CHAPTER 4

Hydrologic Analysis

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4-1 Introduction

This chapter presents and defines the minimum computational standards for the types of hydrologic analyses required to design the various stormwater best management practices (BMPs) described in detail in Chapter 5 and the *Temporary Erosion and Sediment Control Manual* (TESCM). It also provides an explanation of the methods to be used for the modeling of stormwater facilities and the supporting data and assumptions that will be needed to complete the design. The computational standards, methods of analysis, and necessary supporting data and assumptions for designs in western Washington are different than those in eastern Washington. As a result, Section 4-3 includes design criteria and guidelines for western Washington, and Section 4-4 includes design criteria and guidelines for eastern Washington. The hydrologic analysis tools and methodologies presented in this chapter support the following tasks:

- Designing stormwater runoff treatment and flow control facilities
- Designing infiltration facilities
- Closed Depression Analyses
- Analyzing wetland hydroperiod effects

This manual makes numerous references to the *Hydraulics Manual*, where additional design guidelines can be found, including the minimum computational standards, methods of analysis, and necessary supporting data and assumptions for analysis and design of the following:

- General hydrology
- Culverts and other fish passage structures
- Open channel flow
- Storm sewer design
- Drainage from highway pavement (inlet spacing and curb and gutter)
- Hydraulics issues associated with bridge structure design
- Downstream analysis
- Pipe classification and materials

4-2 Project Considerations

Prior to conducting any detailed stormwater runoff calculations, consider the overall relationship between the proposed project site and the runoff it will create. This section provides guidelines regarding what parameters the PEO should review to adequately evaluate the project.

The general hydrologic characteristics of the project site dictate the amount of runoff that will occur and where stormwater facilities can be placed. Several sources of information will be useful in determining the information necessary for preliminary and final runoff analyses. Determine drainage patterns and contributing areas by consulting topographic contour maps generated from surveys of the area for the proposed project or by using contour maps from a previous project in the same area.

4-2.1 Estimating Preliminary Stormwater BMP Areas

Develop preliminary estimates of the area that will be required for stormwater BMPs when the project layout is first being determined. These estimates of stormwater BMP sizes and areas may dictate changes to the roadway or other infrastructure design and support decisions to purchase additional right of way for the project. Make assumptions for any information that is not available and document them in the analysis. The following information is required to successfully estimate the approximate area required for preliminary stormwater treatment and flow control facilities:

- The footprint of the proposed roadway or other new infrastructure or improvements on the project
- The general hydrologic characteristics of the project site
- The amount of area flowing to each BMP location to make sure HRM Minimum Requirements for runoff treatment and/or flow control are satisfied
- Account for project-triggered retrofits (see Section 3-4)

4-2.2 Local and State Requirements

In most cases, the minimum requirements for stormwater facilities described in the *Highway Runoff Manual* (HRM) will be adequate to meet other state agency and local jurisdiction requirements. Section 1-2.1 explains to what extent a local jurisdiction’s stormwater requirements apply to Washington State Department of Transportation (WSDOT) projects. The first part of any hydrologic analysis involves research to determine whether the project is located in an area where additional requirements prevail. The PEO can typically accomplish this by consulting with Region Hydraulics Engineer. When stricter standards do apply, they are usually related to unique runoff treatment concerns, a need for flow control under more extreme storm conditions than is required by the HRM, or a need for lower site discharge rates than are required by this manual. Either case is easily applied to the methods of analysis outlined in this chapter.

4-2.3 Soils

Quite often, additional sources of information are needed to adequately characterize on-site soils, particularly within existing highway rights of way and in other urban areas. The WSDOT Materials Lab can provide detailed information on soils and shallow groundwater characteristics in conjunction with geotechnical field data collection efforts. Typically, the PEO must inform the

Materials Lab of the need for gathering additional data for drainage analysis purposes early in the project design phase. This is very important for determining infiltration rates.

4-2.4 Determining Existing Conditions

Access information on existing drainage facilities and conveyance system locations in Hydraulic Reports from previous projects in the same vicinity, the Highway Activities Tracking Database (HATS), the Stormwater BMP Specifications (SWABS) web application, or in as-built plans for the existing roadway. The local jurisdiction may have mapping and/or as-built information for storm drainage facilities near the WSDOT right of way and may know of other projects in the vicinity that documented drainage conditions.

A site visit will help the PEO determine the basic hydrological characteristics of the proposed project site. Observations the PEO makes during a field visit will serve to verify the information the PEO obtains through research and will show where that information may have been deficient. In nearly every instance, the information the PEO gains by visiting the site prior to designing the stormwater facilities will benefit the ensuing design effort.

4-2.5 Mapping Drainage Basins and Threshold Discharge Areas

The final part of determining the site's hydrologic characteristics is mapping draining basins to the hydraulic features being designed. Hydraulic features include inlets, pipes, culverts, storm sewer, and ditches. How to determine the drainage basins to these hydraulic features is discussed in Section 2-3 of the Hydraulics Manual. Drainage basins for stormwater BMPs are generally determined by the hydraulic features discussed above since stormwater is usually routed to BMPs by sheet flow or through a conveyance system. Knowing how many threshold discharge areas (TDAs) are within the project is also an important piece of information that is needed understand the hydraulic characteristics of the project. TDAs will help define the HRM Minimum Requirements and determine how much area needs to be captured by each stormwater BMP.

A TDA is defined as an on-site area draining to a single natural or constructed discharge location or multiple natural or constructed discharge locations that combine within ¼ mile downstream—as determined by the shortest flowpath. A TDA delineation begins at the first discharge location that exits WSDOT right of way and is based on preproject conditions. To map a TDA, the PEO must have an understanding of drainage basin delineation per Section 2-3 of the Hydraulics Manual. A TDA is very different from a drainage basin in that a hydraulic feature would never be designed based on the actual area of the TDA. The limits of a TDA are generally right of way line to right of way line and begin project milepost to end project milepost (see Glossary for "project limits"). The limits of a TDA should be large enough to catalog all of the development by the project. If the project were acquiring right of way, the TDA limits would extend to the proposed right of way limits. In certain situations (for example a divided highway with a grassy median), the TDA limits should also be scaled back to only the area undergoing development. For example, if only the northbound lanes (one side of the highway) were undergoing development while the southbound lanes (other side of the highway) and median were not, only the northbound lanes would be shown as a part of TDA delineation (see Glossary for "project site"). The discharge location of stormwater from the right of way is where a TDA delineation begins. Figures 4-1 to 4-4 give examples of how to delineate TDAs. ***Note:*** The PEO must field verify all TDAs.

In Figure 4-1, each drainage area (A1 – A4) is delineated by the crown of the roadway to the top of the ditch back slope (right of way limit) and between each vertical curve crest. Figure 4-3 shows the roadway profile and cross section. In drainage area A1, roadway runoff sheet flows off of the pavement into the ditch that eventually flows into the culvert. Flows from drainage area A1 combine with flows from drainage area A2 and leave WDSOT right of way using flow path A2. The same conditions occur with drainage areas A3 and A4, which leave the right of way using flow path A4. If flow paths A2 and A4 join within ¼ mile downstream from the right of way, all four drainage areas would combine to make one TDA (as indicated in Figure 4-1). If the discharges remain separate for at least ¼ mile downstream of the project site right of way, drainage areas A1 and A2 combine to make one TDA and drainage areas A3 and A4 combine to make a second TDA.

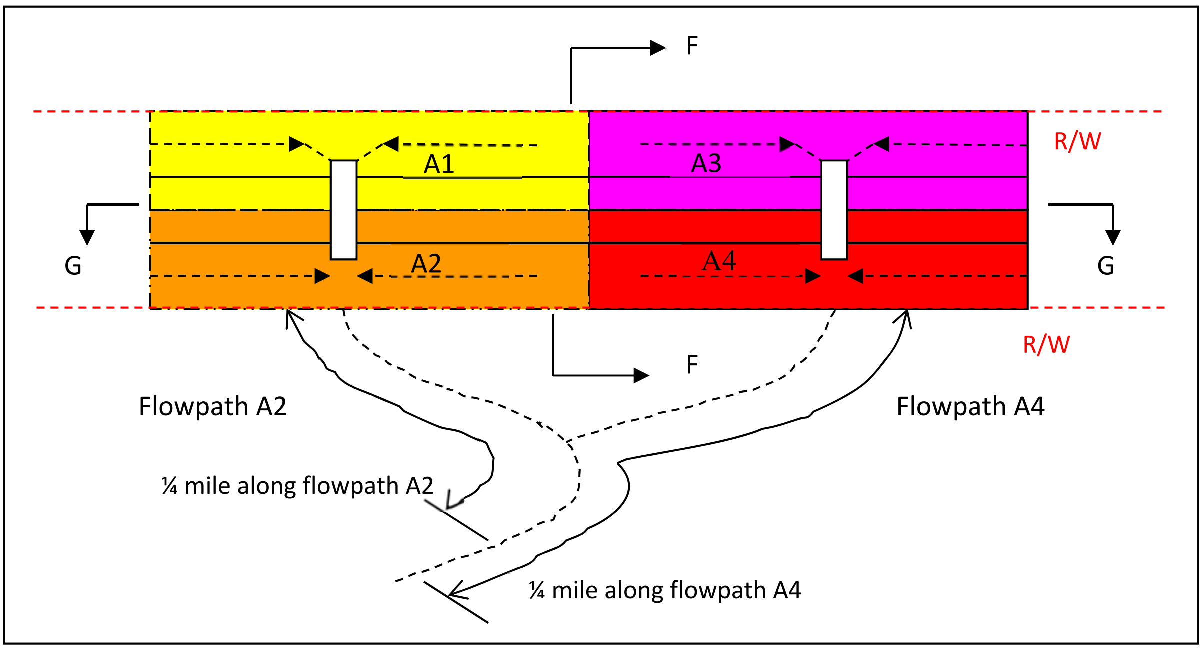


Figure 4-1 Threshold discharge areas (plan view)

Figure 4-2 illustrates the situation where the flow paths do not combine within ¼ mile and result in two separate TDAs (assuming drainage areas A1, A2, A3, and A4 are within one TDA and are represented by Flowpath A2). Measure ¼ mile along Flowpath A6. If Flowpath A2 (the most upstream flow path) and Flowpath A6 join within the shortest measured ¼-mile flow path, all areas are considered one TDA. Figure 4-2 shows Flowpath A2 and Flowpath A6 do not combine within the ¼ mile, measured along the shortest flow path, so areas A1, A2, A3, and A4 combine to form one TDA, while areas A5 and A6 combine to form a separate TDA. Flow path A6 would be used to measure against any other additional flowpaths for combining areas to form the next TDA.

The above TDA delineation guidance is not all-inclusive. Direct project-specific questions regarding TDA delineations to the Region Hydraulics Engineer or the HQ Hydraulics staff. For eastern Washington regions, with the approval of the Region Hydraulics Engineer, the project may be considered as one TDA in certain instances, based on site conditions. Once the PEO completes TDA delineations, tally the quantities of new, replaced, and existing impervious areas (and PGIS) for each TDA. Apply minimum requirement thresholds to each TDA based on tallied quantities. (See Chapter 3 for minimum requirement applicability.)

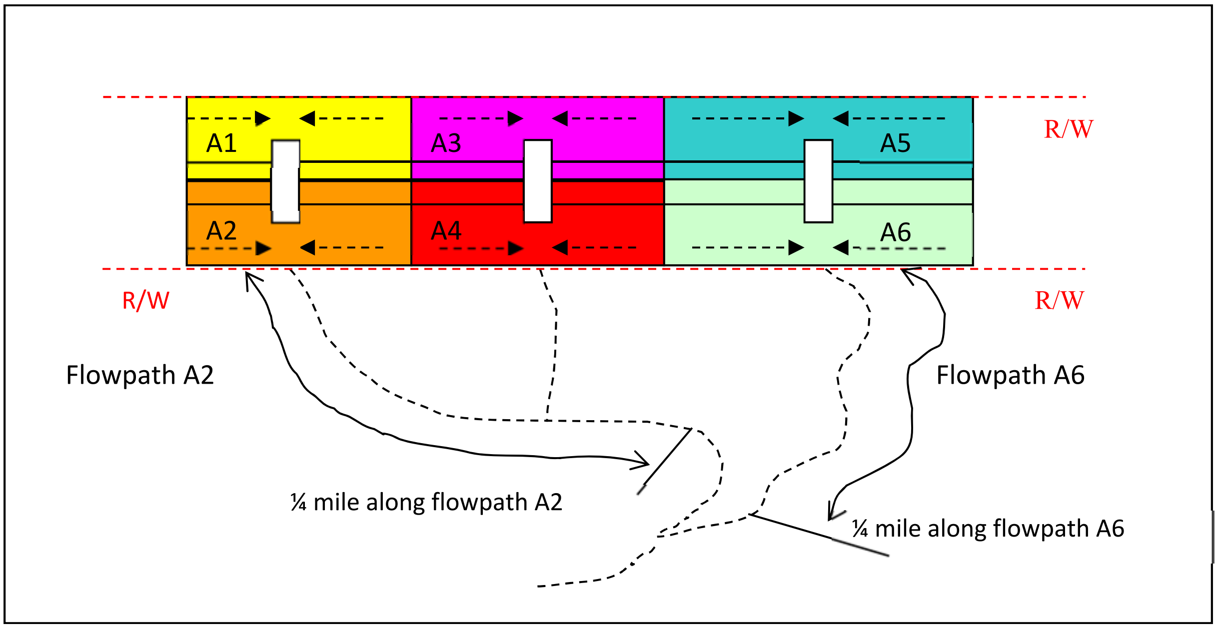
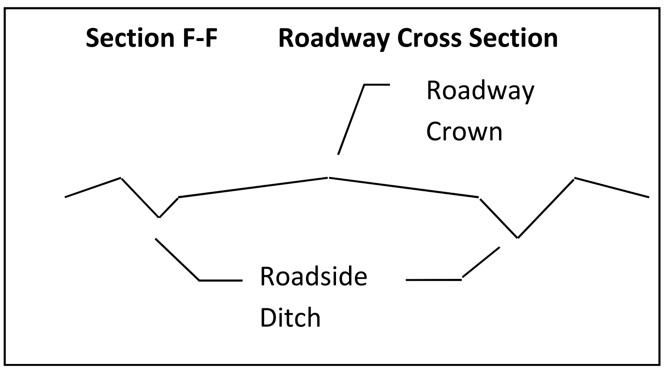


Figure 4-2 Threshold discharge areas (plan view)



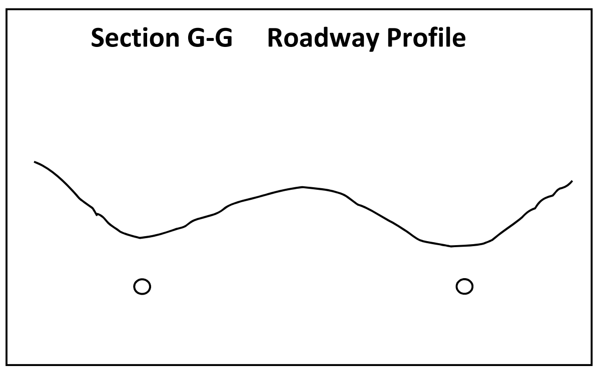


Figure 4-3 Threshold discharge areas (section and profile).

4-2.6 Calculating Final Stormwater BMP Areas

Once the PEO understands the Minimum Requirements for each TDA and is familiar with the general hydrologic characteristics of the site, the PEO can calculate the size of stormwater BMPs by examining the proposed project layout and determining the most suitable locations for BMPs. The PEO must ensure enough area is being captured and treated by stormwater BMPs to satisfy Minimum Requirements. The PEO should also account for any Puget Sound Basin Retrofit requirements (see Section 3-4). Flow charts are presented in Figures 4-4 and 4-5 to help the PEO navigate through the requirements of Chapter 4 and hydrologic analyses for typical projects.

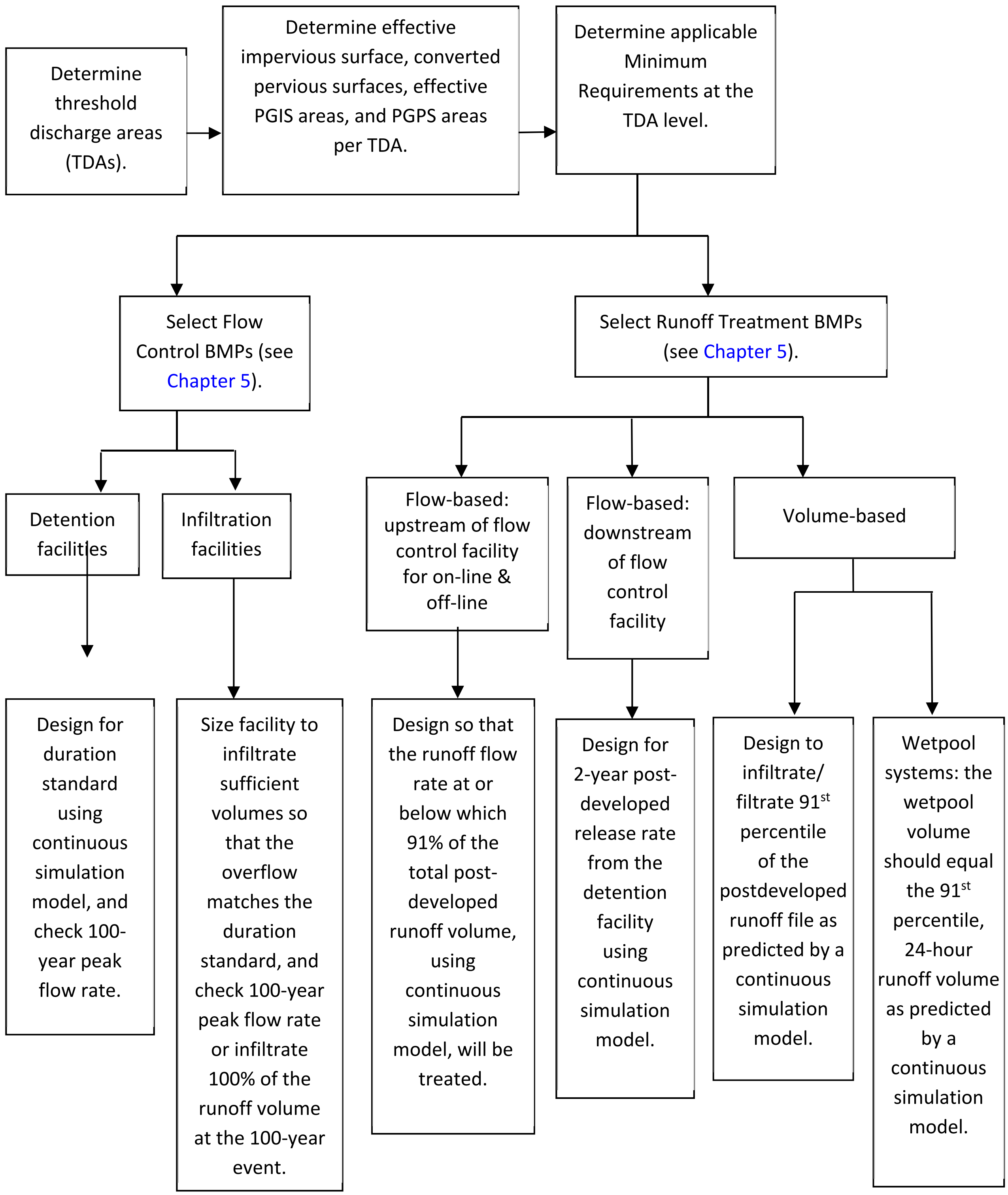


Figure 4-4 **Hydrologic analysis flowchart for western Washington.**

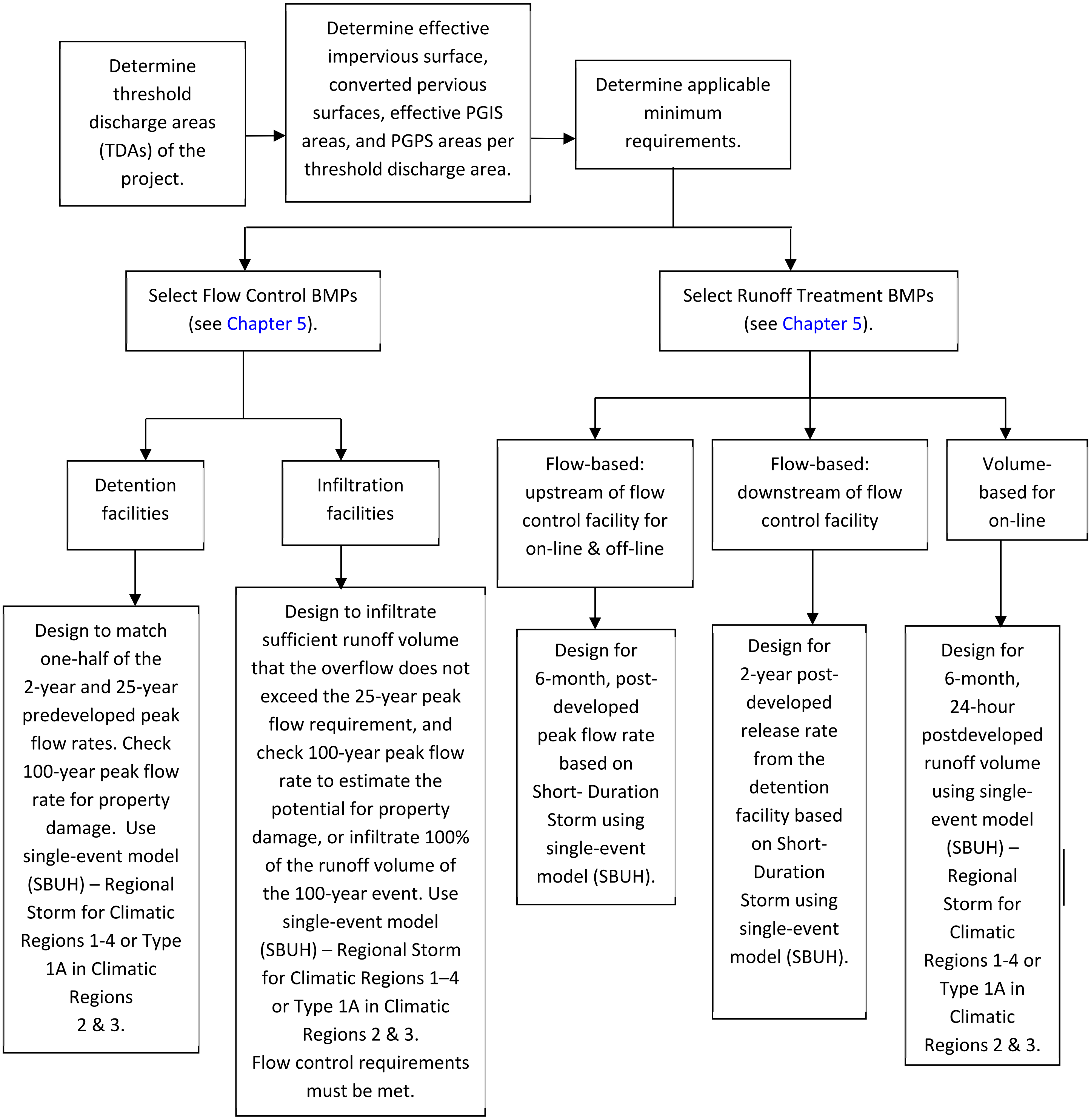


Figure 4-5 Hydrologic analysis flowchart for eastern Washington.

4-3 Western Washington Design Criteria

4-3.1 Runoff Treatment Flow-Based and Volume-Based BMPs

4-3.1.1 Flow-Based Runoff Treatment

Use an approved continuous simulation hydrologic model based on the U.S. Environmental Protection Agency's (U.S. EPA's) Hydrologic Simulation Program – Fortran (HSPF) when designing runoff treatment BMPs based on flow rate, in accordance with WSDOT Minimum Requirement 5 in Section 3-3.5. Use **MGSFlood** for designing flow-based runoff treatment BMPs in WSDOT right of way unless prior approval to use an alternate (equivalent Ecology approved) program is given by the Region or HQ Hydraulics Engineer. The design flow rate for these types of facilities is dependent upon whether the treatment facility is located upstream or downstream of a flow control facility and whether it is an *on-line* or *off-line* facility (see Figure 4-6).

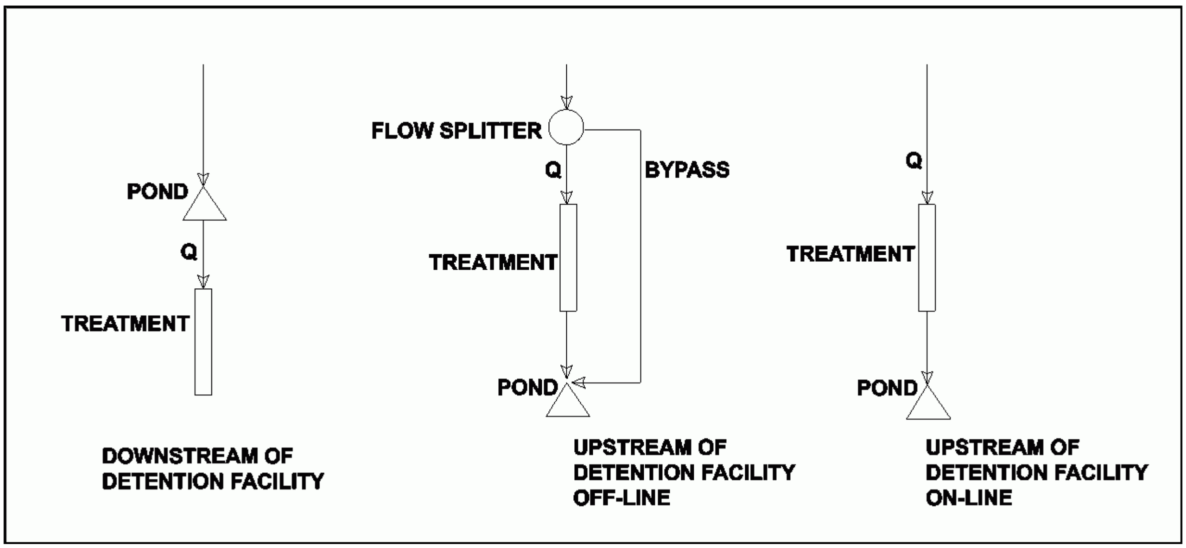


Figure 4-6 Typical on-line and off-line facility configurations.

Downstream of Flow Control Facilities

If the runoff treatment facility is located downstream of a stormwater flow control facility, use the full 2-year recurrence interval release rate from the flow control facility, as estimated by an approved continuous simulation model, to design the treatment facility. For biofiltration swale design, the 2-year recurrence interval release rate from detention pond is Q_{wq} and is "online".

Upstream of Flow Control Facilities: Off-Line

The design flow rate for an off-line treatment facility located upstream of a flow control facility is the flow rate where 91% of the runoff volume for the developed TDA will be treated, based on a 15-minute time step, as estimated by an approved continuous simulation model. The bold horizontal line in Figure 4-7 is an example that shows the 91% runoff volume flow rate. All flows below that line will be treated, and the incremental portion of flow above that line will bypass the runoff treatment facility.

Use a high-flow bypass (flow splitter) to route the incremental flow in excess of the treatment design flow rate around the treatment facility. (See Section 5-4.3 for more details on flow splitters.) It is assumed that flows from the bypass enter the conveyance system downstream of the treatment facility but upstream of the flow control facility.

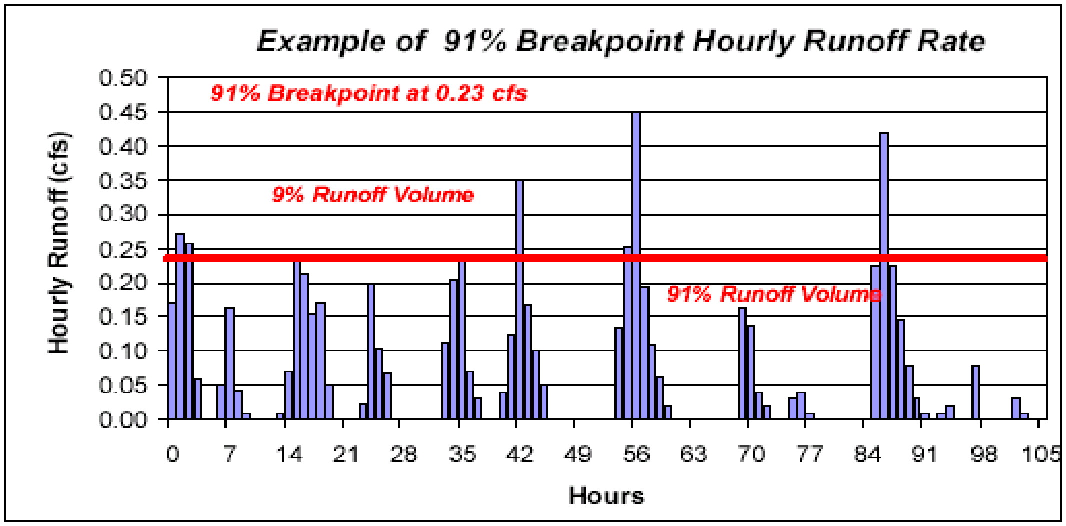


Figure 4-7 **Example showing calculation of runoff treatment discharge for off-line treatment facilities—computed as 0.23cfs.**

Upstream of Flow Control Facilities: On-Line

On-line runoff treatment facilities do not include a high-flow bypass for flows in excess of the runoff treatment design flow rate, and all runoff is routed through the facility. The design flow rate for these types of on-line treatment facilities is the flow rate at which 91% of the runoff volume occurs, based on a 15-minute time step, as estimated by an approved continuous simulation model, to be in compliance with Minimum Requirement 5 (see Section 3-3.5). MGSFlood will determine the hourly runoff treatment design flow rate as the rate corresponding to the runoff volume that is greater than or equal to 91% of the hourly runoff volume entering the treatment facility. The simulation model automatically generates 15-minute time step flows based on hourly flows. Because on-line treatment facilities receive greater volumes of inflow than off-line facilities, the design flow rate corresponding to the 91% breakpoint is higher than for off-line facilities. The higher design flow rate will result in a slightly larger treatment facility. Figure 4-8 shows that the facility will receive all the flow, but will be sized for only 91% runoff volume flow rates, minus the red bars in its calculations for the developed TDA.

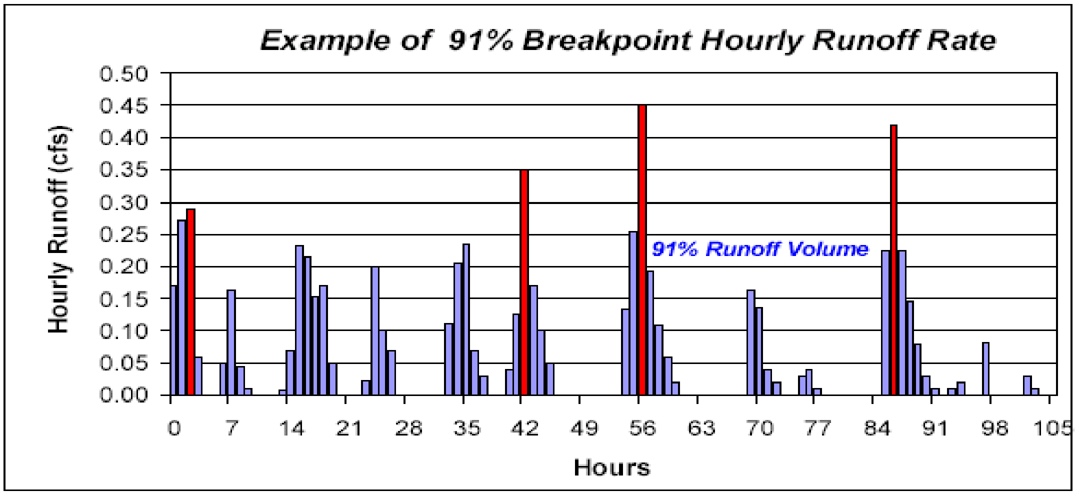


Figure 4-8 **Example showing calculation of runoff treatment discharge for on-line treatment facilities—computed as 0.28cfs.**

4-3.1.2 Volume-Based Runoff Treatment

Design volume-based runoff treatment BMPs as on-line facilities. In accordance with Minimum Requirement 5 (see Section 3-3.5), the PEO can use the following methods to derive the minimum required storage volume:

- Wetpool: An approved continuous simulation hydrologic model based on the U.S. EPA's HSPF can be used. MGSFlood must be used on WSDOT projects unless approved to use an equivalent (Ecology approved) program by the Region or HQ Hydraulics Engineer. For wetpools, the required total wetpool volume is the 91st percentile, 24-hour runoff volume (no credit is given for infiltration losses) based on the long-term runoff record generated in the TDA of concern—as predicted based on a 15-minute time step.
- For other volume-based systems such as infiltration and filtration BMPs, the minimum treatment needed is the storage volume that is necessary to achieve treatment of 91% of the influent runoff file as predicted using a continuous runoff model and a design infiltration/filtration rate.

If runoff from the new impervious surfaces and converted pervious surfaces is not separated from runoff from other surfaces on the project site and/or is combined with run-on from areas outside of the right of way, the PEO must size volume-based runoff treatment facilities based on runoff from the entire drainage area. This is because runoff treatment effectiveness can be greatly reduced if inflows to the facility are greater than the design flows that the facility was designed to handle. For infiltration facilities, the PEO must infiltrate the 91st percentile, 24-hour runoff volume within 48 hours.

For a summary of the flow rates and volumes needed for sizing runoff treatment facilities for various situations, see Table 3-3.

4-3.2 Flow Control Volume and Flow Duration-Based BMPs

Use an approved continuous simulation hydrologic model, based on HSPF, for designing flow control BMPs in accordance with Minimum Requirement 6 (see Section 3-3.6). The PEO must use MGSFlood for designing flow control BMPs in WSDOT right of way unless prior approval to use an alternate (equivalent Ecology approved) program is given by the Region or HQ Hydraulics Engineer. Ensure stormwater discharges match the developed discharge durations to the predeveloped durations for the range of predeveloped discharge rates from 50% of the 2-year peak flow up to the full 50-year peak flow. Check the 100-year peak flow for flood control and prevention of property damage using the continuous simulation model.

Infiltration facilities for flow control must either infiltrate the entire runoff file, or provide sufficient infiltration so that the predicted overflows match the predeveloped durations for the range of predeveloped discharge rates from 50% of the 2-year peak flow up to the full 50-year peak. Table 3-6 summarizes the volumes needed for sizing flow control facilities for various situations.

Refer to the TESCM for additional TESC BMP design criteria.

4-3.3 Exemptions for Flow Control

WSDOT has developed a standardized process to help the designer produce an acceptable hydraulic analysis for determining flow control exemptions. The process helps the PEO determine how extensive an analysis needs to be for a particular project. (See Chapter 3 for a process that has been established for lakes and some river systems.) For further details on exemptions, flow dispersion, and flow control thresholds, see Minimum Requirement 6 in Section 3-3.6.

4-3.4 Hydrologic Analysis Methods for Designing BMPs in Western Washington: HSPF versus SBUH

Refer to the *Hydraulics Manual* for a detailed discussion.

4-3.5 Hydrologic Analysis Methods and Details for Flow Control and Runoff Treatment Facility Design

This section presents a detailed discussion for some of the parameters necessary to design a stormwater flow control facility using an approved continuous simulation model. A basic overview of the continuous simulation method can be found in Chapter 2 of the WSDOT *Hydraulics Manual*.

4-3.5.1 Continuous Simulation Method

WSDOT's continuous simulation hydrologic model MGSFlood uses the HSPF routines for computing runoff from rainfall on pervious and impervious land areas. Specifically, the program is intended to size stormwater detention and infiltration ponds, as well as calculate runoff treatment flow rates and volumes, to meet the requirements of Ecology's *Stormwater Management Manual for Western Washington* (SWMMWW). Do not use it for conveyance design unless the conveyance system is downstream of a stormwater pond. (See Appendix 4A for a link to a detailed example of this modeling approach and for information on how to obtain a copy of the public domain program.)

MGSFlood does not include routines for simulating the accumulation and melt of snow, and its use should be limited to lowland areas where snowmelt is typically not a major contributor to floods or to the annual runoff volume. In general, these conditions correspond to an elevation below approximately 1,500 feet. Other notable limitations are included in Section 2 of the MGSFlood User's Manual. If a drainage basin falls outside the modeling guidelines above, contact Region or HQ hydraulics staff for assistance.

Several factors must be considered in the design of a stormwater flow control facility. Based on the proposed project improvements, the PEO can determine watershed and drainage basins and apply precipitation and runoff parameters to them. The continuous simulation model uses this information to simulate the hydrologic conditions at the site and estimate runoff. The PEO can then size the flow control facility to detain the runoff in a way that closely mimics the runoff from the predeveloped site conditions. The PEO must verify that the flow control performance is in accordance with Minimum Requirement 6 in Section 3-3.6. Key elements of continuous simulation modeling are presented below.

4-3.5.2 Predevelopment Land Cover

The first consideration when modeling project site runoff for flow control BMP sizing is the amount of pervious cover versus impervious surface in the overall basin. The hydrologic analysis for flow control to protect a receiving water body is based on mitigating floods and erosion. The predeveloped land cover assumptions for modeling effective impervious surfaces for both eastern and western Washington can be found in Chapter 3, Minimum Requirement 6. (See the Glossary for the definitions of "historic land cover" and "existing land cover.") For information on the predeveloped condition for stormwater retrofits, see Figure 3-4 and Section 3-4.

4-3.5.3 Reversion of Existing Impervious Surface Areas

Opportunities may emerge to remove an existing impervious surface due to roadway realignment, roadway abandonment, or other project condition rendering the existing impervious surface obsolete. Under these circumstances, reverting an existing impervious surface to a pervious surface may improve the hydrological functions of an area, thereby providing a proportional reduction in the amount of runoff generated.

Note: The concept of reversion of existing impervious surfaces only applies to flow control thresholds ("net-new impervious"; it does not apply to runoff treatment thresholds.

Follow the *two-step approach* (Full Reversion and Partial Reversion) below to analyze reversion of existing impervious surface areas for possible flow control benefits for the TDA. Reversion areas should be documented like Dispersion BMPs and listed in HATS and SWABS.

Step 1: Full Reversion (minimum requirement benefits and flow modeling benefits)

The first step involves evaluating the potential for stormwater impacts based on the concept and application of *net-new impervious surface*. Applying the net-new impervious surface concept requires removing existing impervious surface, incorporating soil amendments into the subsurface layers, and revegetating the area with evergreen trees—unless the predeveloped condition was prairie, which may be the case in some parts of eastern Washington. In this case, apply the net-new impervious surface concept at the threshold discharge area (TDA) level when determining if triggers for flow control (see Minimum Requirement 6) have been exceeded, as specified in Section 3-3.6, and then only if the following criteria can be met:

- Existing impervious areas removed must be replaced with soils meeting the soil quality and depth requirements of the soil amendment criteria in Chapter 5.
- The new pervious area must be planted with native vegetation, including evergreen trees. For further guidelines, see the *Roadside Policy Manual* and the *Roadside Manual*.
- The new pervious area must be designated as a stormwater management area on the project's right of way plans or on the drainage plans.
- The new pervious area must be permanently protected from development. If the area is sited off WSDOT's right of way, it must be protected with a conservation easement or some other legal covenant that allows it to remain in native vegetation.

  Full reversion can also use the below guidance for flow modeling benefits.

Step 2: Partial Reversion (flow modeling benefits only)

If the PEO concludes that triggers for that particular TDA have been exceeded and any of the above criteria cannot be fully implemented (only low-lying native vegetation can be planted due to clear-zone restrictions), then using the net-new impervious surface concept is not applicable and the PEO must evaluate the reversion area strictly as a land use modification when modeling for flow control. In this case, if it is feasible and there is an opportunity within any TDA to rehabilitate an existing impervious area to a pervious area, the PEO should do it, and apply techniques for flow control modeling (as explained below in Section 4-3.5.5 Modeling Best Management Practices).

4-3.5.4 Flow Control Modeling Scenarios, Off-Site Flow, and Flow-Through Areas

The following guidelines primarily apply to meeting flow control requirements and do not generally apply to meeting runoff treatment requirements unless otherwise noted. These guidelines deal with how to generally set up a stormwater modeling scenario, what areas need to be shown in the model, and how to represent the land cover of those areas in the model. *On-site flow* generally refers to flows generated from areas within WSDOT right of way that are also in the project limits. *Off-site flow* generally refers to flows that are generated outside of and pass through WSDOT right of way. To minimize stormwater BMP sizes, WSDOT does not allow, or it significantly restricts, off-site flows from entering into stormwater BMPs.

For western Washington flow control designs, WSDOT has a spreadsheet that **the PEO is required to complete** to track all areas in the TDA. The spreadsheet will help the PEO capture all of the land cover conversions in the TDA to help set up the predeveloped and developed modeling scenarios in MGSFlood. Fill out the spreadsheet for each TDA and attach those completed spreadsheets in the Appendix of the Hydraulic Report. Access the spreadsheet here: http://www.wsdot.wa.gov/Design/Hydraulics/HighwayRunoffManual.htm

The "50 Percent Rule" allows areas not required to receive flow control to pass through a flow control facility, up to a certain limit. This area is called a *flow through* area which can be on-site and/or off-site are. In the stormwater model, *flow through* areas appear in the predeveloped and postdeveloped conditions with the same size and land cover. The 100-year peak flow rate of the *flow through* area, assuming it is undetained, must be less than 50% of the 100-year peak flow rate from the area receiving flow control. Otherwise, the PEO would have to reduce the *flow through* area until the limit is not exceeded.

Stormwater modeling generally falls under one of three scenarios presented below:

1. **Equivalent area option.** When the situation arises where an area that needs to be treated for stormwater flow control and/or runoff treatment cannot physically be captured, the *equivalent area* option usually provides a workable solution. The equivalent area option allows the designer to find an *equivalent area* that can be treated to provide the same amount of required runoff treatment and flow control. *Equivalent* means equal in area, located within the same TDA, and having an ADT that is greater than or equal to the original area) to the impervious surface area being traded. The equivalent area should be upgradient of or in close proximity to the discharge from the new area. The drawing on the left side of Figure 4-9 shows that the flow control facility needs to be sized for 10 acres of new impervious surface. Using the equivalent area option, runoff from the existing impervious areas and new impervious areas would be routed to the facility so that 10 acres within the same TDA drains to the facility. This concept can also be applied to meeting the minimum requirement for runoff treatment. Note that the 50 Percent Rule applies for any *flow through* areas.

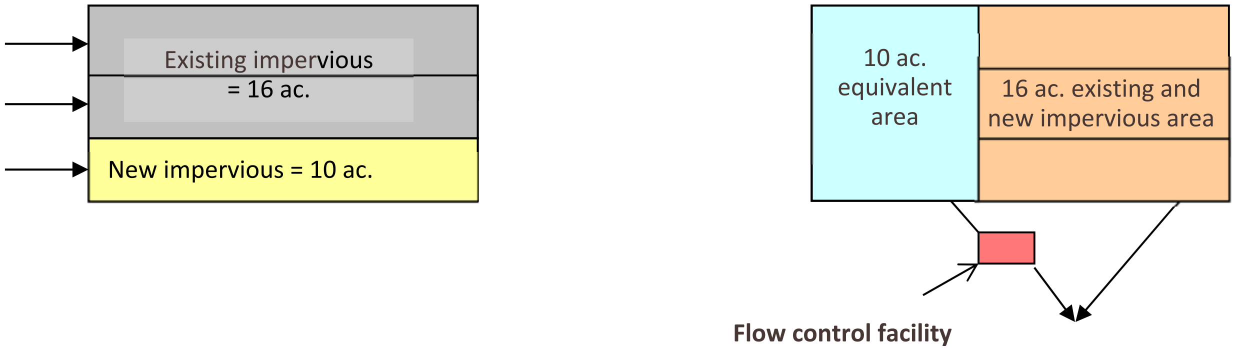


Figure 4-9 Equivalent area option.

2. **On-site, full area option.** The second option deals with the situation where on-site and off-site flows cannot be separated before going into a flow control facility. Note that the 50 Percent Rule does not apply for this option. **The PEO must get prior approval from the Region Hydraulics Engineer before using this option.**

   The intent of this option is to size the detention facility for just the required amount of area (effective impervious and converted pervious surfaces) per HRM minimum requirements, but additionally have both unmitigated on-site and off-site areas flow to the facility (see Figure 4-10). This will require two separate model runs, as follows:

   Model Run #1 – Size the detention facility and the outlet release structure initially using the drainage area (mitigated) for which flow control is required.

   Model Run #2 – Conduct a second modeling exercise that routes flow from unmitigated on-site and off-site areas through the previously designed pond and outlet structure in Model Run #1. If the flow can pass through the outlet structure without overtopping the pond (engaging the emergency overflow structure), it is a successful design. If the pond does overtop, then the design is inadequate. Consider the following two options for a successful design:

   a. Increase the distance between the design water surface elevation and the emergency overflow structure by raising the elevation of the emergency overflow structure and the pond embankment (note that a minimum of 1 foot of freeboard is required above the pond design water surface elevation).

   b. Redesign the outlet structure. Increase the diameter of the riser while keeping the orifices the same so that the higher flows can be discharged. However, the PEO must demonstrate that the new outlet structure design could meet the flow control duration requirement if the pond were only serving the mitigated area (the initial design condition). This option would provide flow control for all of the impervious surface draining to the stormwater facility, but the PEO would apply the duration standards only to the mitigated area, even though there will be higher flows passing through the facility.

The on-site, full area option does not meet a retrofit standard and is applicable for flow control facilities only. If the pond also provides runoff treatment, size the dead storage volume for the entire area flowing to the pond. Once Model Run #2 is complete, verify that the pond still meets the flow control standards for the mitigated area by rerunning Model Run #1 analysis with the updated pond structure and geometry.

Figure 4-10 shows a detention pond that is initially sized for 10 acres, as required by HRM Minimum Requirements. After, the full 10 acres plus 22 acres (nonmitigated area) are modeled to show that the pond does not go into emergency overflow.

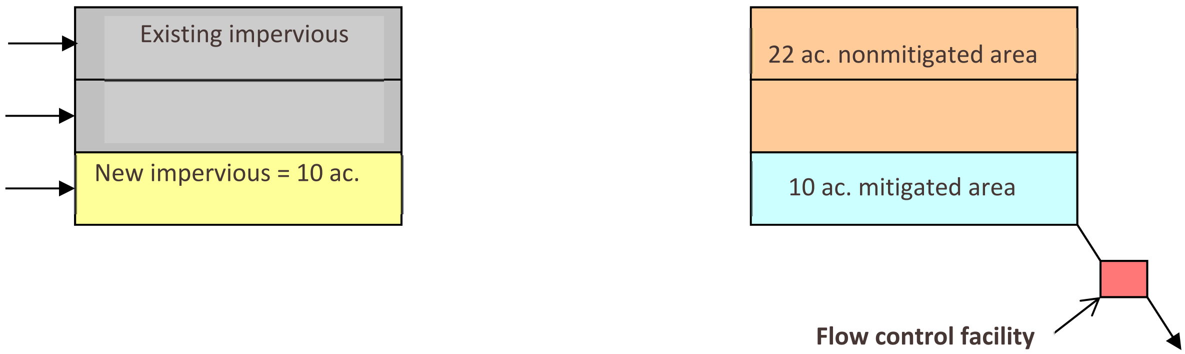


Figure 4-10 Full area option.

3. **Point of Compliance option.** There may be instances when some of the area that must be captured to meet the flow control requirement cannot be captured and not enough equivalent area can be captured to make up the difference. The following option, as depicted in Figure 4-11, provides a way to meet the overall intent of the flow control requirement for the total area that must be mitigated while allowing some of the required area to bypass the flow control facility. The analysis focuses on a point of compliance downstream where flows from the flow control facility and the bypass area combine.

   To use this scenario, **all** of the following conditions must be met. These criteria apply only to that portion of the area that must be mitigated and for the area that is bypassed. (See Appendix 4A for a link to an example that explains how a point of compliance analysis can be modeled using MGSFlood.)

   - Runoff from both the bypass area and the flow control facility converges within ¼ mile downstream of the project site discharge point.
   - If the bypass area flows to the point of compliance via overland flow, the 100-year developed peak flow rate from the bypass area will not exceed 0.4 cfs. If the bypass area flows through a constructed conveyance channel or pipe, then the 0.4 cfs criteria does not apply.
   - Runoff from the bypass area will not create a significant adverse impact to downstream drainage systems or properties.
   - Runoff treatment requirements applicable to the bypass area are met.

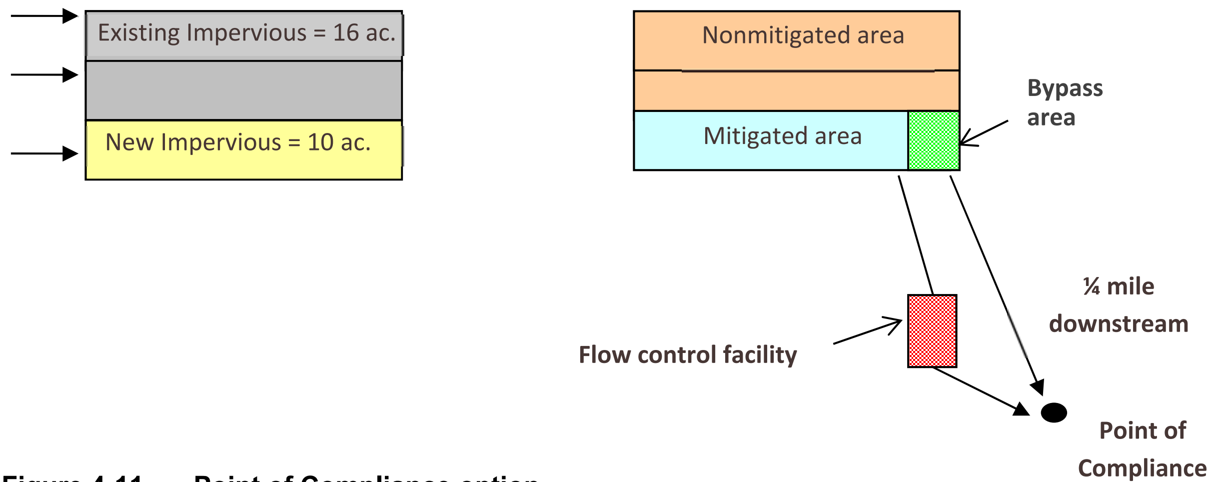


Figure 4-11 Point of Compliance option.

4-3.5.5 Modeling Best Management Practices (BMPs)

Flow control BMP design focuses on infiltrating, dispersing, and, as a last resort, detaining and discharging stormwater. In contrast to conventional BMPs that receive runoff at one location on the site, low-impact development (LID) BMPs manage stormwater in small-scale dispersed facilities located as close to the source of the runoff as possible. Due to the many different factors affecting both stormwater runoff treatment and flow control, there is no one technique that will work in all situations. Consider the following list of modeling strategies when modeling BMPs:

1. **General modeling guidelines:** In determining the appropriate modeling approach, it is important to understand how stormwater infiltration, dispersion, and runoff occurred historically on the site. Determining existing conditions (see Section 4-2) will provide information on how the site and the surrounding areas currently process stormwater and how they processed stormwater before any land use changes had altered them. This information should aid the PEO in determining the best site layout and help choose appropriate BMPs that will either maintain or restore the natural predeveloped stormwater processes. Use the following items from the site analysis to determine appropriate site layouts and BMPs:
   - Location and quantity of off-site drainage entering and on-site drainage leaving the site, if any.
   - Slopes throughout the site.
   - Locations of existing mature vegetation (trees and shrubs) that has upper soil profiles for stormwater processing.
   - Depth of the seasonal high groundwater table.
   - Depths and conditions of the upper soil profile (the A and B horizons), along with the identification of the lower soils.
2. Modeling and sizing of multiple BMPs with a continuous simulation model is possible with MGSFlood. In order to incorporate low-impact development (LID) BMPs into the MGSFlood

model, Table 4-1 and Table 4-2 have been created to show what land covers to assume for each BMP. Table 4-1 lists the assumed land covers broken down by outwash or till soils. Outwash soils would represent soils in Hydrologic Soil Group A and some uncompacted soils in Hydrologic Soil Group B. Till soils would represent some compacted soils in Hydrologic Soil Group B, as well as soils in Hydrologic Soil Groups C and D.

Table 4-1 Flow control modeling techniques based on land use.

BMP Type: Land Use	Assume the TDA is Composed of the Following: Outwash Soil	Till Soil
Reversion of impervious surface[1]	100% Pasture	100% Pasture
Landscaped with amended soils[2]	100% Pasture	100% Pasture
Permeable pavement without perforated drain pipe[3]	Represented in MGSFlood internally as its own land use	Represented in MGSFlood internally as its own land use
Permeable pavement with perforated drain pipe[3]	100% Impervious	100% Impervious
Reverse slope sidewalks	100% Grass	100% Grass

[1] See Step 2 in Section 4-3.5.3 Reversion of Existing Impervious Surface Areas and Section 5-4.3.2 Soil Amendments.

[2] See Section 5-4.3.2 Soil Amendments.

[3] See BMP IN.06 Permeable Pavement Surfaces in Chapter 5.

Table 4-2 Flow control modeling techniques for LID BMPs.

BMP Type: Structural	Assume the Following Process for the Interim: Outwash Soil	Till Soil
CAVFS, Bioretention Area, Infiltration Pond, Infiltration Trench, Infiltration Vault*	Represented in MGSFlood internally as its own land use	Represented in MGSFlood internally as its own land use
Drywells	See BMP IN.05	See BMP IN.05

*These BMPs can be modeled using MGSFlood. Contact the Region Hydraulics Engineer first to obtain procedures, or access the following link: www.wsdot.wa.gov/design/hydraulics/training.htm

Flow Control Facility Design

Complete flow control facility design by: defining the pond hydraulics in the *Pond Hydraulics Excel Spreadsheet* (www.wsdot.wa.gov/design/hydraulics/programdownloads.htm) or using the optimization routine in MGSFlood. Regardless of the method the PEO uses for sizing a flow control facility, the detention pond design must take into account the effect that the actual pond will have as a land use change in the postdeveloped condition. Therefore, the flow control analysis should also include the pond surface area in the postdeveloped condition as an impervious surface, since the precipitation falling on the detention pond surface will result in a runoff volume that will contribute directly to the flow control facility. In the predeveloped condition, represent the detention pond top surface area by its existing land cover condition. This will require at least two iterations using MGSFlood to properly size the facility. Use the water quality flow rates determined from this analysis to size runoff treatment BMPs that are downstream of the flow control facility. Use a separate model without the pond area for sizing runoff treatment BMPs that are upstream of the flow control facility, since the runoff volume from this pond area will not contribute to the runoff treatment BMP.

WSDOT projects designing flow control BMPs must use the MGSFlood Inputs Spreadsheet to document the type of flow control scenario (Section 4-3.5.4), type of flow control BMP, and to determine if enough area is being captured to meet flow control requirements for the TDA. The spreadsheet will help determine the inputs needed for MGSFlood. The spreadsheet if at: http://www.wsdot.wa.gov/Design/Hydraulics/HighwayRunoffManual.htm.

Flow Frequency and Duration Statistics Check

To analyze a stormwater pond's effectiveness at reducing postdevelopment flows to pre-developed levels, first route flows through the pond. Compute statistics and create graphs to show the performance graphically. Assess pond performance by comparing the flow frequency and duration statistics for the pond outflow with the statistics computed for the predeveloped condition. The designer must also check the 100-year peak flow for flood control and property damage. Review the history file and verify that the postdeveloped 100-year peak is less than the predeveloped 100-year peak flow. If the postdeveloped peak flow is not less than the predeveloped 100-year peak flow, field-verify that property damage will be prevented.

Expanding an Existing Flow Control Ponds Built to the 1995 HRM

Detention ponds that were designed using the 1995 HRM method (SBUH or single even model) can be modified to accept additional runoff from roadways that require widening and flow control. The PEO must do an analysis to determine if expanding the existing detention pond is possible. Contact the HQ Hydraulics Section for current modeling guidance.

4-4 Eastern Washington Design Criteria

This section provides a discussion of the methodologies used for calculating stormwater runoff from project sites in eastern Washington. The hydrologic analysis method for most WSDOT project sites in eastern Washington is either the SCS or SBUH method. The input required for a single-event hydrograph method includes pervious and impervious areas; times of concentration; pervious and impervious curve numbers; design storm precipitation; and a design storm hyetograph. An approved single-event model, such as StormShed3G, should be used for calculating runoff characteristics. Single-event models are explained in more detail in Section 4-4.6.

Note: The threshold discharge area concept must also be applied to projects in eastern Washington (see Section 4-2.5).

Note: The threshold discharge area concept must also be applied to projects in eastern Washington (see Section 4-2.5).

4-4.1 Runoff Treatment Flow-Based and Volume-Based BMPs

Runoff treatment BMPs are used to treat the stormwater runoff from pollutant-generating surfaces and should be designed in accordance with Minimum Requirement 5 (see Section

3-3.5). Some treatment BMPs are sized based on flow rate, while others are sized based on volume of runoff. For example, a bioswale or proprietary filtration BMP is sized based on flow rate, whereas an infiltration pond is sized based on runoff volume. Sizing is dependent on flow rates or volumes, as detailed in the following sections. The criteria for sizing runoff treatment facilities in eastern Washington are summarized in Table 3-4.

4-4.1.1 Flow-Based Runoff Treatment

The design flow rate for these types of facilities is dependent on whether the treatment facility is located upstream of a flow control facility and whether it is an *on-line* or *off-line* facility (see Section 4-3.1.1 for examples). The PEO can design most treatment facilities as on-line systems, with flows greater than the runoff treatment design flow rate simply passing through the facility as overflow, with lesser or no pollutant removal. However, it is sometimes desirable to restrict flows to treatment facilities and bypass the remaining higher flows around them. These are called off-line systems.

4-4.1.2 Volume-Based Runoff Treatment

Runoff treatment facilities are designed based on volumes and must be sized for the entire flow volume that is directed to them. Use the following method to derive the storage volume:

- **Wetpool** and **Infiltration:** The NRCS curve number equations (see *Hydraulics Manual*, Section 2-6.3) can be used to determine the runoff treatment design storm runoff volume. This is the volume of runoff from the storm noted in Table 3-4. WSDOT prefers that StormShed3G, a SBUH-based program, be used for this method to size volume-based runoff treatment BMPs. The size of the wetpool or infiltration storage volume is the same whether it is located upstream or downstream of a flow control facility or coupled with the flow control facility.

If the runoff from the new impervious surfaces and converted pervious surfaces is not separated from runoff from other surfaces on the project site, and/or is combined with run-on from areas outside the right of way, the runoff treatment facilities must be sized for the entire flow volume that is directed to them. Infiltration facilities must infiltrate 6-month, 24-hour total runoff volume within 72 hours after precipitation has ended.

4-4.2 Flow Control BMPs

An approved single-event model must be used when designing flow control BMPs, in accordance with Minimum Requirement 6 (see Section 3-3.6). WSDOT prefers that StormShed3G be used for designing flow control BMPs in WSDOT right of way. Stormwater discharges to surface waters must match developed peak flows to predeveloped peak flows for the range of predeveloped discharge rates noted in Table 3-7.

4-4.3 Temporary Construction Site Erosion and Sediment Control

Refer to the *Temporary Erosion and Sediment Control Manual* for information on designing construction stormwater BMPs.

4-4.4 Exemptions for Flow Control

WSDOT has developed a standardized process to aid the PEO in producing an acceptable hydraulic analysis for determining flow control exemptions. The process will help the PEO determine how extensive an analysis must be for a particular project. (See Chapter 3 for a process that has been established for lakes and some river systems.) Please refer to Minimum Requirement 6 (see Section 3-3.6) for further details on exemptions, flow dispersion, and flow control thresholds.

4-4.5 Hydrologic Analysis Methods for Flow Control and Runoff Treatment Facility Design

This section presents the general process involved in conducting a hydrologic analysis using single-event hydrograph methods to (1) design retention/detention/infiltration flow control facilities and (2) determine runoff treatment volumes. The exact step-by-step method for entering data into a computer model varies with the different models and is not described here (see the Documentation or Help modules of the computer program). Predeveloped and postdeveloped site runoff conditions must be determined and documented in the Hydraulic Report.

The process for designing retention/detention/infiltration flow control facilities in eastern Washington is presented below. Review Minimum Requirement 6 (see Section 3-3.6) to determine all the requirements that will apply to the proposed project.

1. Determine rainfall depths for the site (see Appendix 4A or WSDOT GIS Environmental Workbench).
   - 2-year – 24-hour
   - 25-year – 24-hour
   - 100-year – 24-hour
2. Determine predeveloped soils type and hydrologic group (A, B, C, or D) from SCS maps.
3. Determine predeveloped and postdeveloped pervious and impervious area (in acres) contributing to the BMP (see Section 4-2.5 for more details).
4. Determine curve numbers for pervious and impervious area using hydrologic soil groups for both the predeveloped and postdeveloped conditions (see Section 3-3.6.4, Appendix 4B, and Equations 4-1 and 4-2).
5. Determine predeveloped and postdeveloped time of concentration. StormShed3G will do this calculation if the PEO enters length, slope, roughness, and flow type.
6. Select storm hyetograph and analysis time interval. Check that the analysis time interval is appropriate for use with storm hyetograph time increment (see Appendix 4C).
7. For each BMP, input the data obtained above into the computer model for each predeveloped and postdeveloped storm event.
8. Have the computer model compute the hydrographs.

9. Review the peak flow rate for the predeveloped conditions in the 2-year and 25-year storm events. The allowable release rate is listed in Table 3-7. ***Note:*** In some cases, the predeveloped 2-year peak flow rate may be 0.00 cfs, which means there is no discharge from the site. The 2-year postdeveloped flows in this situation must be retained as dead storage that will ultimately infiltrate or evaporate.
10. Review the peak flow rate for postdeveloped conditions in the 2-year and 25-year storms.
11. Assume the size of the detention facility and input the data into the computer model. Refer to the volume of the postdeveloped design storm hydrograph computed in Step 8 for a good initial assumption of the detention volume required.
12. Assume the size of the orifice structure and input the data into the computer model. A single orifice at the bottom of the riser may suffice in some cases. In other projects, multiple orifices may result in decreased pond sizes. A good approximation would be to assume a 1-inch-diameter orifice per 0.05 cfs outflow for a typical pond.
13. Use the computer model to route the postdeveloped hydrographs through the detention facility and orifice structure. Compare the postdeveloped peak outflow rates to allowable release rates from Step 9.
14. If the postdeveloped peak outflow rates exceed the allowable release rates, adjust detention volume, orifice size, orifice height, or number of orifices. Keep running the computer model and adjusting the parameters until the post-developed outflow rates are less than or equal to the allowable release rates.
15. The PEO must include the pond surface area in the postdeveloped condition as an impervious surface, since the precipitation falling on the detention pond surface will result in a runoff volume that will contribute directly to the flow control facility. In the predeveloped condition, represent the pond top surface area by its existing land cover condition. This will require at least two iterations using StormShed3G to properly size the detention facility. Use the water quality flow rates determined from this analysis to size runoff treatment BMPs that are downstream of the flow control facility. Use a separate model without the pond area for sizing runoff treatment BMPs that are upstream of the flow control facility, since the runoff volume from this pond area will not contribute to the runoff treatment BMP.
16. Check the 100-year release rate and compare to predeveloped conditions, and check for potential property damage.
17. Calculations are complete.

Examples can be found through the web links, which are provided in Appendix 4A.

Following is the process for calculating runoff treatment design volumes or flow rates. Note that the data for many of the initial steps matches the data used in designing retention/detention flow control facilities described above.

1. Review Minimum Requirement 5 (see Section 3-3.5) to determine all requirements that will apply to the proposed project.

2. Determine the climatic region and Mean Annual Precipitation (MAP) (see Appendix 4A).
3. Determine the rainfall for the site depending on the treatment BMP (see Appendix 4A and Section 4-4.1).
4. Multiply the rainfall by the appropriate coefficient to determine the 6-month precipitation (see Appendix 4C).
5. Determine the existing soils type and hydrologic group (A, B, C, or D) from SCS maps (see *Hydraulics Manual*, Section 2-6.2).
6. Determine postdeveloped pervious and impervious area (in acres) requiring treatment that contributes flow to the treatment BMP.
7. Determine curve numbers for pervious and impervious area using the hydrologic soil group for the postdeveloped condition (see Appendix 4B).
8. Determine postdeveloped time of concentration; StormShed3G computes this when the PEO inputs length, slope, roughness, and flow type (see the *Hydraulics Manual*, Section 2-6.2).
9. If modeling the short-duration storm hyetographs, select the short-duration rainfall type in StormShed3G. Determine that the analysis time interval is appropriate for use with the storm hyetograph time increment (see Appendix 4C).
10. Input data obtained from above into StormShed3G for the postdeveloped storm event.
11. Have the model compute the hydrograph.
12. For the design of *flow-based* treatment BMPs, note that the computed peak flow from the 6-month, 3-hour hydrograph is the design flow.
13. For the design of *volume-based* treatment BMPs, note that the computed volume from the 6-month, 24-hour storm is the design volume.

Examples can be found through the web links, which are provided in Appendix 4A.

4-4.6 Single-Event Hydrograph Method

In eastern Washington, a single-event hydrograph method is typically used for calculation of runoff, with an integrated set of hydrology design tools developed to address the needs of conventional engineering practice. There are many single-event models based on the SCS (Soil Conservation Service) and SBUH methodologies that include level pool routing, pipe and ditch conveyance system analysis, and backwater computation. Appendix 4A provides a link to the approved WSDOT single-event model. Single-event models are described in more detail in Chapter 2 of the WSDOT *Hydraulics Manual*. Runoff curve numbers and the precipitation data differ considerably in eastern and western Washington (see Appendix 4B). Refer to Appendix C for a discussion on the eastern Washington design storm events.

4-4.7 Eastern Washington Design Storm Events

When rainfall patterns during storms were analyzed in eastern Washington, it was concluded that the SCS Type II rainfall does not match the historical records. Two types of storms were found to be prominent on the east side of the state: short-duration thunder storms (later spring through early fall seasons) and long-duration winter storms (any time of year, but most common in the late fall through winter period and the late spring and early summer period). The short-duration storm normally generates the greatest peak discharges from small impervious basins; use it to design flow-based BMPs. The long duration storm occurs over several days, generating the greatest volume; use it to design volume-based BMPs.

When using the long-duration storm, note that eastern Washington has been divided into the following four climatic regions:

1. East Slope Cascades
2. Central Basin
3. Okanogan, Spokane, Palouse
4. NE and Blue Mountains

The long-duration storms in Regions 2 and 3 are similar to the SCS Type 1A storm. Designers in those regions can choose to use either the long-duration storm or the SCS Type 1A storm. Eastern Washington design storm events are further discussed in Appendix 4C.

4-4.8 Modeling Using Low-Impact Development Techniques in Eastern Washington

Low-impact development (LID) is a BMP application that manages stormwater on a small scale and disperses it into a facility as close as possible to the source of runoff. This is in contrast to conventional BMP applications that manage stormwater at one location on the project site.

Design of low-impact development BMP drainage features in eastern Washington requires a different approach than in western Washington, since the sizing of these systems is based on a single-event hydrologic model. Adjustments to site runoff parameters are based on the SCS Curve Numbers (CNs) applicable to the site ground cover and soil conditions. Appendix 4B presents the adjusted runoff CNs for selected soil and ground cover combinations, reflecting the reduced values for situations where pervious areas drain to low-impact BMPs. (See the *Hydraulics Manual*, Section 2-6.2, for soil type definitions and more discussion on CN values.) ***Note:*** The analysis described in this section typically uses StormShed3G.

Composite custom CN values are calculated using a weighted approach based on individual land covers, without considering disconnectivity of the site's impervious surfaces. This approach is appropriate because it places increased emphasis on minimal disturbance to, and retention of, site areas that have potential for runoff storage and infiltration. This approach also provides an incentive to save more trees and shrubs and maximize the use of Type A and B soils for recharge.

If the impervious surface coverage on the site is less than 30% of the site area, the percentage of unconnected impervious areas within the watershed influences the calculation of the CN value. For linear transportation systems, evaluate the percentage of impervious surface based on a "unit length" method, such as a drainage area 30 feet wide that is bound by the crown of the roadway centerline to the right of way limit.

Use Equation 1 when disconnectivity of impervious areas is not considered.

$$CN_c = \frac{CN_1 A_1 + CN_2 A_2 ... + CN_j A_j}{A_1 + A_2 ... + A_j} \qquad \text{(E-1)}$$

where: CN_c = Composite Curve Number
A_j = Area of each land cover in ft^2
CN_j = Curve number for each land cover

Use Equation 2 for sites with less than 30% impervious surface coverage where those impervious surfaces are disconnected.

$$CN_c = CN_p + \left(\frac{P_{imp}}{100}\right) x \left(98 - CN_p\right) x \left(1 - 0.5R\right) \qquad \text{(E-2)}$$

where: CN_c = Composite Curve Number
CN_p = Composite pervious Curve Number
P_{imp} = Percentage impervious site area
R = Ratio of unconnected impervious area to total impervious area*

*Unconnected impervious areas are impervious areas without any direct connection to a drainage system or other impervious surface.

After the calculation of the CN_c is complete, use the SBUH method to determine stormwater runoff volumes and rates from the unit length of roadway basin (for example, 30-foot width for continuous roadway prisms with consistent soils/vegetation) for the applicable runoff treatment and flow control design storms. The PEO can also apply this method to specific roadway lengths (noncontinuous width) where soils and roadway character vary.

It is extremely important to verify soil infiltration capacity and vegetative cover in all areas where the SBUH method is to be applied. Determine the natural infiltration capacity of the roadside area where runoff will be distributed. The WSDOT Materials Lab should provide the infiltration rates (see Section 4-5.3). If the resultant infiltration rate *(Q)* of the receiving area is greater than the peak 25-year design flow rate of the contributing drainage basin, all stormwater will be infiltrated along the roadside and no further analysis is needed. Perform the calculation of the infiltrative flow rate (Q_i) as follows:

Calculation of Infiltrative Flow Rate

$$Q_i = \frac{F \times A}{43200 \frac{in/hr}{ft/s}} \tag{E-3}$$

where: Q_i = Flow rate in cfs
A = Area available for infiltration in ft^2
F = Saturated infiltration rate in inches/hour

Should peak flow rates of the contributing drainage basin exceed the infiltrative flow rate of the receiving roadside area, further analysis is required and some storage of stormwater will be necessary. In semiarid nonurban areas, formalized detention ponds are usually not the best solution. Storage of minor to moderate amounts of stormwater runoff can be accomplished by using natural depression storage. This includes depressions in the roadside topography, swales, and even roadway ditches. Each of these features can accommodate stormwater storage and allow for releasing runoff through infiltration over a longer time scale.

To determine the needed runoff retention volume, subtract the continuous saturated infiltration rate from the 25-year storm hydrograph produced from the SBUH method. The resulting quantity represents the runoff volume that needs to be detained until infiltration can "catch up" with the runoff. Check to see if this volume can be accommodated in the existing roadside landscape or roadway ditches. If roadside hydraulic conveyance capacity allows, the PEO may place *check dams* in ditches to detain stormwater in noncentralized locations. This method for small-scale flow detention will require a site-specific analysis; a continuous linear approach may not be valid.

4-5 Infiltration Design Criteria and LID Feasibility

LID is a stormwater and land use management strategy that strives to mimic predisturbance hydrologic processes of dispersion, infiltration, filtration, storage, evaporation, and transpiration by emphasizing conservation and use of on-site natural features, site planning, and distributed stormwater management practices that are integrated into a project design. Road and highway projects rely on dispersion and infiltration to meet LID requirements.

Infiltration facilities provide stormwater flow control by containing excess runoff in storage facilities, then percolating runoff into the surrounding soil. Infiltration facilities can provide runoff treatment and flow control, but to do so requires certain site and soil characteristics. Sections 4-5.1 and 4-5.2 provide a detailed discussion of the site and soil characteristics needed to determine which types of infiltration facilities are most appropriate for the site.

Surface infiltration BMP designs and subsurface infiltration BMP designs follow different criteria. Infiltration ponds, infiltration vaults, infiltration trenches, bioinfiltration ponds, dispersion, bioretention areas, continuous inflow compost amended biofiltration swales (CICABS), and CAVFS are considered surface infiltration BMPs and are based on infiltration rates. In order to compute these infiltration rates, make a determination of the soil saturated hydraulic conductivity. Infiltration trenches designed as an end-of-pipe application (with underdrain pipe) and drywells are considered subsurface infiltration BMPs and regulated by the Underground Injection Control (UIC) Rule, which is intended to protect underground sources of drinking water. As a result, subsurface infiltration BMPs are known as underground injection facilities and designed dependent on the treatment capacity of the subsurface soil conditions or have pretreatment BMPs to pretreat the stormwater prior to injection.

The sections that follow provide detailed information on site suitability criteria, LID feasibility, determination of saturated hydraulic conductivity, determination of infiltration rates, and underground injection facilities.

4-5.1 Site Suitability Criteria (SSC)

This section specifies the site suitability criteria that must be considered for siting infiltration treatment systems. When a site investigation reveals that any of the following eight applicable criteria cannot be met, the PEO must implement appropriate mitigation measures so that the infiltration facility will not pose a threat to safety, health, or the environment.

For infiltration treatment, site selection, and design decisions, a qualified engineer with geotechnical and hydrogeological experience should prepare a geotechnical and hydrogeological report. A comparable professional may also conduct the work if it is under the seal of a registered Professional Engineer (PE). The PEO may use a team of certified or registered professionals in soil science, hydrogeology, geology, and other related fields.

To design infiltration facilities, follow SSC 1, when applicable, in addition to those SSCs described in the infiltration BMP descriptions in Chapter 5. Figures 4-12 through 4-15 are flow charts of the Site Suitability Criteria, and the PEO can use them to determine the suitability of a site for infiltration facilities. Please note there are addition considerations for LID BMPs in Section 4-5.2.

SSC 1 – Setback Requirements

Setback requirements for infiltration facilities are generally provided in local regulations, Uniform Building Code requirements, or other state regulations. Use the following setback criteria unless otherwise required by Critical Area Ordinance or other jurisdictional authorities.

- In general, locate infiltration facilities 20 feet downslope and 100 feet upslope from building foundations and 50 feet or more behind the top of slopes steeper than 15%. Request a geotechnical report for the project that would evaluate structural site stability impacts due to extended subgrade saturation and/or head loading of the permeable layer, including the potential impacts to downgradient properties (especially on hills with known side-hill seeps). Ensure the report addresses the adequacy of the proposed BMP locations and recommend any adjustments to the setback distances provided above, either greater or smaller, based on the results of this evaluation.
- Set infiltration facilities back at least 100 feet from drinking water wells, septic tanks or drain fields, and springs used for public drinking water supplies. Ensure infiltration facilities upgradient of drinking water supplies and within 1-, 5-, and 10-year time of travel zones comply with health department requirements (Washington Wellhead Protection Program, WAC 246-290-135).

- Consider additional setbacks if roadway deicers or herbicides are likely to be present in the influent to the infiltration system.
- Locate infiltration facilities at least 20 feet from a native growth protection easement (NGPE).
- Locate infiltration facilities a minimum of 5 feet from any property line and vegetative buffer. The PEO may increase this distance based on permit conditions required by the local government.

SSC 2 – Seepage Analysis and Control

Determine whether there would be any adverse effects caused by seepage zones near building foundations, roads, parking lots, or sloping sites. Infiltration of stormwater is not allowed on or upgradient of a contaminated site where infiltration of even clean water can cause contaminants to mobilize. If contaminants are known or suspected to be on site, do not use infiltration facilities without the concurrence of the Region Hydraulics Engineer and the ESO Hazardous Materials Unit. A WSDOT geotechnical engineer may also be consulted if determined to be needed by the Region Hydraulics Engineer.

Sidewall seepage is not usually a concern if seepage occurs through the same stratum as the bottom of the facility. However, for engineered soils or soils with very low permeability, the potential to bypass the treatment soil through the sidewalls may be significant. In those cases, the sidewalls must be lined, either with an impervious liner or with the same depth of treatment soil as on the pond bottom, to prevent seepage of untreated flows through the sidewalls.

SSC 3 – Groundwater Protection Areas

A site is not suitable if the infiltrated stormwater will cause a violation of the Ecology water quality standards for groundwaters (WAC 173-200). Consult local jurisdictions to determine applicable pretreatment requirements and whether the site is located in an aquifer-sensitive area, a sole-source aquifer, or a wellhead protection zone.

SSC 4 – Depth to Bedrock, Water Table, or Impermeable Layer

The base of all infiltration basins or trench systems must be ≥ 5 feet above the seasonal high water mark, bedrock (or hardpan), or other low-permeability layer. Consider a separation down to 3 feet if the design of the overflow and/or bypass structures is judged by the site professional to be adequate to prevent overtopping and meet the SSC specified in this section.

SSC 5 – Soil Infiltration Rate

For runoff treatment infiltration facilities, the maximum final infiltration rate is 3.0 inches per hour. Calculate the final infiltration rate as described in Appendix 4D, Section 4D-6. This infiltration rate is typical for soil textures that have sufficient physical and chemical properties for adequate treatment, particularly for soluble pollutant removal. The soil should have characteristics similar to those specified in SSC 7. Using Ecology's Default Bioretention Soil Mix satisfies the SSC5 requirement.

SSC 6 – Drawdown Time

For western Washington, the 91% percentile, 24-hour runoff volume must be infiltrated within 48 hours. Runoff treatment in eastern Washington is designed to completely drain ponded runoff within 72-hours in order to meet the following objectives:

- Enhance the biodegradation of pollutants and organics in the soil.
- Aerate vegetation and soil to keep the vegetation healthy and prevent anoxic conditions in the treatment soil.

In general, this drawdown requirement is applicable only if it is intended for the infiltration facility to provide treatment. It is also used to address storage capacity if a single-event hydrograph model is used. Drawdown time criteria are not applicable for infiltration facilities designed for flow control in western Washington.

SSC 7 – Soil Physical and Chemical Suitability for Treatment

Consider soil texture and design infiltration rates, along with the physical and chemical characteristics specified below, to determine whether the soil is adequate for removing the target pollutants. Carefully consider the following soil properties in making this determination:

- Cation exchange capacity (CEC) of the treatment soil must be ≥5 milliequivalents CEC/100 g dry soil (U.S. EPA Method 9081). Consider empirical testing of soil sorption capacity, if practicable. Ensure soil CEC is sufficient for expected pollutant loadings, particularly heavy metals. CEC values of >5 meq/100g are expected in loamy sands (Buckman and Brady 1969). Consider lower CEC content if it is based on a soil loading capacity determination for the target pollutants that is accepted by the local jurisdiction.
- Depth of soil used for infiltration treatment must be a minimum of 18 inches, except for designed, vegetated infiltration facilities with an active root zone, such as CICABS and CAVFS (see BMP description in Chapter 5 for maximum soil depths). Depth of soils used for infiltration runoff treatment below IN.06 Permeable Pavement Surfaces that are PGIS may be reduced to 1.0 foot if the permeable pavement does not accept run-on from other surfaces.
- The organic matter content of the treatment soil (ASTM D 2974) can increase the sorptive capacity of the soil for some pollutants. The site professional should evaluate whether the organic matter content is sufficient for control of the target pollutant(s). The minimum organic content is 1.0 percent.
- Do not use waste fill materials as infiltration soil media, nor should the PEO place such media over uncontrolled or nonengineered fill soils.
- Use engineered soils to meet the design criteria in this chapter and the runoff treatment targets in Table 3-1. (See Soil Amendments in Chapter 5.)

SSC 8 – Cold Climate and Impacts of Roadway Deicers

- For cold climate design criteria (snowmelt/ice impacts), refer to the D. Caraco and R. Claytor document, Stormwater BMP Design Supplement for Cold Climates, U.S. EPA, December 1997.
- Consider the potential impact of roadway deicers on potable water wells in the siting determination. Implement mitigation measures if infiltration of roadway deicers can cause a violation of groundwater quality standards. For assistance, contact Region or HQ hydraulics staff.

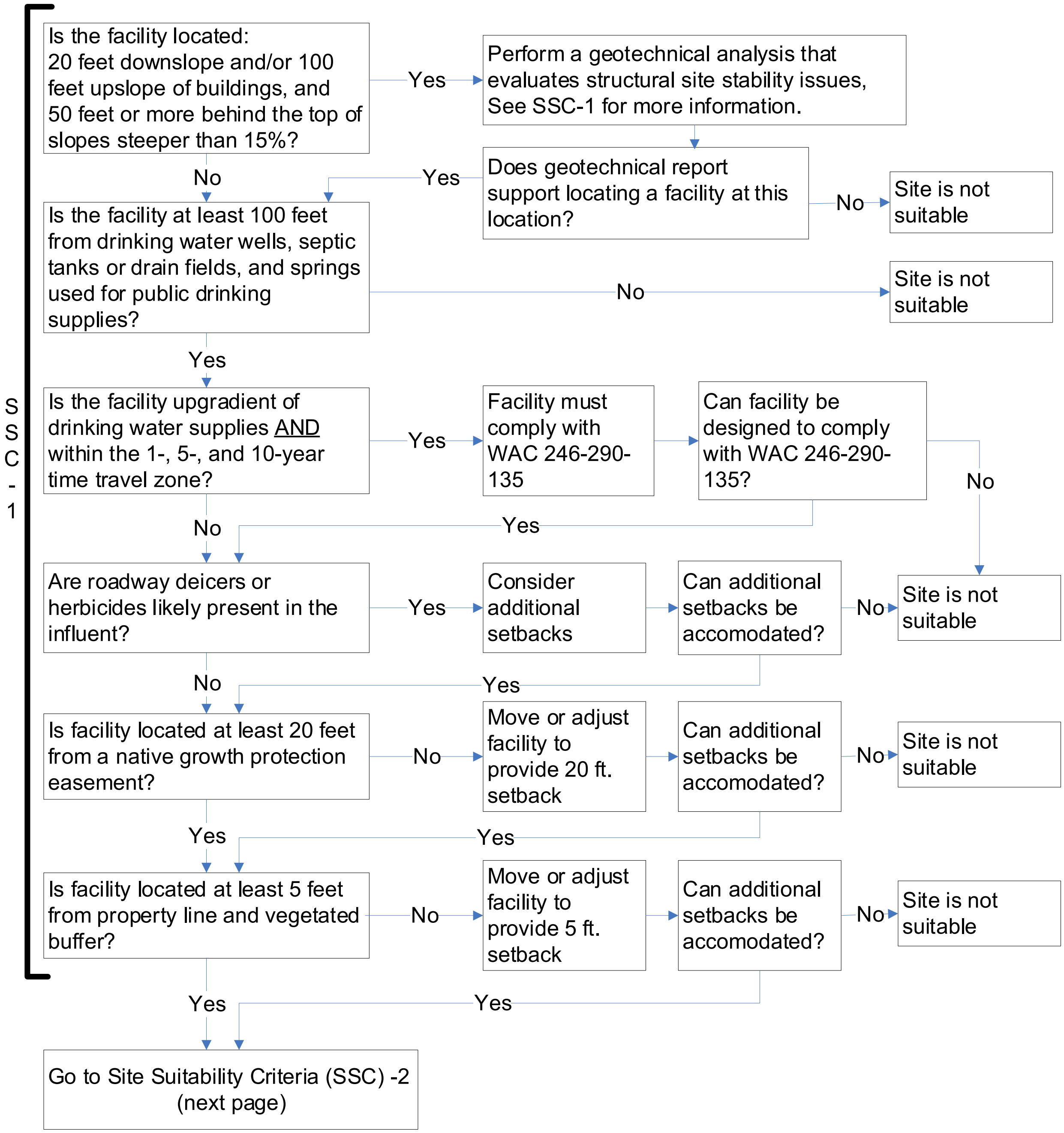


Figure 4-12 Soil Suitability Criteria 1 Flow Chart.

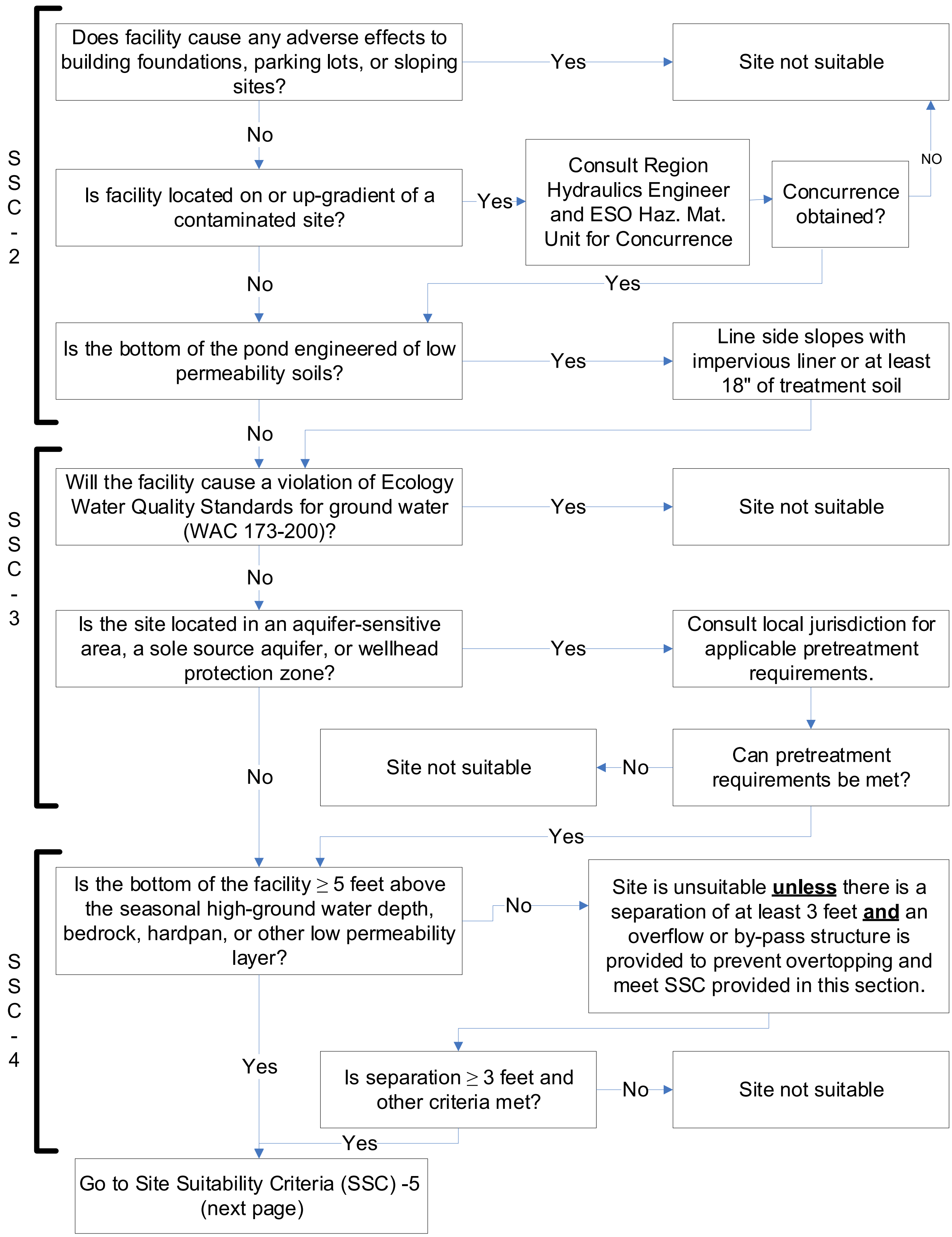


Figure 4-13 Soil Suitability Criteria 2-4 Flow Chart.

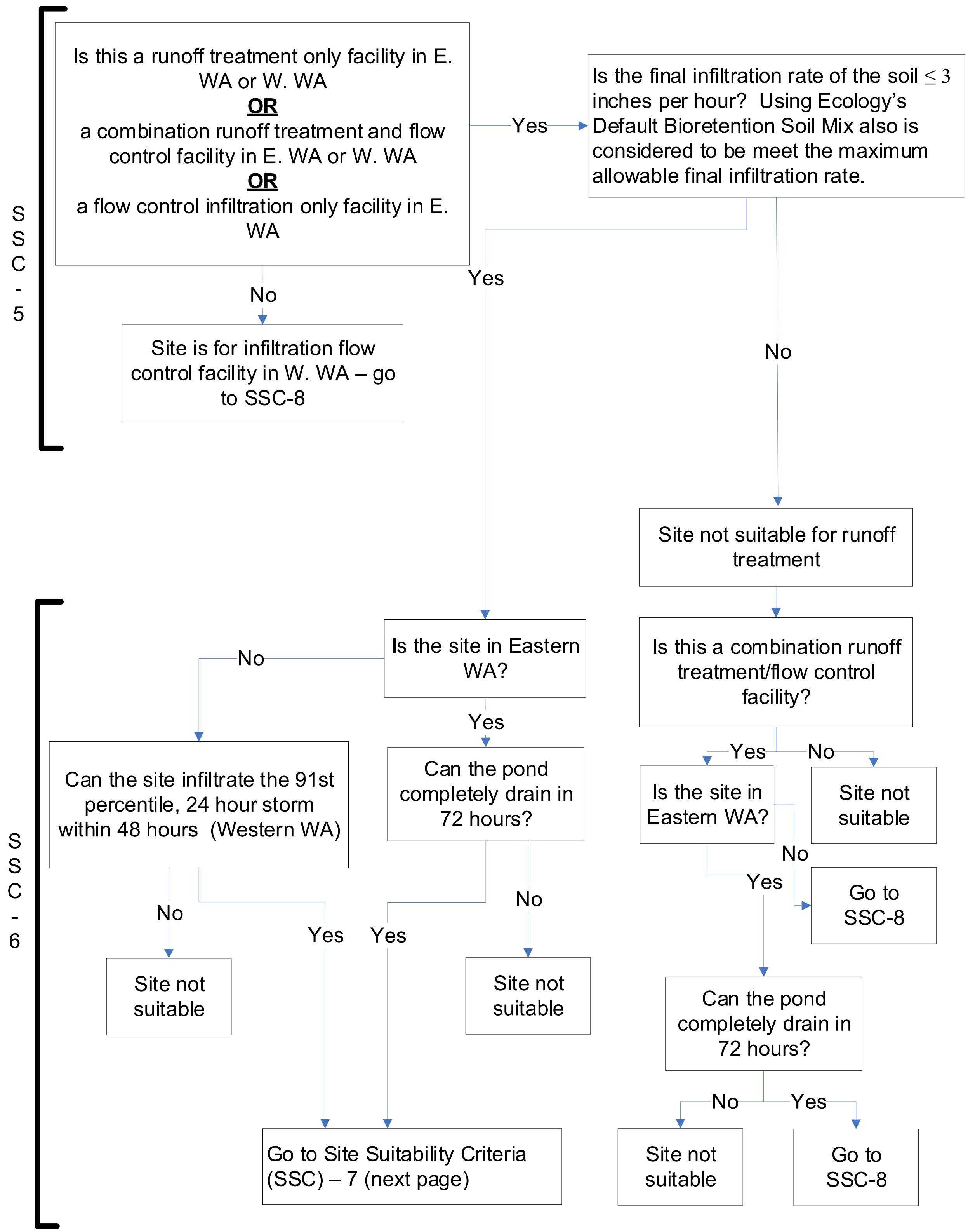


Figure 4-14 Soil Suitability Criteria 5-6 Flow Chart.

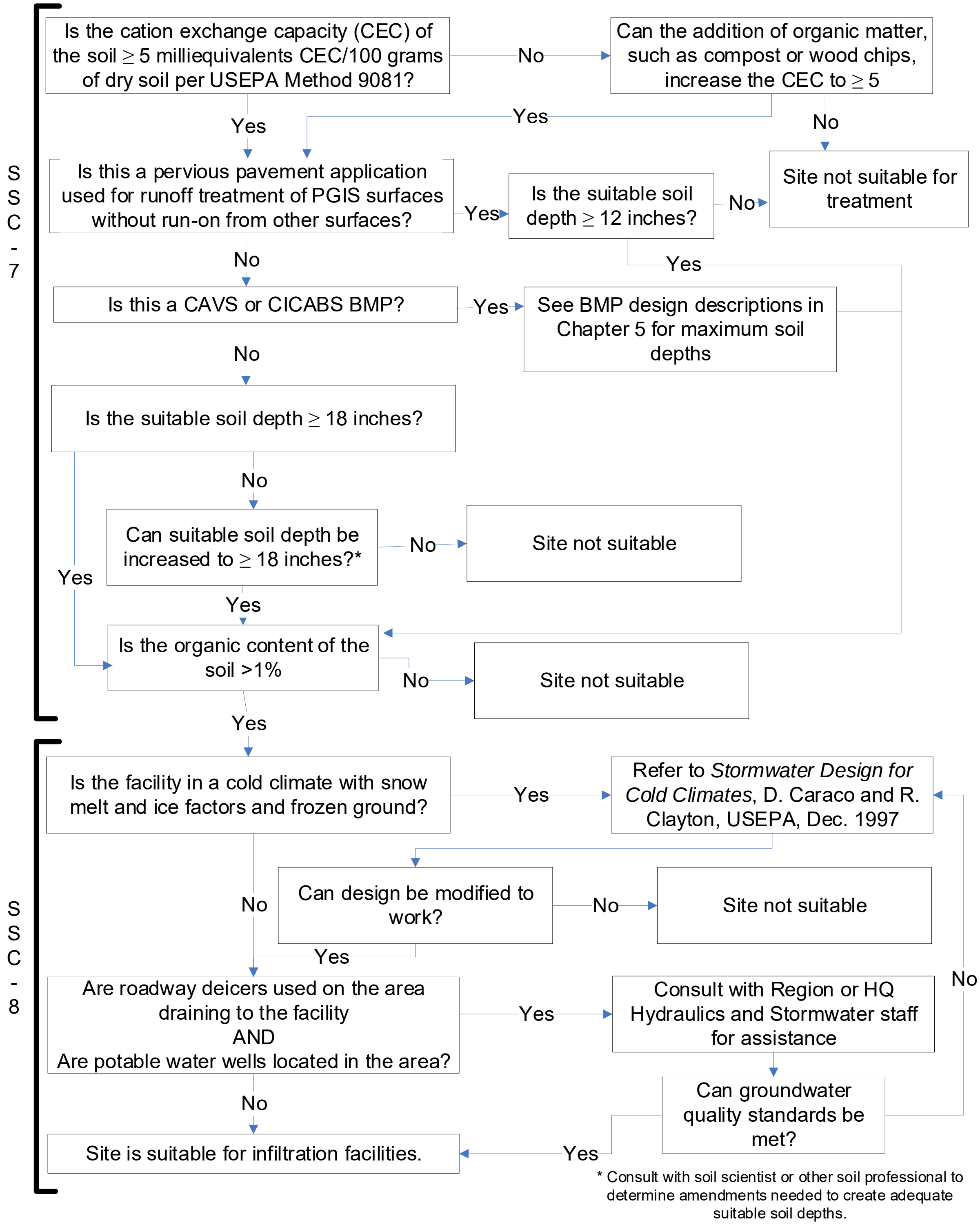


Figure 4-15 Soil Suitability Criteria 7-8 Flow Chart.

4-5.2 LID Feasibility

There are many types of LID and infiltration BMPs listed in Chapter 5. They include natural and engineered dispersion, compost-amended vegetated filter strips (CAVFS), continuous inflow compost-amended biofiltration swales (CICABS), media filter drains (MFD), bioretention areas, bioinfiltration ponds, natural depression areas, infiltration ponds, vaults, trenches, and drywells. Each BMP has its own distinct set of LID infeasibility criteria that is listed in the BMP descriptions in Chapter 5. There are some LID infeasibility criteria that are shared among all of the BMPs; they are listed below.

The following criteria describe conditions that make LID BMPs infeasible to meet the LID requirement per the BMP selection process in Section 5-3. It is important to note that even though a LID BMP is infeasible to meet the LID requirement, the PEO can still design and use the LID BMP to meet the runoff treatment and/or flow control requirement for the TDA. Base the citation of any of the below infeasibility criteria on an evaluation of site-specific conditions and document in the project's Hydraulic Report via the LID Feasibility Checklist, along with any applicable written recommendations from an appropriate licensed professional (e.g., engineer, geologist, hydrogeologist). Refer to Appendix 4A for a link to the LID Feasibility Checklist.

Scoping-Level Feasibility

- Does the area have groundwater that drains into an erosion hazard or landslide hazard area?
- Does the only area available for siting the LID BMP threaten the safety or reliability of preexisting: underground utilities, underground storage tanks, structures, or road or parking lot surfaces?
- Are there houses or buildings in the project area that may have basements that might be threatened by infiltrating stormwater from the area?
- Would the LID BMP be within setbacks from structures as established by the local government with jurisdiction?
- Is the land for the LID BMP within an area designated as an erosion hazard or landslide hazard?
- Is the LID BMP within 50 feet from the top of slopes that are greater than 20% and over 10 feet of vertical relief?
- Is the proposed site on property with known soil or groundwater contamination (typically federal Superfund sites or state cleanup sites under the Model Toxics Control Act (MTCA))?
- Is the proposed LID BMP within 100 feet of an area known to have deep soil contamination?
- Would the LID BMP be within any area where it would be prohibited by an approved cleanup plan under the state Model Toxics Control Act or federal Superfund law, or an environmental covenant under Chapter 64.70 RCW?

- Is the LID BMP within 100 feet of a closed or active landfill?
- Is the LID BMP within 100 feet of a drinking water well or a spring used for drinking water supply?
- Is the LID BMP within 10 feet of a small on-site sewage disposal drain field, including reserve areas, and grey water reuse systems? For setbacks from a "large on-site sewage disposal system," see Chapter 246-272B WAC.
- Is the LID BMP within 10 feet of an underground storage tank and connecting underground pipes when the capacity of the tank and pipe system is 1,100 gallons or less OR within 100 feet of an underground storage tank and connecting underground pipes when the capacity of the tank and pipe system is greater than 1,100 gallons? An underground storage tank means any tank used to store petroleum products, chemicals, or liquid hazardous wastes of which 10% or more of the storage volume, including the volume in the connecting piping system, is beneath the ground surface.

Project-Level Feasibility

- Is there insufficient space for a LID BMP within the existing public right of way on public road projects?
- Does the only area available for siting the LID facility not allow for a safe overflow pathway to the municipal separate storm sewer system?
- Is the LID BMP not compatible with surrounding drainage system as determined by the local government with jurisdiction (e.g., project drains to an existing stormwater collection system whose elevation or location precludes connection to a properly functioning bioretention facility)?
- Is the LID BMP within 10 feet of an underground storage tank and connecting underground pipes when the capacity of the tank and pipe system is 1,100 gallons or less OR within 100 feet of an underground storage tank and connecting underground pipes when the capacity of the tank and pipe system is greater than 1,100 gallons? An underground storage tank means any tank used to store petroleum products, chemicals, or liquid hazardous wastes of which 10% or more of the storage volume, including the volume in the connecting piping system, is beneath the ground surface.
- Does a professional geotechnical/geologic evaluation recommend infiltration not be used due to reasonable concerns about erosion, slope failure, or downgradient flooding?
- Would infiltrating water threaten shoreline structures such as bulkheads?
- Does field testing indicate that LID BMP areas have a measured (a.k.a., initial) native soil saturated hydraulic conductivity less than 0.30 inches per hour?
- For properties with known soil or groundwater contamination (e.g., federal Superfund sites), does groundwater modeling indicate infiltration will likely increase or change the direction of the migration of pollutants in the groundwater?

- Properties with known soil or groundwater contamination (e.g., federal Superfund sites), where surface soils have been found to be contaminated, need to be removed within 10 horizontal feet from the infiltration area/LID BMP. Would there be any problems keeping this 10 horizontal foot distance from contaminated surface soils?
- A minimum vertical separation of 1 foot is required between the seasonal high water table, bedrock, or other impervious layer to the bottom of the LID BMP that would serve a drainage area that is: (1) less than 5,000 sq. ft. of pollution-generating impervious surface, (2) less than 10,000 sq. ft. of impervious surface, and (3) less than ¾ acres of pervious surface. Are there any problems achieving this separation?
- A minimum vertical separation of 3 feet is required between the seasonal high water table, bedrock or other impervious layer to the bottom of the LID BMP that: (1) would serve a drainage area that meets or exceeds 5,000 square feet of pollution-generating impervious surface, OR 10,000 sq. ft. of impervious surface, OR ¾ acres of pervious surfaces; and (2) cannot reasonably be broken down into amounts smaller than indicated in (1). Are there any problems achieving this separation?

4-5.3 Infiltration Rates, Saturated Hydraulic Conductivity, and Hydraulic Gradients

Once a site is determined suitable for infiltration, the PEO can begin the infiltration design. The sizing of an infiltration BMP is dependent on the infiltration rate of the soils over which the BMP is located. Appendix 4D discusses the various ways to determine an infiltration rate. Infiltration rates are based on two components: the soil's saturated hydraulic conductivity (K_{sat}) and the hydraulic gradient. An overview of the infiltration design procedure is provided in Figures 4D-3 and 4D-4 in Appendix 4D. The focus of these design procedures is to size the facility. For other geotechnical aspects of the facility design, including geotechnical stability of the facility and constructability requirements, see Chapter 5 and the *Design Manual*. A multidisciplinary approach is required to design infiltration facilities, as described in Chapter 2. Section 4D-4 in Appendix 4D describes the three approaches for determining the saturated hydraulic conductivity (K_{sat}) of soils.

1. 1 Perform grain size analyses and use correlations between grain size distribution and K_{sat}.
2. Conduct K_{sat} laboratory tests to measure K_{sat} directly for specimens taken from the soil column during the geotechnical subsurface field investigation.
3. Use field tests to measure K_{sat} in-situ.

WSDOT mainly uses the modified Slichter methodology to that was developed from recent WSDOT research to develop the K_{sat} to design:

- Bio-infiltration pond (BMP IN.01)
- Infiltration pond (BMP IN.02)
- Infiltration trench (BMP IN.03)

- Infiltration vault (BMP IN.04)
- Underlying soils of CAVFS (BMP RT.02)
- Drywell (BMP IN.05)
- Natural dispersion (BMP FC.01)
- Engineered dispersion (BMP FC.02)

Please note at this time, the use of the optimized Slichter method and other equations developed in Allen 2017 are only for use by WSDOT on WSDOT projects. The optimized Slichter method and other equations developed in Allen 2017 are not currently within the SWMMWW, SWMMEW, or other Ecology approved equivalent manuals. These Manuals are intended to provide jurisdictions with technically sound stormwater management practices which are presumed to protect water quality and instream habitat, and meet the stated environmental objectives of the regulations described in the SWMMWW and SWMMEW.

Jurisdictions always have the option of not following the stormwater management practices in the SWMMWW, SWMMEW, or other Ecology approved equivalent manuals. However, if a project proponent chooses not to follow the practices in those Manuals then the project proponent may be required to individually demonstrate and document that the project will not adversely impact water quality by collecting and providing appropriate supporting data to show that the alternative approach is protective of water quality and satisfies State and federal water quality laws. Ecology, EPA, or a third party may review such documentation to ensure that they satisfy those laws.

Refer to Appendix 4D for more information on how to determine K_{sat}, the hydraulic gradient, and the infiltration rate.

4-5.4 Underground Injection Wells

Infiltration is one of the preferred methods for disposing of excess stormwater in order to preserve natural drainage systems in Washington. Subsurface infiltration is regulated by the Underground Injection Control (UIC) Rule, which is intended to protect underground sources of drinking water (http://apps.leg.wa.gov/WAC/default.aspx?cite=173-218). By definition, a UIC well includes a constructed subsurface fluid distribution system or a dug hole that is deeper than the largest surface dimension. For the purposes of this section, infiltration systems include drywells (BMP IN.05) and infiltration trenches with perforated underdrain pipes (BMP IN.03) designed to discharge stormwater directly into the ground. The following are not regulated as stormwater underground injection facilities:

- Infiltration trenches that do not include perforated underdrain pipes
- Infiltration vaults (BMP IN.04)
- Buried pipe and/or tile networks that serve to collect water and discharge that water to a conveyance system or a surface water
- Any facilities that are designed to receive fluids other than stormwater

For UIC wells designed in western Washington, see Ecology's SWMMWW Volume I Chapter 4 or for UIC wells designed in eastern Washington, see Ecology's SWMMEW Chapter 1.4.5 for guidance and design criteria for protection of groundwater.

4-6 Wetland Hydroperiods

An important consideration in the stewardship of certain wetland functions is the protection and control of an existing wetland's *hydroperiod*. The hydroperiod is the pattern of fluctuation of water depth and the frequency and duration of water levels on the site. This includes the duration and timing of drying in the summer. A hydrologic assessment is useful to measure or estimate elements of the hydroperiod under existing **preproject** and anticipated **postproject** conditions. This assessment involves reviewing and applying the best available science to assess potential impacts and deciding whether hydrological modeling is warranted. Refer to Minimum Requirement 7 (see Section 3-3.7) for the process, if applicable.

4-7 Closed Depression Analysis

This BMP has been moved to the HRM Category 1 BMPs document found here:

http://www.wsdot.wa.gov/Design/Hydraulics/FAQ.htm

4-8 References

Allen, T.M., 2017, *Stormwater Infiltration in Highway Embankments – Saturated Hydraulic Conductivity Estimation for Uncompacted and Compacted Soils*, WSDOT Research Report WA-RD 872-1, 161 pp.

Brater, E.F. and H.W. King. 1976. Handbook of Hydraulics. McGraw-Hill Company, New York.

Buckman, Harry O. and Brady, Nyle C., The Nature of Properties of Soils, Collier Macmillian Ltd., Toronto, Ontario, 1969.

Chow, V.T. 1959. Open Channel Hydraulics. McGraw-Hill Book Company.

Daughtery, R.L. and J.B. Franzini. 1977. Fluid Mechanics with Engineering Applications. McGraw-Hill, New York.

Ecology, Washington State Department of. *Stormwater Management Manual for Eastern Washington*. September 2004.

Ecology, Washington State Department of. *Stormwater Management Manual for Western Washington*. August 2005.

King County Surface Water Management Division. 1999. King County Runoff Timeseries (KCRTS), *Computer Software Reference Manual*, Version 4.4. January 1999.

King County. *Washington Surface Water Design Manual*. September 1998.

"Low-Impact Development Design Strategies, An Integrated Design Approach," prepared by Prince George's County, Maryland, Department of Environmental Resources, Programs and Planning Divisions. June 1999.

Maryland *Stormwater Manual*.

Massman, Joel, Carolyn Butchart, and Stephanie Stolar. 2003. University of Washington, Final Research Report-T1803, Task 12, "Infiltration Characteristics, Performance, and Design of Stormwater Facilities."

Massmann, J.W. April 2004. *An Approach For Estimating Infiltration Rates For Stormwater Infiltration Drywells*, WSDOT, Agreement Y-7717 Task Order AU.

Massmann, J.W. October 2003. *A Design Manual for Sizing Infiltration Ponds*. WSDOT, WA-RD 578.2. 61 pp.

Miller, J.F., R.H. Frederick, and R.S. Tracey. 1973. NOAA Atlas 2, Precipitation Frequency Atlas of the Western United States, Volume IX-Washington. U.S. Dept. of Commerce, NOAA, National Weather Service. Washington D.C.

Oregon Climate Service. 1997. Mean Annual Precipitation Maps for Western United States, prepared with PRISM Model for NRCS, Corvallis, Oregon.

Pierce County *Stormwater Manual*.

Pitt, R., S.E. Chen, S. Clark, J. Lantrip, C.K. Ong, and J. Voorhees. 2003. "Infiltration Through Compacted Urban Soils and Effects on Biofiltration Design," *Stormwater and Urban Water Systems Modeling, Models, and Applications to Urban Water Systems*, Ed. – W. James, CHI, Guelph, Ontario, Vol. 11. pp. 217-252.

Schaefer, M.G. 1981. "Shaft Spillways, Fundamental Hydraulics and Hydrology of Dam Design." University of Missouri Short Course, available through Dam Safety Section, Washington Department of Ecology. May 1981.

Schaefer, M.G. and B.L. Barker. 2002. "Extended Precipitation Time Series for continuous hydrological modeling in Western Washington," prepared for Washington State Department of Transportation by MGS Consulting Inc. April 2002.

Schaefer, M.G. and B.L. Barker. 2003. MGS Flood – *Proprietary Version User Manual*, prepared for Washington State Department of Transportation by MGS Consulting Inc., Version 2.2. March 2003.

U.S. Bureau of Reclamation. 1987. Design of Small Dams. U.S. Department of the Interior, U.S. Government Printing Office, 3rd edition.

USDA-SCS. 1986. Technical Release No. 55: Urban Hydrology for Small Watershed.

U.S. EPA. 1984. *Hydrological Simulation Program-Fortran HSPF User Manual* for Release 9. EPA 600/3-84-066. Environmental Research Laboratory, Athens, GA. June 1984.