
25th Percentile	-0.80	-3.68	-10.13	-314.59
75th Percentile	-0.07	-1.31	-3.74	-41.48
St. Dev.	1.00	4.69	58.26	242.85

The median infiltration reduction per applied load for each bin was used to develop the relationship between infiltration rate and applied load (Table 5). The median was selected as it is resistant to outliers.

The rate of reduction is greatest for the highest infiltration rate bin and progressively diminishes for lower infiltration rate bins. This generally aligns with the shape of the infiltration degradation curve for most studies/columns evaluated. The applied load to rehabilitative maintenance is calculated based on an interpolation of Table 5 using the user provided initial and final infiltration rates. The infiltration rate per time graph presented in the Results Summary Report (Figure 9) is a translation of the median graph shown in Figure 12 with the y-intercept set to the initial infiltration rate and the x-axis multiplied by the annual unit area loading rate (lb/ft^2/yr) to convert from applied load to years.

Table 5. Median rate of reduction and applied load based on infiltration bins

Initial Infiltration Rate (in/hr)	Final Infiltration Rate (in/hr)	Count	Rate of Reduction (in/hr/lb/ft^2)	Applied Load (lb/ft^2)
150	25	9	-180.27	0.69
25	2.5	32	-9.72	2.32
2.5	0.75	17	-2.27	0.77
0.75	0.25	23	-0.57	0.88
Total		81		4.66

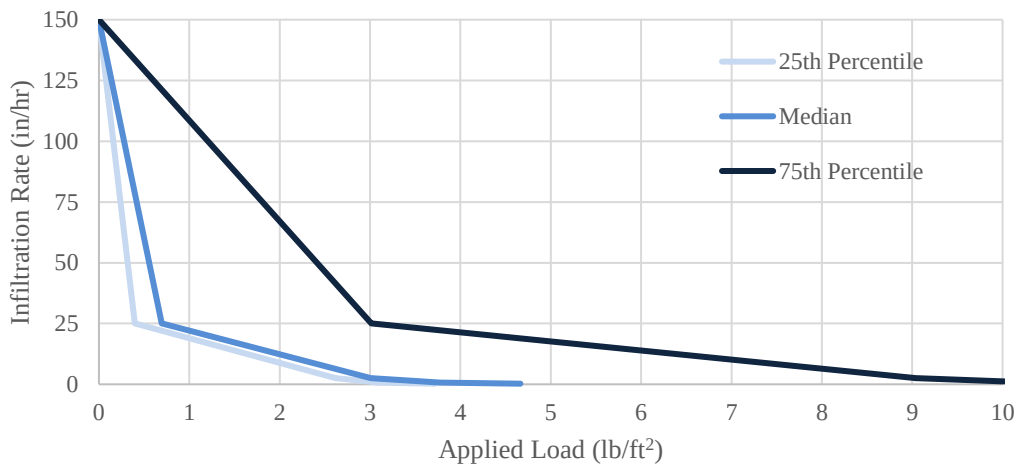


Figure 12. Infiltration rate per applied load

7.2 Tool Calculations

Refer to Figure 1 for a description of how the following calculations are linked in the tool.

1. Roadway Sediment Load

The annual roadway sediment load is calculated based on user inputs for precipitation, roadway tributary area and runoff concentration. Default average annual precipitation values are provided for 343 NOAA COOP stations, one present for each major ecoregion of the contiguous United States (Taylor et al., 2014).

Default roadway sediment concentrations are presented based on median values from the Highway Runoff Database (HRDB) for different average annual daily traffic volumes (AADT; Granato & Cazenas, 2009).

The average annual sediment load is calculated using the following steps:

1. **Determine runoff coefficient:** The runoff coefficient is determined based on the percent imperviousness using the two-line regression model developed by Granato (2010):

$R_v = 0.225\ x\ \%\ impervious + 0.05$ For % impervious $< 55\%$ (Equation 1)

$R_v = 1.14\ x\ \%\ impervious + 0.371$ For % impervious $> 55\%$

2. **Calculate average annual runoff volume:** The average annual runoff volume is calculated using Equation 2:

$R = P\ x\ A\ x\ R_v\ x\ C$ (Equation 1)

Where: R = Average annual runoff (inches)

P = Average annual rainfall (inches)

A = Roadway tributary area (ac)

R_v = Runoff coefficient

C = Unit conversion (3630 cf/acre-in)

3. **Determine average annual load:** The average roadway TSS concentration, either user input or calculated based on AADT and median HRDB values, is multiplied by the average annual runoff volume (Equation 2) to determine the average annual load.

2. Off-Site Sediment Load

Off-site sediment loading is calculated based on application of the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). This approach is used to account for sediment loading from pervious areas which is highly variable and dependent on land cover and geography parameters. User inputs are entered to calculate each of the RUSLE factors. Refer to Renard et al. (1997) for a description of the RUSLE equation and calculation methods.

3. Unit Area Loading Rate

The user entered TSS removal efficiency for pretreatment and the BMP sediment capture rate are used to determine the fraction of influent load that is retained by the BMP and contributes to clogging:

$L_c = L_i\ x\ (1 - RE_{Pre})\ x\ CR$ (Equation 3)

Where: L_c = Annual captured load (lb/yr)

L_i = Influent load, sum of roadway and off-site annual loads (lb/yr)

RE_{Pre} = Removal efficiency of pretreatment (%)

CR = BMP sediment capture rate (%)

The user entered BMP infiltrating surface area is used to determine the unit area loading rate (lb/ft^2/yr) by dividing the annual captured load (lb/yr; Equation 3) by the infiltrating surface area (ft^2). The storage volume input is used to determine the effective drawdown depth dividing the storage volume (ft^3) by the infiltrating surface area (ft^2). Using the entered initial and final infiltration rates, the drawdown time is calculated by dividing the effective drawdown depth (in) by the infiltration rate (in/hr). This value is used to alert the user of designs with prolonged drawdown times which may be infeasible. The drawdown time calculation does not impact the load to clog calculation.

4. Load to Rehabilitative Maintenance

The initial infiltration rate is defined by the user based on the filter media used or in situ soil. The final infiltration rate is set by the user to represent the minimum allowable before the practice is considered clogged and rehabilitative maintenance is needed. Based on the specified initial and final infiltration rates, the load to clog is calculated using the median values of the binned infiltration rate reduction analysis (Table 5). The rate of infiltration reduction defined for each infiltration bin (Table 5) is used to determine the load applied to reduce the infiltration rate from the initial to final value. Linear interpolation is used to determine the applied load for bins in which the initial or final infiltration rate is within the bin range.

5. Time to Rehabilitative Maintenance

The time to rehabilitative maintenance (yr) is estimated d by dividing the load to clog (lb/ft2) by the unit area loading rate (lb/ft2/yr). Due to data limitations in defining the load to clog, the time to rehabilitative maintenance should be interpreted as an estimate used to gauge the risk of clogging and not a precise estimate of time to clog. Times to rehabilitative maintenance below 10 years are flagged by the tool as having high potential clogging risk. Note that in some cases, one may decide to proceed with a project with a lower time to clogging, recognizing that more frequent rehabilitative maintenance might be required. Particularly for media filters this may be acceptable give other site and receiving water conditions/constraints.

7.3 Known Limitations/Potential Future Improvements

This tool is believed to be the first of its kind to attempt to provide a semi-quantitative estimate of clogging risk that accounts for the range of factors discussed above. However, available data remain relatively limited to support the primary computation metric (length to time to rehabilitative maintenance) while considering the range of factors that may influence clogging. Note that future field and laboratory studies that target the question of clogging could be used to help update or revise this tool.

Several known limitations include:

- Estimates are mostly based on column studies which do not represent the scale, heterogeneity, or weathering processes of full-scale facilities. While estimates should ideally be derived from field studies, there is a lack of studies that have characterized the total mass load to a BMP and measured progressive clogging in response to this loading.
- As evidenced in Figure 11, there is a large amount of variability in the rate of permeability decline in response to sediment loading. This suggests that there are other factors, besides simply

sediment loading, that influence clogging. Different system responded to sediment loading quite differently, and it was not possible to identify the factors that explained these differences.

- There were inadequate data to assess the effects of vegetation on decline in permeability. However, qualitatively, both Le Coustumer et al. (2012) and Limouzin et al. (2011) found that some types of vegetation could be effective in halting declines in infiltration rate and in some cases were associated with a rebound in infiltration rate. This magnitude of this effect could not be quantified for incorporation into the tool. Note that root improvement in media filter beds could result in short-circuiting of the media if the filter bed is not outlet controlled.
- The RUSLE calculation for adjacent pervious area is highly uncertain. It can be improved with careful local parameterization and comparison to local monitoring data but should still be regarded as a rough estimate. However, sediment loading from these areas can be a major factor in clogging, therefore accounting for this load is important to support design decisions. When there is doubt about the erodibility of this area, the best practice is to fully isolate it from infiltration or filtration BMPs. Alternative methods (e.g., RUSLE2, local monitoring) can be used to improve estimates.
- The tool does not directly account for the degree of "site stabilization" associated with establishment of vegetation after construction, but could be used to assess that via a scenario with changed RUSLE parameters to account for vegetation coverage initially, etc. If the run shows early clogging, additional erosion control measures might be warranted or perhaps some temporary bypass of the infiltration bed until the site is stable.
- The tool does not account for the effects of deicing salts on soil characteristics. Ions associated with salts have the potential to change the overall properties of soil, including destabilizing clay particles. This consideration is handled narratively in infiltration suitability guidelines in the Guidance Manual.
- The tool does not directly account for loading from wind-borne particles (dust) or from traction sand. The effect of these processes on TSS-size particles should be accounted for by adjusting the roadway TSS concentrations. Data may be inadequate to quantify these effects; therefore, this may increase the uncertainty in clogging estimates.
- This tool is based only on TSS load from roadways and may not account for coarser sediment than typical TSS. The literature review conducted to develop this tool identified greater importance of finer sediment in clogging, therefore neglecting particles coarser than TSS was not considered to be a significant limitation. Also, the tool allows override of TSS defaults, and the user could use a higher influent concentration to account for sediment not accounted for in TSS concentrations.

Despite these limitations, the tool is considered to provide a more robust estimate than a simple "load to clog" calculation approach, which has been the standard approach recommended in literature studies thus far. Future field and laboratory studies could be conducted to reduce the impact of the limitations above.

8. References

Clark, S. E., & Pitt, R. (1999). *Stormwater treatment at critical areas: Evaluation of filtration media.* National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency. EPA/600/R-00/010. Washington, D.C.

Clark, S. E., & Pitt, R. (2009). Solids removal in storm-water filters modeled using a power equation. *Journal of Environmental Engineering*, *135*(9), 896-899.

Granato, G, and Cazenas, P. (2009). Highway-Runoff Database (HRDB Version 1.0)--A data warehouse and preprocessor for the stochastic empirical loading and dilution model: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration. FHWA-HEP-09-004. https://webdmamrl.er.usgs.gov/g1/fhwa/seldm.html/

Granato, G. E., (2010). *Methods for development of planning-level estimates of stormflow at unmonitored sites in the conterminous United States*. Washington, D.C.: U.S. Department of Transportation, Federal Highway Administration, FHWA-HEP-09-005, 90 pp.

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2008). Hydraulic and pollutant removal performance of fine media stormwater filtration systems. *Environmental Science & Technology*, *42*(7), 2535-2541.

Kandra, H. S., McCarthy, D., Fletcher, T. D., & Deletic, A. (2014a). Assessment of clogging phenomena in granular filter media used for stormwater treatment. *Journal of Hydrology*, *512*, 518-527.

Kandra, H. S., Deletic, A., & McCarthy, D. (2014b). Assessment of impact of filter design variables on clogging in stormwater filters. *Water Resources Management*, *28*(7), 1873-1885.

Le Coustumer, S., Fletcher, T. D., Deletic, A., Barraud, S., & Poelsma, P. (2012). The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. *Water Research*, *46*(20), 6743-6752.

Limouzin, M., Lawler, D. F., & Barrett, M. E. (2011). *Performance comparison of stormwater biofiltration designs*. Center for Research in Water Resources, Online Report 10-05. University of Texas at Austin.

Pitt, R., & Clark, S. E. (2010). *Evaluation of biofiltration media for engineered natural treatment systems.* Submitted to Geosyntec Consultants. Santa Barbara, CA.

National Resources Conservation Service (NRCS) Soil Survey Staff. (2017). Web Soil Survey. United States Department of Agriculture. Internet Site. Available at http://websoilsurvey.nrcs.usda.gov/

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1997). *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. Agricultural Handbook No. 703. https://naldc.nal.usda.gov/download/11126/PDF

Strecker, E., Poresky, A., Roseen, R., Johnson, R., Soule, J., Gummadi, V., Dwivedi, R., Questad, A., Weinstein, N., Ayers, E., Venner, M., 2015. Volume Reduction of Highway Runoff in Urban Areas: Guidance Manual (No. 802). National Cooperative Highway Research Program, Washington, D.C.

Taylor, S., Barrett, M., Leisenring, M., Sahu, S., Pankani, D., Poresky, A., ... & Venner, M. (2014). Long-Term Performance and Life-Cycle Costs of Stormwater Best Management BMPs. NCHRP Report 792. Retrieved from http://www.trb.org/Publications/Blurbs/171471.aspx

Washington State Department of Ecology (WSDOE). (2017). Stormwater Treatment Technologies Approved through TAPE and CTAPE. Internet Site. Available at http://www.ecy.wa.gov/programs/wq/stormwater/newtech/technologies.html

Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses.* Agriculture Handbook No. 537, (537), 285–291. https://data.globalchange.gov/report/usda-aghandbook-537