Chapter 2 Hydrology

2-1 Introduction

This chapter presents WSDOT's procedures and acceptable methodologies for hydraulics and hydrologic analyses for transportation hydraulic features. The procedures and methodologies presented in this chapter are based on a basic understanding of the science of hydrology and its principles. Additionally, the PEO should be familiar with the regulations and requirements of various state and federal agencies that regulate water-related construction, as they may be applicable to proposed improvements.

WSDOT uses several methods for determining runoff rates and/or volumes. However, documented reporting and high-water mark observations shall be used wherever possible to calibrate or validate the results of the below statistical and empirical methods. Where calculated results vary from on-site observations, further investigation may be required. The following methods are discussed in detail in subsequent sections of this chapter:

1. Rational Method
2. Santa Barbara Urban Hydrograph (SBUH) Method
3. Continuous-Simulation Hydrologic Model (MGSFlood)
4. Published flow record
5. United States Geological Survey (USGS) regional regression equations
6. Existing hydrologic studies
7. Documented reporting

   Documented testimony of long-time residents should be given serious consideration by the PEO. Independent calculations should be made to verify this type of reporting and observations. The information furnished by residents of the area should include, but not be limited to, the following:

   e. Dates of past floods
   f. High-water marks
   g. Amount of drift
   h. Any changes in the channel that may be occurring (i.e., streambed stability—is the channel widening, migrating, or meandering)
   i. Estimated velocity
   j. Description of flooding characteristics between normal flow to flood stage

8. High-water mark observations

   High-water marks can be used to reconstruct discharge from past flood events on existing structures or on the bank of a stream or ditch. However, caution should be applied if the high-water marks are from a similar period (e.g., bathymetry/topography similar, flood event did not inundate nearby culverts or bridges causing backwater, was not significant debris, etc.). These marks, along with other data, can be used to determine discharge by methods discussed in Chapter 3 or Chapter 4.

Additional hydrologic procedures are available including complex computer models, which can give the PEO accurate flood flow predictions. The State Hydraulics Office shall be contacted before a procedure other than those listed above is used in a hydrologic analysis.

The State Hydraulics Office and RHE require one of the first six methods listed above. Exceptions will be permitted if adequate justification is provided and approved by the RHE.

Section 2-2 discusses how to select the appropriate method of assessing hydrology for a given site. Sections 2-3 and 2-5 discuss other important considerations, including the size of the basin and things to consider in cold climate areas. The remainder of the chapter describes each of the methods in more detail, followed by some examples in Section 2-12.

2-2 Selecting a Method

The first step in performing a hydrologic analysis is to determine the most appropriate method. The methods for determining runoff rates and volumes are summarized below, and Table 2-1 provides a comparison table. Subsequent sections provide a more detailed description of each method. Additional guidance will be provided in future revisions to the *Hydraulics Manual*.

- **Rational Method (Kuichling 1889):** This method is used when peak discharges for basins up to 200 acres must be determined. This method does not provide a time series of flow or flow volume. It is a simple and accurate method, especially when the basin is primarily impervious. The Rational Method is appropriate for culvert design, pavement drainage design, and storm sewer design. It is also appropriate for some stormwater facility designs in eastern Washington.
- **Santa Barbara Urban Hydrograph (SBUH) Method (Stubchaer 1975):** This method is used when estimation of a runoff hydrograph is necessary. The SBUH Method also can be used when retention and detention must be evaluated. The SBUH Method can be used for drainage areas up to 1,000 acres. The SBUH Method can be used for stormwater facility designs in eastern Washington and for culvert and storm sewer designs through the entire state.
- **Continuous-simulation hydrologic model:** For western Washington, calibrated continuous-simulation hydrologic models, based on the Hydrological Simulation Program-Fortran (HSPF) routine, have been created for computing peak discharges and runoff volumes. These models are used for stormwater facility designs in western Washington and estimating seasonal runoff for temporary stream diversions. WSDOT uses the continuous-simulation hydrologic model MGSFlood

when calculating runoff treatment rates and volumes for stormwater facility design. Programs other than MGSFlood may be used if approved by the State Hydraulics Office.

- **Published flow record:** This method shall be used whenever appropriate stream gage data are available. This is a collection of data rather than a predictive analysis like the other methods listed. USGS, cities, counties, and other agencies gather stream flow data on a regular basis. Collected data can be analyzed statistically to predict flood flows and are more accurate than simulated flows. Published flow records are most appropriate for culvert and bridge design.
- **USGS regional regression equations (Mastin et al. 2016):** This method can be used when no appropriate stream gage data are available. It is a set of regression equations that were developed using data from stream flow gaging stations. The regression equations are simple to use but are less accurate than published flow records. USGS regression equations are appropriate for culvert and bridge design and are intended for use in rural and predominantly undeveloped basin areas. PEOs should consult the USGS regression equation documentation for limitations when computing flows in urban basins (basins with greater than 5 percent impervious area).
- **Existing hydrologic studies:** This method uses existing studies or models of the watershed of interest, including Federal Emergency Management Agency (FEMA) flood insurance studies, smaller urban drainages, citywide or countywide drainage master plans, and calibrated HSPF models. Often these values are accurate because they were developed from an in-depth analysis. Flood report data can be derived from FEMA and other approved sources, including the State Hydraulics Office. Obtained data may be appropriate for culvert and bridge design.
- **Basin transfer of gage data with regional USGS equations:** When a project is located on an ungaged stream, but a stream is nearby with a substantial flow record, it is possible to extrapolate flows from one basin to the other, provided that certain criteria are met. The watersheds of the gaged and ungaged streams must have similar geology and soils, elevation range, vegetation, and canopy cover, and must be roughly the same size. The concept is simple (see Equation 2-1):

$$Q_{ungaged} = Q_{gaged}(A_{ungaged}/A_{gaged}) \qquad (2\text{-}1)$$

where:

Q = discharge
A = drainage area

USGS offers a spreadsheet called Flood Q Tools that includes the Flood Q Ratio Tool, which incorporates weighting of the ratio-based discharge. The weighting function uses the appropriate regional regression equation. Flood Q Tools can be found at the following link: FloodQtools.xlsm (live.com).

The Flood Q Ratio Tool puts bounds on the ungaged site—it must be within 50 percent of the area of the gaged basin and on the same stream. However, if no other tools are available, it may be used to estimate flows on a different stream, provided that all other parameters (basin size, soils, elevation, etc.) are similar. This tool also has the functionality of using the regression-based weighting of the Q derived from the area ratio. Additional inputs for this technique are mean annual precipitation and percent canopy cover (for Regions 1 and 2) in the ungaged basin.

Table 2-1 Methods for Estimating Runoff Rates and Volumes

Method	Assumptions	Data Needs
Rational	• Basins <200 acres • Time of concentration <1 hour • Storm duration less than or equal to concentration time • Rainfall uniformly distributed in time and space • Runoff is primarily overland flow • Negligible channel storage (such as detention ponds, channels with significant volume, and floodplain storage)	• Time of concentration (minutes) • Drainage area (acreage) • Runoff coefficient (C values) • Rainfall intensity (use m, n values to calculate inches/hour)
Santa Barbara Urban Hydrograph	• Rainfall uniformly distributed in time and space • Runoff is based on surface flow • Small to medium basins <1,000 acres • Urban type area (pavement usually suffices) • Regional storms (eastern Washington)[a] • Short-duration storm for stormwater conveyance • Long-duration storm for stormwater volume • Type 1A storm (western Washington)[a] (stormwater conveyance)	• Curve number (CN values) • Drainage area (acreage) • Digital precipitation values in the WSDOT GIS, National Oceanic and Atmospheric Administration Atlas, or (isopluvials) precipitation values
Continuous-simulation hydrologic model (western Washington)	• HSPF routine for stormwater BMPs for flow control facilities, such as detention and infiltration ponds, and water quality facilities, such as vegetated filter strips and bioswales • Elevations below 1,500 feet	• Drainage basin area (acreage) • Land cover (impervious, vegetation), soils (outwash, till, saturated) • Climatic region (mean annual precipitation)
Published flow record	• Basins with stream gage data • Appropriate station and/or generalized skew coefficient relationship applied	• 10 or more years of gaged flood records (contact the State Hydraulics Office for additional guidance)
USGS regional regression equations	• Appropriate for culvert and bridge design • Midsized and large basins • Simple but lack accuracy of flow records for basins with more than 5% total impervious area	• 2016 regional equations • Annual precipitation (inches) • Drainage area (square miles) • Area-weighted forest Canopy (percent)
Existing hydrologic studies	• Appropriate for culvert and bridge design • Midsized and large watersheds • Report accuracy varies so confirm level of accuracy with entity that the report derives from	• Available from FEMA or local flood administrative agency—typically the city or county (however, this method is not used for culverts or bridges unless verified)

Notes:
HSPF = Hydrological Simulation Program-Fortran.

a. The *Highway Runoff Manual* provides detailed guidance for design storms.

2-3 Drainage Basin

Drainage basins are the areas that contribute runoff to a point of interest such as catch basins, inlets, culverts, drainage ditches, and stormwater BMPs. These areas may include both on-site and off-site runoff and areas that extend outside of WSDOT ROW and beyond the project.

The size of the drainage basin is one of the most important parameters regardless of which method of hydrologic analysis is used.

2-4 Site Basins

To determine the basin area, use the StreamStats web application, quadrangle maps, or ArcMap/GIS Workbench. These tools cannot be used in urban areas and all subbasins should be delineated by variation in soil and drainage characteristics.

All basins shall be field-verified to the maximum extent feasible. Select the best available topographic map (GIS or other approved mapping software) or best available data that cover the entire area contributing surface runoff to the point of interest. In areas under urban influence, flow paths do not always follow topography because of the presence of streets, buildings, and enclosed drainage (catch basins/pipes). In most cases, drainage patterns and catchment areas cannot be deduced from an in-office terrain analysis. Field verification of how the impervious areas and pervious areas are connected or disconnected to the flow paths may be required.

2-5 Cold Climate Considerations

Snowmelt and rain on snow is a complicated process and can result in greater runoff rates. There are two parts to this section: Section 2-5.1 focuses on calculating the impacts of snowmelt and Section 2-5.2 provides additional considerations for PEOs when evaluating the impacts of snowmelt in a project location.

2-5.1 *Calculating Snowmelt*

When the project is listed as a mountainous route, per the WSDOT Highway Log, or is over an elevation of 1,500 feet, the project shall consider snowmelt impacts. The PEO shall apply the method described in this section and consult the RHE, the local Maintenance Office, the local PEO, and historical data. Then in the hydraulic report, the PEO shall describe in detail what value (if any) was determined to most accurately represent snowmelt at a project location.

The first question PEOs should consider is whether snowmelt effects will impact a project. In particular, PEOs should check the snow record to determine the maximum monthly average snow depths for the project location. Snow depths can be found at the following websites or by contacting the RHE or State Hydraulics Office:

- Washington Climate Summaries
- Washington Snow Map

The following equation uses a factor of 5, developed from the energy budget equation by the United States Army Corps of Engineers (USACE), and available snow for eastern Washington cities to convert depth to snow water equivalent. This amount shall be added to the 100-year, 24-hour precipitation value when designing for flood conditions for rain on snow or snowmelt. The equation below should be applied only when the average daily snow depth within the month at a project location meets or exceeds 2 inches:

(2-2)

$$Snow/Water\ equivalent = \frac{Average\ snow\ depth\ (maximum\ per\ month\ [inches/day])}{5}$$

The snow/water equivalent shall not be greater than 1.5 inches.

2-5.2 *Additional Considerations*

Regardless of snowmelt impacting a project site, PEOs should consider the following issues to provide adequate road drainage and prevent flood damage to downstream properties:

- **Roadside drainage:** During the design phase, consideration should be given to how roadside snow will accumulate and possibly block and erode inlets and other flow paths for water present during the thawing cycle. If it is determined that inlets could be blocked by the accumulation of plowed snow, consideration should be given to an alternate course of travel for runoff. This will help prevent the water ponding that sometimes occurs in certain areas because of snowmelt and rain not having an open area in which to drain off the roadway. This may require coordination with the WSDOT Maintenance Office.
- **Retention ponds:** When detention or retention ponds are located near the roadway, the emergency spillway should be located outside of any snow storage areas that could block overflow passage, or an alternative flow route should be designated. This may require coordination with the WSDOT Maintenance Office.
- **Frozen ground:** Frozen ground coupled with snowmelt or rain on snow can cause unusually adverse conditions. These combined runoff sources are generally reflected in the USGS regression equations and in the historical gage records. No corrections or adjustments need to be made to these hydrology methods for frozen ground or snowmelt. For smaller basins, the SBUH Method and Rational Method are used to determine peak volume and peak runoff rates. The curve number (CN) value for the SBUH Method and the runoff coefficient for the Rational Method do not need to be increased to account for frozen ground in snowy or frozen areas as consideration has been given to this in the normal precipitation amounts and in deriving the snowmelt equation.

2-6 Rational Method

This section presents a description of the Rational Method.

2-6.1 *General*

The Rational Method is used to predict peak flows for small drainage areas, which can be either natural or developed. The Rational Method can be used for culvert design, pavement drainage design, storm sewer design, and some eastern Washington stormwater facility design. The greatest accuracy is obtained for areas smaller than 100 acres and for developed conditions with large portions of impervious surface (pavement, roof tops, etc.).

Basins up to 200 acres may be evaluated using the rational formula (Equations 2-3 and 2-4); however, results for large basins often do not properly account for effects of infiltration and thus are less accurate. PEOs should never perform a Rational Method analysis on a mostly undeveloped basin that is larger than the lower limit specified for the USGS regression equations, because the USGS regression equations will yield a more accurate flow prediction for that size of basin. The formula for the Rational Method is as follows:

$$Q = \frac{CIA}{K_C} \tag{2-3}$$

where:

Q = runoff in cubic feet per second (cfs)

C = runoff coefficient in dimensionless units

I = rainfall intensity in inches per hour

A = drainage area in acres

Kc = conversion factor of 1 for English units

When several subareas within a drainage basin have different runoff coefficients, the rational formula can be modified as follows:

$$Q = \frac{I\Sigma CA}{K_C} \tag{2-4}$$

where:

$$\Sigma CA = C_1 x A_1 + C_2 x A_2 + \cdots + C_n x A_n$$

Hydrologic information calculated by the Rational Method shall be submitted as a calculation package within the hydraulic report using the spreadsheet found on WSDOT's hydraulics and hydrology webpage under tools, templates, and links or other similar forms approved by the State Hydraulics Office that best describe the project's hydraulic information.

This spreadsheet contains all the required input information and the resulting discharge.

The description of each area should be identified by name or station so the area may be easily located. A plan sheet or map showing the delineation of these areas shall be included with the hydraulic report along with the appropriate calculations.

2-6.2 *Runoff Coefficients*

The runoff coefficient “C” represents the percentage of rainfall that becomes runoff. The Rational Method implies that this ratio is fixed for a given drainage basin. In reality, the coefficient may vary with respect to prior wetting and seasonal conditions. The use of an average coefficient for various surface types is quite common, and it is assumed to stay constant through the duration of the rainstorm.

When considering frozen ground, PEOs should review Section 2-5.2, No. 3. In a high growth rate area, runoff factors should be projected that will be characteristic of developed conditions 20 years after project construction. Even though local stormwater practices (where they exist) may reduce potential increases in runoff, prudent engineering should still make allowances for predictable growth patterns.

The coefficients in Table 2-2 are applicable for peak storms of 10-year frequency. Less frequent, higher-intensity storms will require the use of higher coefficients because infiltration and other losses have a proportionally smaller effect on runoff. Generally, when designing for a 25-year frequency, the coefficient shall be increased by 10 percent; when designing for a 50-year frequency, the coefficient shall be increased by 20 percent; and when designing for a 100-year frequency, the coefficient shall be increased by 25 percent. The runoff coefficient shall not be increased above 0.95, unless approved by the RHE. Higher values may be appropriate for steeply sloped areas and/or longer return periods, because in these cases infiltration and other losses have a proportionally smaller effect on runoff.

Table 2-2 Runoff Coefficients for the Rational Method: 10-Year Return Frequency

Cover Type	Flat	Rolling (2%–10%)	Hilly (Over 10%)
Pavement and roofs	0.90	0.90	0.90
Earth shoulders	0.50	0.50	0.50
Drives and walks	0.75	0.80	0.85
Gravel pavement	0.50	0.55	0.60
City business areas	0.80	0.85	0.85
Suburban residential	0.25	0.35	0.40
Single-family residential	0.30	0.40	0.50
Multi units, detached	0.40	0.50	0.60
Multi units, attached	0.60	0.65	0.70
Lawns, very sandy soil	0.05	0.07	0.10
Lawns, sandy soil	0.10	0.15	0.20
Lawns, heavy soil	0.17	0.22	0.35
Grass shoulders	0.25	0.25	0.25
Side slopes, earth	0.60	0.60	0.60
Side slopes, turf	0.30	0.30	0.30
Median areas, turf	0.25	0.30	0.30
Cultivated land, clay, and loam	0.50	0.55	0.60
Cultivated land, sand, and gravel	0.25	0.30	0.35
Industrial areas, light	0.50	0.70	0.80
Industrial areas, heavy	0.60	0.80	0.90
Parks and cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland and forests	0.10	0.15	0.20
Meadows and pasture land	0.25	0.30	0.35
Pasture with frozen ground	0.40	0.45	0.50
Unimproved areas	0.10	0.20	0.30

2-6.3 *Time of Concentration*

Time of concentration (T_c) is defined as the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest in the watershed. Travel time (T_t) is the time water takes to travel from one location to another in a watershed. T_t is a component of T_c, which is computed by summing all the travel times for consecutive components of the drainage flow path. This concept assumes that rainfall is applied at a constant rate over a drainage basin, which would eventually produce a constant peak rate of runoff.

Actual precipitation does not fall at a constant rate. A precipitation event usually begins with less rainfall intensity, builds to peak intensity, and eventually tapers down to no rainfall. Because rainfall intensity is variable, the time of concentration is included in the Rational Method so that the PEO can determine the proper rainfall intensity to apply across the basin. The intensity that should be used for designing is the highest intensity that will occur with the entire basin contributing flow to the flow rate location being studied. This may be a much lower intensity than the maximum intensity because of it taking several minutes before the entire basin is contributing flow; the maximum intensity lasts for a much shorter time, so the rainfall intensity that creates the greatest runoff is less than the maximum by the time the entire basin is contributing flow.

Most drainage basins consist of different types of ground covers and conveyance systems that flow must navigate. These are referred to as flow segments. It is common for a basin to have overland and open-channel flow segments. Urban drainage basins often have flow segments that flow through a storm sewer pipe in addition to overland and open-channel flow segments. A travel time (the amount of time required for flow to move through a flow segment) must be computed for each flow segment. The time of concentration is equal to the sum of all the flow segment travel times.

For a few drainage areas, a unique situation occurs where the time of concentration that produces the largest amount of runoff is less than the time of concentration for the entire basin. This can occur when two or more subbasins have dramatically different types of cover (i.e., different runoff coefficients). The most common case would be a large, paved area together with a long, narrow strip of natural area. In this case, the PEO shall check the runoff produced by the paved area alone to determine if this scenario would cause a greater peak runoff rate than the peak runoff rate produced when both land segments are contributing flow based on a shorter time of concentration for the pavement-only area. The scenario that produces the greatest runoff shall be used, even if the entire basin is not contributing flow to this peak runoff rate.

The procedure for determining the time of concentration for overland flow, which was developed by the Natural Resources Conservation Service (NRCS, formerly known as the Soil Conservation Service [SCS]), is described below. It is sensitive to slope, type of ground cover, and channel size. If the total time of concentration is less than 5 minutes, a minimum of 5 minutes shall be used as the duration (see Section 2-6.4 for details). Table 2-3 lists ground cover coefficients.

The time of concentration can be calculated as in Equations 2-5 and 2-6:

$$T_1 = \frac{L}{K\sqrt{S}} = \frac{L^{1.5}}{K\sqrt{\Delta H}} \qquad (2\text{-}5)$$

$$T_C = T_{t1} + T_{t2} + \cdots + T_{tnz} \qquad (2\text{-}6)$$

where:

T_t = travel time of flow segment in minutes
T_c = time of concentration in minutes
L = length of segment in feet
ΔH = elevation change across segment in feet
K = ground cover coefficient in feet
S = slope of segment $\Delta H/L$ in feet per feet

Table 2-3 Ground Cover Coefficients

Type of Cover	Flow depth (inches)	K (feet)
Forest with heavy ground cover	--	150
Minimum tillage cultivation	--	280
Short pasture grass or lawn	--	420
Nearly bare ground	--	600
Small roadside ditch with grass	--	900
Paved area	--	1,200
Gutter flow	4	1,500
	6	2,400
	8	3,100
Storm sewers	12-inch diameter	3,000
	18-inch diameter	3,900
	24-inch diameter	4,700
Open-channel flow (n = 0.040) Narrow channel (w/d =1)	12	1,100
	24	1,800
	48	2,800
Open-channel flow (n = 0.040) wide Channel (w/d =9)	12	2,000
	24	3,100
	48	5,000

Notes:
-- = not applicable.
w/d = width/depth ratio.

2-6.4 *Rainfall Intensity*

After the appropriate storm frequency for the design has been determined (see Chapter 1) and the time of concentration has been calculated, the rainfall intensity can be calculated. Rainfall intensity is the average of the most intense period enveloped by the time of concentration and is not instantaneous rainfall. Rainfall intensity, duration, and frequency (IDF) curves can be used to estimate rainfall intensity. Regional IDF curves are available from the National Oceanic and Atmospheric Administration (NOAA). Curves for Washington State can be found on NOAA's Precipitation Frequency Data Server.

PEOs shall never use a time of concentration that is less than 5 minutes for intensity calculations, even when the calculated time of concentration is less than 5 minutes. The 5-minute limit is based on two ideas:

- Shorter times give unrealistic intensities. Many intensity-duration-frequency curves are constructed from curve-smoothing equations and not based on actual data collected at intervals shorter than 15 to 30 minutes. Making the curves shorter involves extrapolation, which is not reliable.
- Rainfall takes time to generate runoff within a defined basin, thus it would not be

realistic to have less than 5 minutes for a time of concentration.

Rainfall intensity is the average of the most intense period enveloped by the time of concentration and is not instantaneous rainfall. Equation 2-7 calculates rainfall intensity.

$$I = \frac{m}{(T_c)^n} \quad (2\text{-}7)$$

where:

I = rainfall intensity in inches per hour
T_c = time of concentration in minutes
m and n = coefficients in dimensionless units (Table 2-4)

The coefficients (m and n) have been determined for all major cities for the 2-, 5-, 10-, 25-, 50-, and 100-year MRI. The coefficients listed in Table 2-4 are accurate from 5-minute durations to 1,440-minute durations (24 hours).

The PEO, with RHE assistance, shall interpolate between the two or three nearest cities listed in Table 2-4 when working on a project in an unlisted location. Consult with the State Hydraulics Office if help is needed with interpolating which values to use.

Table 2-4 Inches to Rainfall Coefficients

Location	2-Year MRI		5-Year MRI		10-Year MRI		25-Year MRI		50-Year MRI		100-Year MRI	
	m	n	m	n	m	n	m	n	m	n	m	n
Aberdeen and Hoquiam	5.10	0.488	6.22	0.488	7.06	0.487	8.17	0.487	9.02	0.487	9.86	0.487
Bellingham	4.29	0.549	5.59	0.555	6.59	0.559	7.90	0.562	8.89	0.563	9.88	0.565
Bremerton	3.79	0.480	4.84	0.487	5.63	0.490	6.68	0.494	7.47	0.496	8.26	0.498
Centralia and Chehalis	3.63	0.506	4.85	0.518	5.76	0.524	7.00	0.530	7.92	0.533	8.86	0.537
Clarkston and Colfax	5.02	0.628	6.84	0.633	8.24	0.635	10.07	0.638	11.45	0.639	12.81	0.639
Colville	3.48	0.558	5.44	0.593	6.98	0.610	9.07	0.626	10.65	0.635	12.26	0.642
Ellensburg	2.89	0.590	5.18	0.631	7.00	0.649	9.43	0.664	11.30	0.672	13.18	0.678
Everett	3.69	0.556	5.20	0.570	6.31	0.575	7.83	0.582	8.96	0.585	10.07	0.586
Forks	4.19	0.410	5.12	0.412	5.84	0.413	6.76	0.414	7.47	0.415	8.18	0.416
Hoffstadt Cr. (SR 504)	3.96	0.448	5.21	0.462	6.16	0.469	7.44	0.476	8.41	0.480	9.38	0.484
Hoodsport	4.47	0.428	5.44	0.428	6.17	0.427	7.15	0.428	7.88	0.428	8.62	0.428
Kelso and Longview	4.25	0.507	5.50	0.515	6.45	0.509	7.74	0.524	8.70	0.526	9.67	0.529
Leavenworth	3.04	0.530	4.12	0.542	5.62	0.575	7.94	0.594	9.75	0.606	11.08	0.611
Metaline Falls	3.36	0.527	4.90	0.553	6.09	0.566	7.45	0.570	9.29	0.592	10.45	0.591
Moses Lake	2.61	0.583	5.05	0.634	6.99	0.655	9.58	0.671	11.61	0.681	13.63	0.688
Mt. Vernon	3.92	0.542	5.25	0.552	6.26	0.557	7.59	0.561	8.60	0.564	9.63	0.567
Naselle	4.57	0.432	5.67	0.441	6.14	0.432	7.47	0.443	8.05	0.440	8.91	0.436
Olympia	3.82	0.466	4.86	0.472	5.62	0.474	6.63	0.477	7.40	0.478	8.17	0.480
Omak	3.04	0.583	5.06	0.618	6.63	0.633	8.74	0.647	10.35	0.654	11.97	0.660
Pasco and Kennewick	2.89	0.590	5.18	0.631	7.00	0.649	9.43	0.664	11.30	0.672	13.18	0.678
Port Angeles	4.31	0.530	5.42	0.531	6.25	0.531	7.37	0.532	8.19	0.532	9.03	0.532
Poulsbo	3.83	0.506	4.98	0.513	5.85	0.516	7.00	0.519	7.86	0.521	8.74	0.523
Queets	4.26	0.422	5.18	0.423	5.87	0.423	6.79	0.423	7.48	0.423	8.18	0.424
Seattle	3.56	0.515	4.83	0.531	5.62	0.530	6.89	0.539	7.88	0.545	8.75	0.5454
Sequim	3.50	0.551	5.01	0.569	6.16	0.577	7.69	0.585	8.88	0.590	10.04	0.593
Snoqualmie Pass	3.61	0.417	4.81	0.435	6.56	0.459	7.72	0.459	8.78	0.461	10.21	0.476
Spokane	3.47	0.556	5.43	0.591	6.98	0.609	9.09	0.626	10.68	0.635	12.33	0.643
Stevens Pass	4.73	0.462	6.09	0.470	8.19	0.500	8.53	0.484	10.61	0.499	12.45	0.513
Tacoma	3.57	0.516	4.78	0.527	5.70	0.533	6.93	0.539	7.86	0.542	8.79	0.545
Vancouver	2.92	0.477	4.05	0.496	4.92	0.506	6.06	0.515	6.95	0.520	7.82	0.525
Walla Walla	3.33	0.569	5.54	0.609	7.30	0.627	9.67	0.645	11.45	0.653	13.28	0.660
Wenatchee	3.15	0.535	4.88	0.566	6.19	0.579	7.94	0.592	9.32	0.600	10.68	0.605
Yakima	3.86	0.608	5.86	0.633	7.37	0.644	9.40	0.654	10.93	0.659	12.47	0.663

2-7 Single-Event Hydrograph Method: Santa Barbara Urban Hydrograph

The SBUH Method is best suited for WSDOT projects where conveyance systems are being designed and for some stormwater treatment facilities in eastern Washington. The SBUH Method was developed to calculate flow occurring from surface runoff and is most accurate for drainage basins smaller than 100 acres, although it can be used for drainage basins up to 1,000 acres. The SBUH Method should not be used where groundwater flow can be a major contributor to the total flow. While not all WSDOT projects are in urban basins, paved surfaces (similar to urban areas) that generate the majority of the total flow may make use of SBUH applicable for highway projects.

An SBUH analysis requires the PEO to understand certain characteristics of the project site, such as drainage patterns, predicted rainfall, soil type, area to be covered with impervious surfaces, type of drainage conveyance, and—for eastern Washington—the flow-control BMPs that are to be provided. The physical characteristics of the site and the design storm determine the magnitude, volume, and duration of the runoff hydrograph. Other factors, such as the conveyance characteristics of channel or pipe, merging tributary flows, and type of BMPs, will alter the shape and magnitude of the hydrograph. The key elements of a single-event hydrograph analysis are listed below and described in more detail in this section:

- Design storm hyetograph
- Runoff parameters
- Hydrograph synthesis
- Hydrograph routing
- Hydrograph summation

Several commercially available computer programs include the SBUH Method. See Chapter 1.

2-7.1 *Design Storm Hyetograph*

The SBUH Method requires the input of a rainfall distribution or a design storm hyetograph. The design storm hyetograph is rainfall depth versus time for a given design storm frequency and duration. For this application, it is presented as a dimensionless table of unit rainfall depth (incremental rainfall depth for each time interval divided by the total rainfall depth) versus time. The type of design storm used depends on the project locations as noted below:

- **Eastern Washington:** For projects in eastern Washington, the design storms are usually the short-duration storm for conveyance design and the regional storm for volume-based stormwater facilities. (Design storms are discussed further in the *Highway Runoff Manual*.) However, occasionally with large basins and long concentration periods, the long duration regional (or Type 1A) storm will produce larger flow (Qs).

- **Western Washington:** For projects in western Washington, the design storm for conveyance is the Type 1A storm. For designs other than conveyance, see Section 2-8 for a description of the Continuous-Simulation Method.

Along with the design storm, precipitation depths are needed and shall be selected for the city nearest to the project site using PRISM data available from ArcGIS Workbench as the primary data source for the most accurate results from its interpolation methodology, followed by using an isopluvial map that clearly identifies the location within the map contours (see Figure 2-1).

2-7.2 *Runoff Parameters*

The SBUH Method requires input of parameters that describe physical drainage basin characteristics. These parameters provide the basis from which the runoff hydrograph is developed. This section describes the three key parameters (contributing drainage basin areas, runoff CN, and runoff time of concentration) that, when combined with the rainfall hyetograph in the SBUH Method, develop the runoff hydrograph.

The proper selection and delineation of the contributing drainage basin areas to the BMP or structure of interest is required in the hydrograph analysis. The contributing basin area(s) used should be relatively homogeneous in land use and soil type. If the entire contributing basin is similar in these aspects, the basin can be analyzed as a single area. If significant differences exist within a given contributing drainage basin, it must be divided into subbasin areas of similar land use and soil characteristics. Hydrographs should then be computed for each subbasin area and summed to form the total runoff hydrograph for the basin. Contributing drainage basins larger than 100 acres shall be divided into subbasins. By dividing large basins into smaller subbasins and then combining calculated flows, the timing aspect of the generated hydrograph can be made more accurate.

2-7.2.1 Curve Numbers

The NRCS has conducted studies into the runoff characteristics of various land types. The NRCS developed relationships between land use, soil type, vegetation cover, interception, infiltration, surface storage, and runoff. The relationships have been characterized by a single runoff coefficient called a curve number. CNs are chosen to depict average conditions—neither dry nor saturated. The PEO shall use the CNs listed in the *Highway Runoff Manual,* the NRCS website, or the GIS Workbench.

The factors that contribute to the CN value are known as the soil-cover complex. The soil-cover complexes have been assigned to one of four hydrologic soil groups according to their runoff characteristics. These soil groups are labeled Types A, B, C, and D, with Type A generating the least amount of runoff and Type D generating the most. The *Highway Runoff Manual* shows the hydrologic soil groups of most soils in Washington State. The different soil groups can be described as follows:

- **Type A:** Soils having high infiltration rates, even when thoroughly wetted, and consisting chiefly of deep, well drained to excessively drained sands or gravels. These soils have a high rate of water transmission.

- **Type B:** Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
- **Type C:** Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine textures. These soils have a slow rate of water transmission.
- **Type D:** Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a hardpan or clay layer at or near the surface, and shallow soils over bedrock or other nearly impervious material. These soils have a very slow rate of water transmission and comprise areas such as wetlands.

The HQ Materials Laboratory can also perform a soil analysis to determine the soil group for the project site. This should be done only if an NRCS soils map cannot be located for the county in which the site is located, the available SCS map does not characterize the soils at the site (many NRCS maps show “urban land” in highway ROWs and other heavily urbanized areas where the soil properties are uncertain), or there is reason to doubt the accuracy of the information on the NRCS map for the particular site.

When performing an SBUH analysis for a basin, it is common to encounter more than one soil type. If the soil types are similar (within 20 CN points), a weighted average can be used. If the soil types are significantly different, the basin should be separated into smaller subbasins (previously described for different land uses). Pervious ground cover and impervious ground cover should always be analyzed separately. If the computer program StormShed3D is used for the analysis, pervious and impervious land segments will automatically be separated, but the PEO will have to combine and manually weigh similar pervious soil types for a basin.

2-7.2.2 Antecedent Moisture Condition

The moisture condition in a soil at the onset of a storm event, referred to as the antecedent moisture condition (AMC), has a significant effect on both the volume and rate of runoff.

Recognizing this, the SCS developed three AMCs as described below:

- **AMC I:** soils are dry but not to the wilting point
- **AMC II:** average conditions
- **AMC III:** heavy rainfall, or light rainfall and low temperatures, has occurred within the last 5 days, and soil is near saturated or saturated

Table 2-5 gives seasonal rainfall limits for the three AMCs. These derive from the amount of rainfall in any 5 days.

Table 2-5 Total Five-Day Antecedent Rainfall

Antecedent Moisture Condition	Dormant Season (inches)	Growing Season (inches)
I	Less than 0.5	Less than 1.4
II	0.5–1.1	1.4–2.1
III	Over 1.1	Over 2.1

The CN values generally listed are for AMC II; if the AMC falls into either group I or III, the CN value will need to be modified to represent project site conditions. The H*ighway Runoff Manual* provides further information regarding when the AMC should be considered and conversions for the CN for different AMCs for the case of Ia = 0.2S. For other conversions, see the *National Engineering Handbook* (NRCS 2010).

2-7.2.3 Time of Concentration

Time of concentration (T_c) is defined as the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest in the watershed. Travel time (T_t) is the time water takes to travel from one location to another in a watershed. T_t is a component of T_c, which is computed by summing all the travel times for consecutive components of the drainage flow path. While this section starts the same as Section 2-6.3, the analysis described in this section is more detailed because water traveling through a basin is classified by flow type.

The different flow types include sheet flow; shallow, concentrated flow; open-channel flow; or some combination of these. Classifying flow type is best determined by field inspection and using the parameters described below:

- **Sheet flow** is flow over plane surfaces. It usually occurs in the headwater areas of streams and for short distances on evenly graded slopes. With sheet flow, the friction value (n_s, which is a modified Manning's roughness coefficient) is used. These n_s values are for shallow flow depths up to about 0.1 foot and are used only for travel lengths up to 150 feet on impervious surfaces without curb and 100 feet on pervious surfaces. The *Highway Runoff Manual* provides the Manning's n values for sheet flow at various surface conditions.

  For sheet flow of up to 100 feet, use Manning's kinematic solution (Equation 2-8) to directly compute T_t:

  $$T_t = (0.42\,(n_s L)0.8)/((P2)0.527(S_o)0.4) \qquad (2\text{-}8)$$

  where:

  T_t = travel time (minutes)
  n_s = sheet flow Manning's coefficient
  (dimensionless) L = flow length (feet)
  P2 = 2-year, 24-hour rainfall (inches)
  S_o = slope of hydraulic grade line (land slope, feet vertical/1 foot horizontal [ft/ft])

- **Shallow flow:** After the maximum sheet flow length, sheet flow is assumed to become shallow concentrated flow. The average velocity for this flow can be calculated using the k_s values from the *Highway Runoff Manual*. Average velocity is a function of watercourse slope and type of channel. After computing the average velocity using the velocity equation (Equation 2-9), the travel time (T_t) for the shallow concentrated flow segment can be computed by dividing the length of the segment by the average velocity.

- **Open channels** are assumed to begin where surveyed cross-section information has been obtained, where channels are visible on aerial photographs, or where lines indicate that streams appear on USGS quadrangle maps. For developed drainage systems, the travel time of flow in a pipe is also represented as an open channel. The k_c values from the *Highway Runoff Manual* used in the velocity equation can be used to estimate average flow velocity. Average flow velocity is usually determined for bankfull conditions. After average velocity is computed, the travel time (T_t) for the channel segment can be computed by dividing the length of the channel segment by the average velocity.

  A commonly used method of computing average velocity of flow, once it has measurable depth, is the following velocity equation:

$$V = (k)(S_o 0.5) \qquad (2\text{-}9)$$

where:

V = velocity (feet per second [ft/s])
k = time of concentration velocity
factor (ft/s) S_o = slope of flow path
(ft/ft)

Regardless of how water moves through a watershed, when estimating travel time (T_t), the following limitations apply:

  - Manning's kinematic solution should not be used for sheet flow longer than 300 feet.
  - The equations given here to calculate velocity were developed by empirical means; therefore, English units (such as inches) must be used for all input variables for the equation to yield a correct answer. Once the velocity is calculated, it can be converted to metric units to finish the travel time calculations in the case of shallow concentrated flow and channel flow.

The *Highway Runoff Manual* shows suggested n and k values for various land covers to be used in travel time calculations. Stormshed3G will calculate time of concentration with inputs of slope and the appropriate coefficient. For small basins, a minimum time of concentration of 5 minutes shall be entered. Additional guidance will be provided in future revisions to the *Hydraulics Manual*.

2-8 Continuous-Simulation Hydrologic Model (Western Washington Only)

When designing stormwater facilities in western Washington, the PEO must use an Ecology-approved continuous-simulation hydrologic model to meet the requirements of the most current version of the *Highway Runoff Manual*. A continuous-simulation hydrologic model captures the back-to-back effects of storm events that are more common in western Washington. These events are associated with high volumes of flow from sequential winter storms rather than high peak flow from short-duration events, as is characteristic in eastern Washington.

WSDOT uses MGSFlood (see *Highway Runoff Manual*), which uses the HSPF routines for computing runoff from rainfall on pervious and impervious land areas. In addition, MGSFlood has the BMP design criteria built into the software and will help the sizing of the stormwater facility to meet the *Highway Runoff Manual*–required runoff treatment and flow control flow rates and volumes. WSDOT also uses MGSFlood to estimate seasonal flows for temporary stream diversion designs.

MGSFlood does have limitations that the PEO should understand before using the program, regarding the project location, conveyance design, and basin size. MGSFlood is for projects in western Washington with elevations below 1,500 feet. The program does not include routines for simulating the accumulation and melting of snow, and its use should be limited to areas where snowmelt is not usually a major contributor to floods or to the annual runoff volume. MGSFlood is not used for conveyance design but is capable for conveyance design when a small time step, such as 5 or 15 minutes, is used. For projects located in western Washington that fall outside the modeling guidelines described in this paragraph, contact the RHE or State Hydraulics Office staff for assistance.

2-8.1 *Modeling Requirements*

MGSFlood should be used once the PEO has selected the BMP(s) for the project site and has determined the input values for precipitation, delineated drainage basin areas, and soil characteristics. Each of these input values is further described in the sections below.

2-8.1.1 Precipitation Input

Two methods for transposing precipitation time series are available in the continuous-simulation model: extended precipitation time series selection and precipitation station selection. The PEO will generally select the extended precipitation time series unless it is not available for a project site; then the precipitation station is selected. Both methods are further described below:

Extended precipitation time series selection: Uses a family of prescaled precipitation and evaporation time series (). These time series were developed by combining and scaling precipitation records from widely separated stations, resulting in record lengths in excess of 100 years. Extended hourly precipitation and evaporation time series have been developed using this method for most of the lowland areas of western Washington where WSDOT projects are constructed. These time series should be used for stormwater facility design for project sites.

Precipitation station selection: For project sites located outside the extended time series region, a second precipitation scaling method is used (). A source gage is selected, and a single scaling factor is applied to transpose the hourly record from the source gage to the site of interest (target site). The current approach for single-factor scaling, as recommended in Ecology's *Stormwater Management Manual for Western Washington* (Ecology 2019), is to compute the scaling factor as the ratio of the 25-year, 24-hour precipitation for the target and source sites. Contact the RHE or State Hydraulics Office staff if assistance is needed in selecting the appropriate gage.

Figure 2-1 Extended Precipitation Time Series Regions

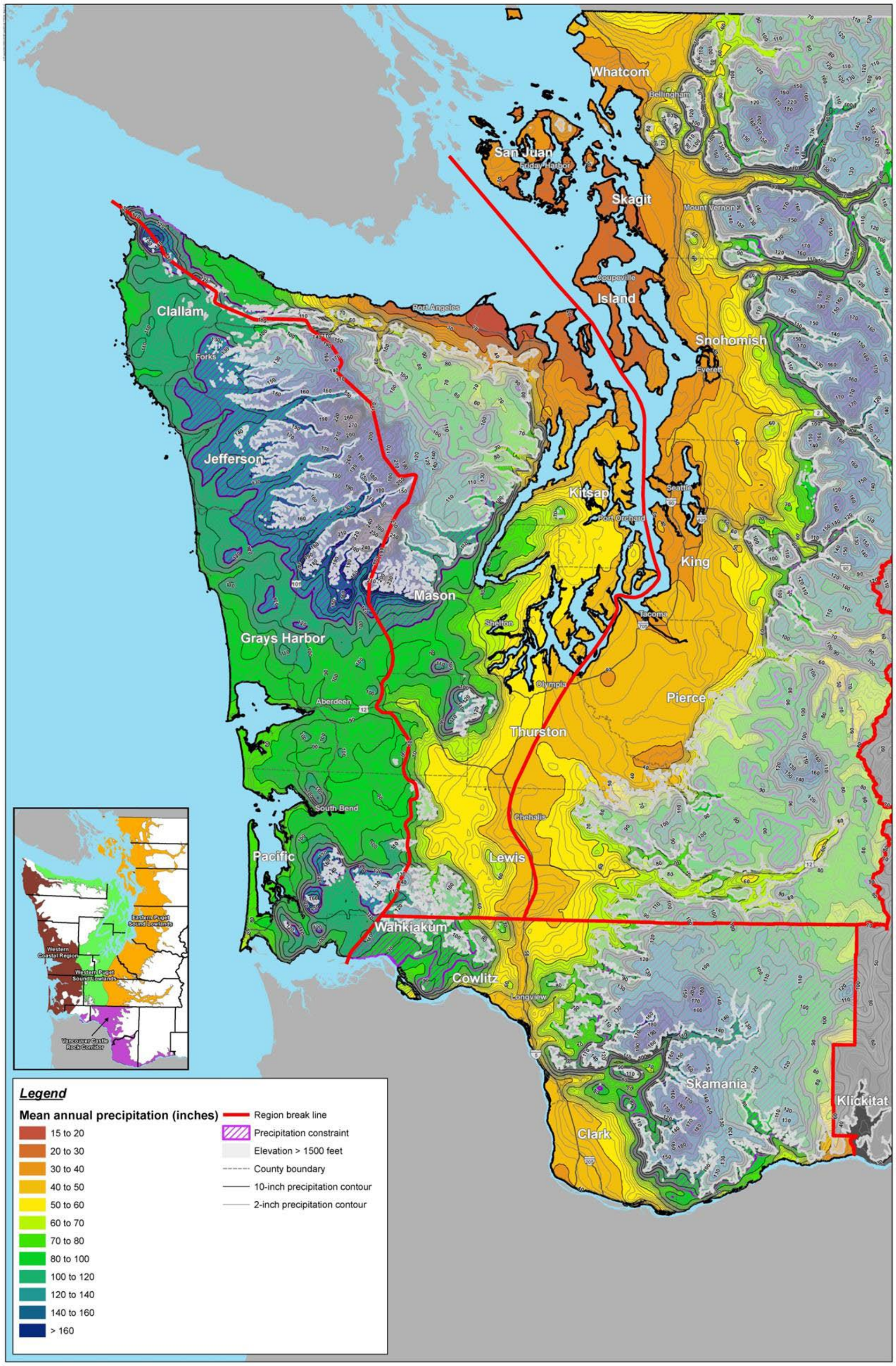
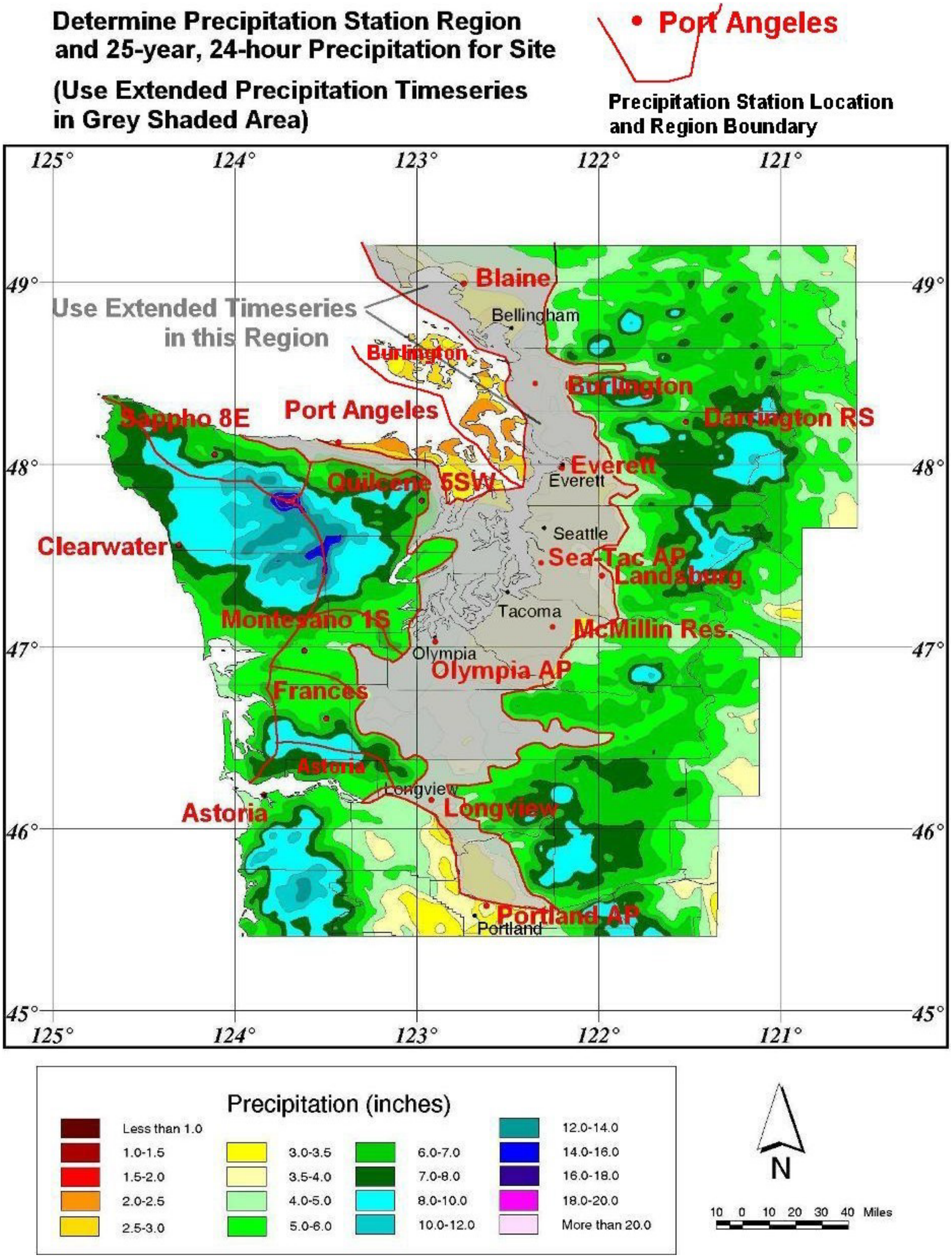


Figure 2-2 Precipitation Station Selection outside Extended Precipitation Time Series Regions



2-8.1.2 Hydrologic Soil Groups

For each basin, land cover is defined in units of acres for predeveloped and developed conditions. Soils must be classified into one of three categories for use in MGSFlood: till, outwash, or saturated soil (as defined by USGS). Mapping of soil types by NRCS is the most common source of soil/geologic information used in hydrologic analyses for stormwater facility design. Each soil type defined by NRCS has been classified into one of four hydrologic soil groups: A, B, C, or D. In western Washington, the soil groups used in MGSFlood generally correspond to the NRCS hydrologic soil groups shown in Table 2-6.

Table 2-6 Relationship between NRCS Hydrologic Soil Group and MGSFlood Soil Group

NRCS Group	MGSFlood Group
A	Outwash
B	Till or outwash
C	Till
D	Saturated

Note:
NRCS = Natural Resources Conservation Service.

NRCS Type B soils can be classified as either glacial till or outwash, depending on the type of soil under consideration. Type B soils underlain by glacial till or bedrock, or that have a seasonally high water table, are classified as till. Conversely, well-drained Type B soils should be classified as outwash. It is important to work with the HQ Materials Laboratory or a licensed geotechnical engineer to confirm that the soil properties and near-surface hydrogeology of the site are well understood, as they are significant factors in the final modeling results. The *Highway Runoff Manual* contains some soils classification information for preliminary work.

Wetland soils remain saturated throughout much of the year. The hydrologic response from wetlands is variable, depending on the underlying geology, the proximity of the wetland to the regional groundwater table, and the geometry of the wetland. Generally, wetlands provide some base flow to streams in the summer months and attenuate storm flows via temporary storage and slow release in the winter. Special design consideration must be given when including wetlands in continuous-simulation runoff modeling.

2-9 Published Flow Records

When available, published flow records provide the most accurate data for designing culverts and bridge openings. This is because the values are based on actual measured flows and not calculated flows. The stream flows are measured at a gaging site for several years. A statistical analysis, using the USGS Regression Peak FQ, is then performed on the measured flows to predict the recurrence intervals.

USGS, Ecology, local and state municipalities, and several utility companies work together to maintain gaging sites throughout Washington State. Flood discharges for these gaging sites, at selected exceedance probabilities (based on historical data up to

2014), can be found in the following websites:

- StreamStats
- https://pubs.er.usgs.gov/publication/sir20165118
- Freshwater DataStream data map

2-10 USGS Regression Equations

While measured flows provide the best data for design purposes, it is not practical to gage all rivers and streams in the state. USGS has developed a set of equations to calculate flows for drainage basins in the absence of a stream flow gage. The equations were developed by performing a regression analysis on stream flow gage records to determine which drainage basin parameters are most influential in determining peak runoff rates.

Estimates of the magnitude and frequency of flood-peak discharges and flood hydrographs are used for a variety of purposes, such as the design of bridges, culverts, and flood-control structures, and for the management and regulation of floodplains.

The equations divide the state into four hydrologic regions, as shown on the map in Figure 2-2. The various hydrologic regions require different input variables, depending on the hydrologic region. Input parameters that may be required include total area of the drainage basin and percentage of the drainage basin that is in forest cover. The PEO can determine these variables through use of site maps, aerial photographs, and site inspections.

The PEO must be aware of the limitations of these equations. They were developed for natural rural basins. The equations can be used in urban ungaged areas with additional backup data (i.e., comparing results to the nearest gage data for calibration and sensitivity analysis, field inspection of high-water lines, and information from local maintenance). PEOs should contact the RHE for further guidance. Also, any river that has a dam and reservoir in it should not be analyzed with these equations. Finally, the PEO must keep in mind that, because of the simple nature of these equations and the broad range of each hydrologic region, the results of the equations contain a wide confidence interval, represented as the standard error.

The standard error is a statistical representation of the accuracy of the equations. Each equation is based on many rivers and the result represents the mean of all the flow values for the given set of basin characteristics. The standard error shows how far out one standard deviation is for the flow that was just calculated. For a bell-shaped curve in statistical analysis, 68 percent of all the samples are contained within the limits set by one standard deviation above the mean value and one standard deviation below the mean value. It can also be viewed as indicating that 50 percent of all the samples are equal to or less than the flow calculated with the equation and 84 percent of all samples are equal to or less than one standard deviation above the flow just calculated.

The PEOs shall use the mean value determined from the regression equations with no standard error or confidence interval. The PEO shall validate the calculated flow rate based on collected field data and site conditions. If the flows are too low or too high for that basin based on information that the PEO has collected, then the PEO may apply the standard error specific to the regression equation accordingly. The PEO should consult the RHE for assistance.

StreamStats is another USGS tool that not only estimates peak flows but also can delineate the basin area and determine the mean annual precipitation as well as other basin characteristics.

2-11 Existing Hydrologic Studies

Existing hydrologic studies have been developed for many rivers in Washington State. FEMA has developed most of these reports. USACE and local agencies have developed other reports.

Many small and medium streams within urbanizing areas have had some modeling by local government. These can be useful and appropriate to adopt for WSDOT use, following examination of model assumptions and drainage basin delineation.

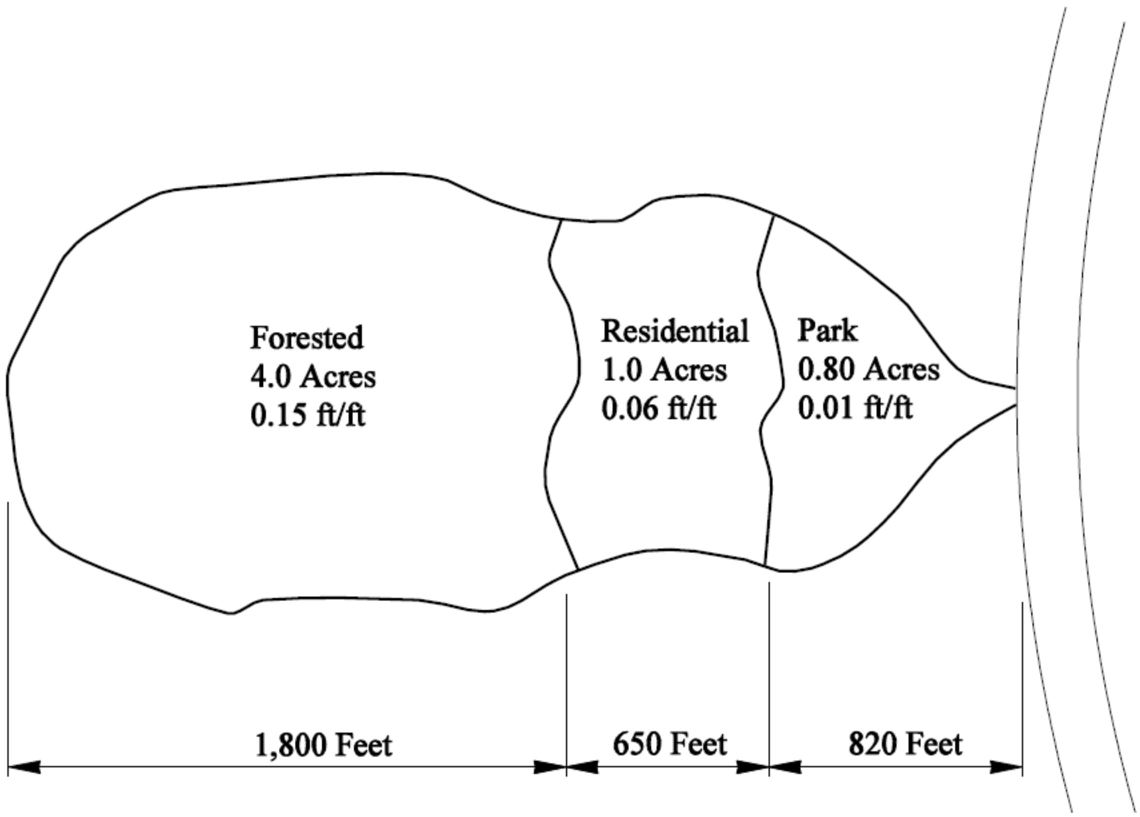
These reports are a good source of flow information because they were developed to analyze the flows during flooding conditions of a particular river or stream. The types of calculations used by the agency conducting the analysis are more complex than the Rational Method or USGS regression equations and are therefore more accurate. The increased time required to perform these complex calculations is not justified for the structure that WSDOT is designing; however, if the analysis has already been performed by another agency, then it is in WSDOT's best interest to use this information.

FEMA reports and USACE existing hydrologic studies are available on the FEMA map service center website. The State Hydraulics Office should be contacted for local agency reports. The State Hydraulics Office may also have basin planning documents or action plans that could contain flow rate information. These studies should be used with caution as they may have been developed for a different purpose and therefore may not be transferable/applicable for the design of transportation infrastructure.

2-12 Examples

Compute the 25-year runoff for the Spokane watershed shown in Figure 2-3. Three types of flow conditions exist from the highest point in the watershed to the outlet. The upper portion is 4.0 acres of forest cover with an average slope of 0.15 foot vertical per 1 foot horizontal (ft/ft). The middle portion is 1.0 acre of single-family residential with a slope of 0.06 ft/ft and primarily lawns. The lower portion is a 0.8-acre park with 18-inch-diameter storm sewers with a general slope of 0.01 ft/ft.

Figure 2-3 Rational Formula Example



$$T_c = \Sigma \frac{L}{K\sqrt{S}} = \frac{1800}{150\sqrt{0.15}} + \frac{650}{420\sqrt{0.06}} + \frac{820}{3900\sqrt{0.01}}$$

$$T_c = 31\,min + 6\,min + 2\text{ min} = 39min$$

$$I = \frac{m}{(T_c)^n} = \frac{9.09}{(39)^{0.626}} = 0.93\ ^{in}/_{hr}$$

$$\Sigma\text{CA} = 0.22(4.0\,acres) + 0.44(1.0\,acre) + 0.11(0.8\,acre) = 1.4\text{ acres}$$

$$Q = \frac{I(\Sigma CA)}{K_c} = \frac{(0.93)(1.4)}{1} = 1.31\,cfs$$

2-13 Appendices

Appendix 2A	Isopluvial and MAP Web Links and Mean Annual Precipitation Data
Appendix 2B	USGS Regression Equation Zone Map

Appendix 2A Isopluvial and MAP Web Links and Mean Annual Precipitation Data

The 24-hour and 2-hour isopluvial maps and mean annual precipitation maps for Washington are available in PDF format on WSDOT's hydraulics and hydrology webpage under tools, templates, and links or by using GIS Workbench. Contact your local GIS group for how to extract digital precipitation data using ArcMap.

Appendix 2B USGS Regression Equation Zone Map