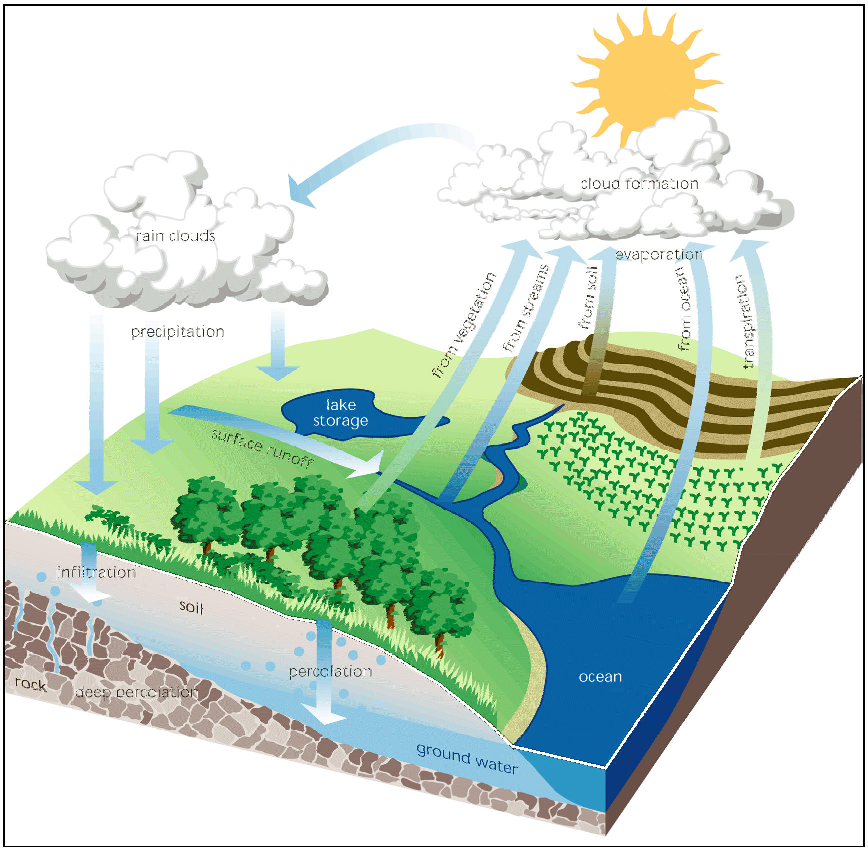
HYDROLOGY APPENDIX

The purpose of this appendix is to provide some understanding of the background and methods used in hydrologic analysis for stream restoration projects. It is intended to both inform the reader of important considerations for project design and direct further study to pertinent sources. It is not a substitute for research and detailed understanding of hydrologic processes in a particular project area. The reader should seek the advice and analysis of an experienced hydrologist or hydrogeologist for the development and review of project plans prior to site work.

References for sources and citations are listed at the end of the appendix.

1 HYDROLOGY

Hydrology is the science of water in motion. It includes the occurrence, movement, and storage of water in the atmosphere, on the land, and in the sea. The occurrence and movement of water is characterized in the hydrologic cycle shown below.



Hydrology Figure 1: Hydrologic cycle.

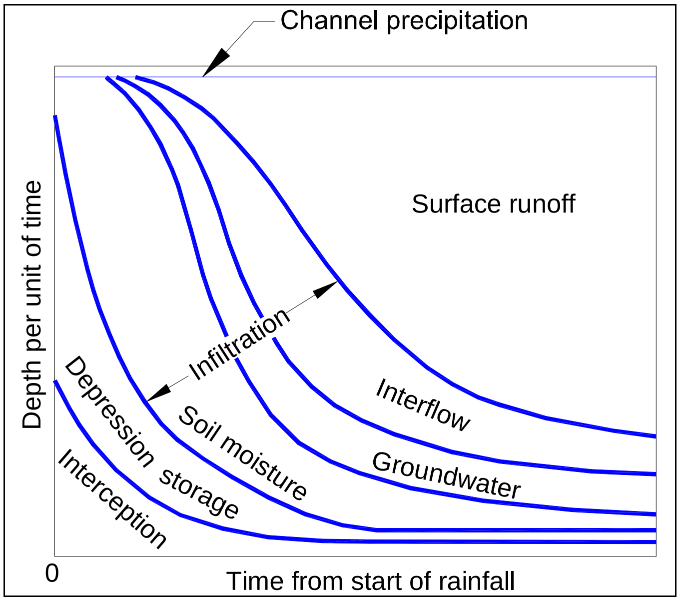
Source: Federal Interagency Stream Restoration Working Group. 1998. Stream Corridor Restoration: Principles, Processes, and Practices” [1]

The hydrologist studies processes and factors that influence the supply, movement, and forms of water in the landscape. Hydrologic studies include climate, geology, geomorphology, vegetation, and land use in varying scales of space and time. The science of hydrology also includes measurement of quantities and rates of movement of water, compilation of quantitative data, and studies to determine the principles and laws of the occurrence, movement, and work of water[2]. Hydrologic measurement requires accurate observations of nature while hydrologic study bases its conclusions on these observations.

"Understanding how water flows into and through stream corridors is critical to restoration. How fast, how much, how deep, how often, and when water flows are important questions that must be answered to make appropriate decisions about stream corridor restoration".

1.1 Runoff

Runoff is precipitation that appears in surface streams. When the rate of rainfall or snowmelt exceeds the rate of soil infiltration, water collects in small depressions until the excess moves downslope as overland flow, as shown below. Water that infiltrates the soil moves downgradient as subsurface flow. This movement may be quick (flashy) in saturated soils on steeper slopes or slow (delayed) in deeper soils and flatter terrain.

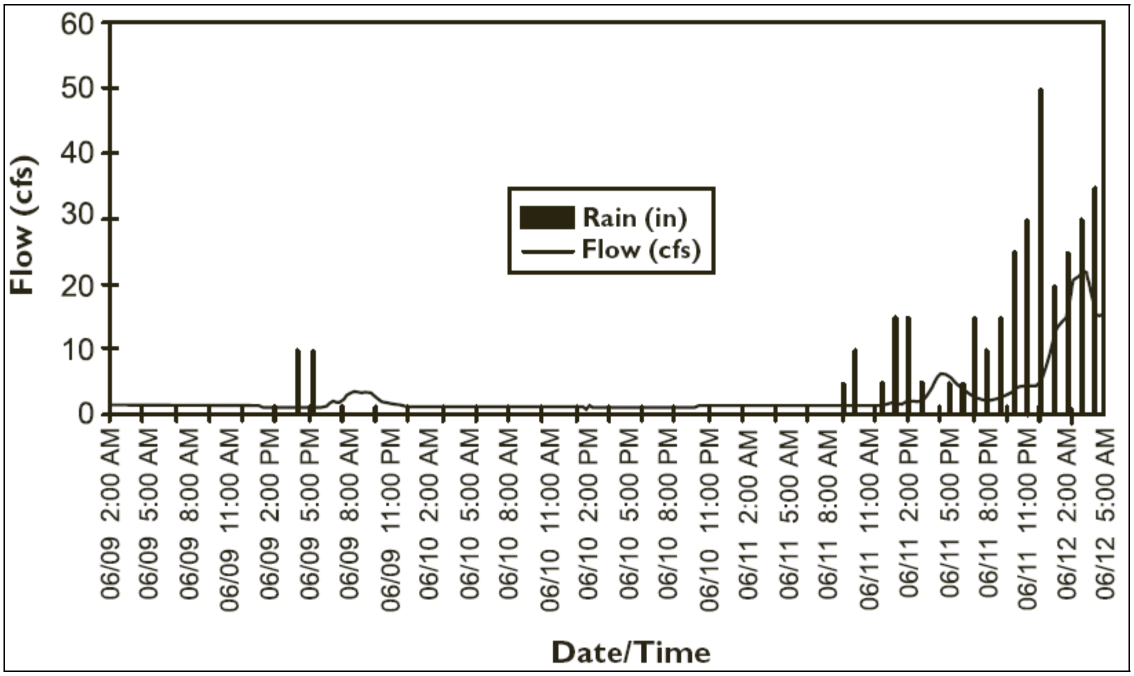


Hydrology Figure 2: Disposition of rainfall to runoff.
Source: Linsley R. K., Kohler M. A., and Paulhus J. L. H. 1975. Hydrology for Engineers.[3]

Water flowing in a stream represents the culmination of one or more runoff processes which transport water from different locations in the watershed by surface and subsurface pathways. Sources of runoff are generally precipitation (rain, fog, or snow) although significant amounts of water may be delivered from outside a watershed by inter-basin transfer for municipal water supply and irrigation. A portion of precipitation is removed by evaporation from open water, soil, and other watershed surfaces, transpiration from plants, recharge to deep groundwater aquifers, and diversion for use outside of the watershed. Water is stored in ponds, lakes, reservoirs, floodplains, and wetlands as well as below ground in soil and aquifers. Stored water may drain to a stream or be lost by processes described above.

Runoff may occur as overland flow, interflow (subsurface stormflow), or baseflow depending on watershed slope, roughness, and absorptive capacity. ***Overland flow*** spreads over a wide surface or slope before it is concentrated or confined to a channel. It occurs when the ability of the watershed surface to absorb water (***infiltration***) is exceeded by the intensity of the water input. Overland flow is commonly associated with soils having either moderate to high silt or clay content or impervious surface in urbanized areas. ***Interflow*** infiltrates the soil and is quickly transported to a stream channel. Interflow may begin shortly after the start of a storm and subside after precipitation ends. It forms the bulk of storm runoff in areas having moderate to steep slopes and highly permeable soils.

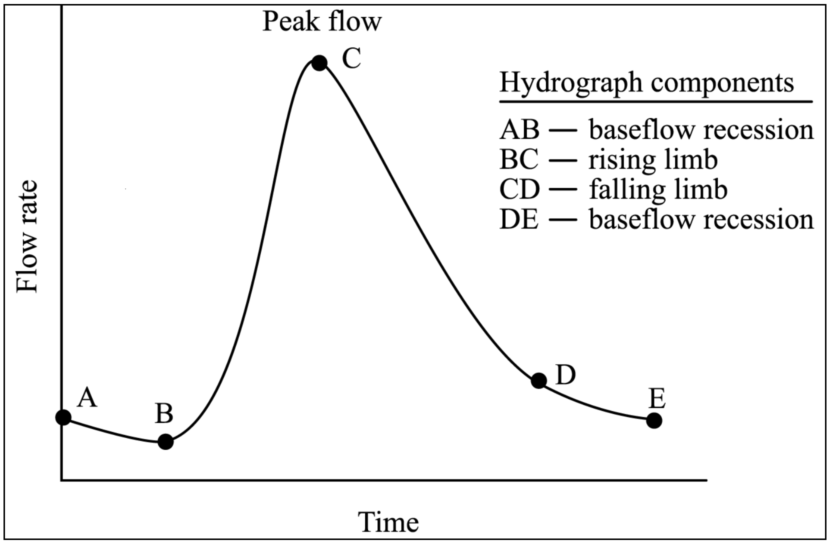
A storm ***hydrograph*** may depict runoff from rainfall in addition to baseflow, as shown below. The ***time-to-peak*** (time of rise) is from the middle of the rainstorm (when half the rainfall which contributes to runoff has fallen) to peak flow. It is an indicator of how rapidly runoff is delivered to that location. The shape of a hydrograph reflects variable rates of inflow, outflow, and changes in storage. A "narrow" storm hydrograph with a short time-to-peak indicates rapid runoff due to overland flow and limited surface storage. A "broad" storm hydrograph, with a longer time-to-peak, reflects a large storage capacity with possibly large areas of wetlands and floodplains.



Hydrology Figure 3: Storm hydrograph.

Source: Dunne, T. and L. B. Leopold. 1978. Water in Environmental Planning.[4]

Specific components of a storm hydrograph are shown below. The curve AB is a period of declining baseflow, or groundwater discharge, before the storm. Curve BC is the "rising limb" of the hydrograph showing direct runoff from the storm. At some point near or after the end of rainfall, ***peak flow*** is attained after which stream flow decreases (curve CD, the "recession limb”), returning to baseflow (curve DE).



Hydrology Figure 4: Specific components of a storm hydrograph.

Source: Chow, V. T., D. R. Maidment and L. W. Mays. 1988. Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering. [5]

1.1.1 Hydrologic Response

The magnitude, duration, and timing of runoff, the distribution of runoff among different pathways, and amount of storage can determine a watershed’s hydrologic response. Factors that alter runoff can change the hydrologic response and may occur naturally (soil formation, beaver activity), or from human activity (diking, urbanization), or as a result of both (fire, or climate change).

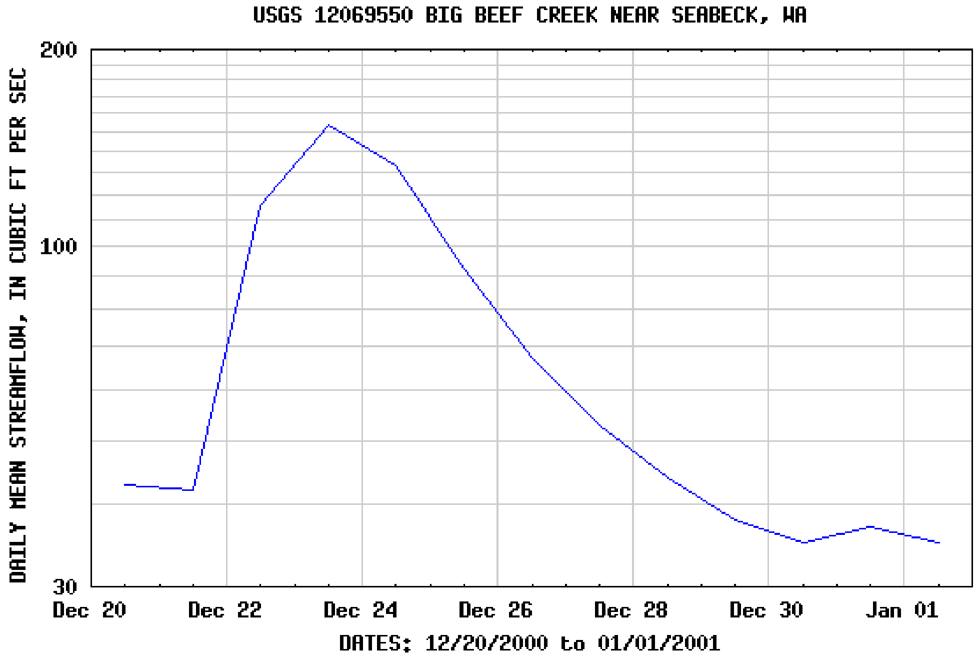
Structural projects in rivers and streams, including dams, diversions for irrigation and municipal/industrial water supply, transportation works, and flood control projects can significantly alter the conveyance element of hydrologic response. Changing land use, particularly urbanization, can alter runoff pathways and reduce watershed storage with potentially severe changes to a watershed’s hydrologic response. Isolation of a stream channel from its floodplain by diking and channelization (1) reduces natural flood storage capacity while (2) eliminating access to highly productive aquatic and riparian habitats. Aquatic habitat restoration projects are often designed to restore watershed storage capacity by removing impervious surfaces, restoring wetlands, replanting forested areas, removing levees, or adding structural complexity to stream channels and overbank areas.

1.2 Stream Flow

Streams may be ephemeral, intermittent, or perennial. Ephemeral steams flow mainly during storms and may or may not have a defined channel. Intermittent streams flow most of the year in most years and usually have a defined channel. Perennial streams flow all year in most years. Some perennial streams have sustained baseflow composed largely of groundwater discharge with additional storm runoff or snowmelt at various times of the year.

Water is in motion and it is natural that water levels go up and down. A change in water levels reflects a change in flow. Stream discharge is calculated by measuring flow through an area of channel. Changing water levels and stream discharge are plotted over a period time as hydrographs. Hydrographs typically depict annual, seasonal, or single storm periods but may depict other periods as well.

An annual hydrograph of discharge for a water year is shown below**.** Annual hydrographs are useful for establishing the seasonal variability and relative magnitude of stream flow over a year and can indicate the dominant sources of stream flow.



Hydrology Figure 5: Annual hydrograph.

Source: USGS. Water Resources of Washington.[6]

1.2.1 Gaining and Losing Reaches

Baseflows typically increase downstream due to accumulating groundwater discharge from shallow aquifers. This is known as a ***gaining*** (or *influent)* ***stream*** and is common in Washington. Baseflows may decrease downstream in a ***losing*** (or *effluent*) ***stream,*** as surface flow is lost to groundwater. Losing streams are common in arid climates where water tables are relatively deep below the ground surface.

Streams may have losing reaches alternating with gaining reaches as depth to the water table fluctuates with seasonal precipitation, groundwater withdrawal, or artificial recharge. Individual reaches can gain through the winter and springtime, lose through the summer and early fall, and "transition" between seasons. Channel boundaries between gaining, losing, and transition reaches may shift throughout the year.

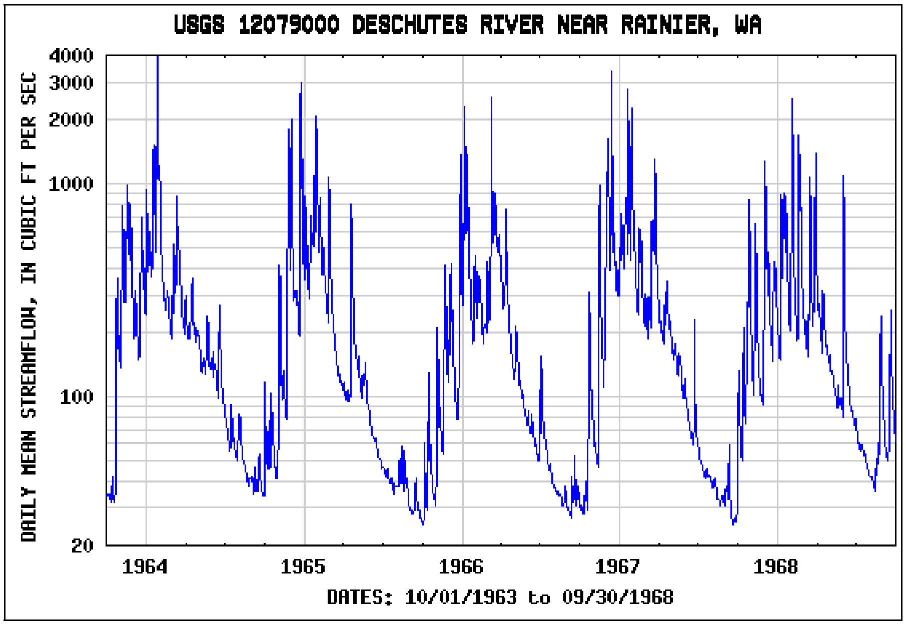
1.2.2 Hyporheic Flows

A ***hyporheic zone*** is defined as "saturated interstitial areas beneath the stream bed and into stream banks that contain some proportion of channel water or that have been altered by channel water infiltration"[7]. The extent of this zone may fluctuate daily, seasonally, and annually. Surface-water/groundwater interactions within the hyporheic zone provide ecologically vital physical, chemical, and biological functions. Bolton and Shellburg (2001)[8] list the following habitat functions provided by the hyporheic zone:

- Water storage and retention
- Stream temperature regulation
- Physical habitat for hyporheic organisms including: invertebrates, spawning incubation, and fishes
- Refugia for hyporheic organisms
- Nutrient retention and transformation
- Controlling ecosystem metabolism
- Promoting aquatic and riparian habitat diversity

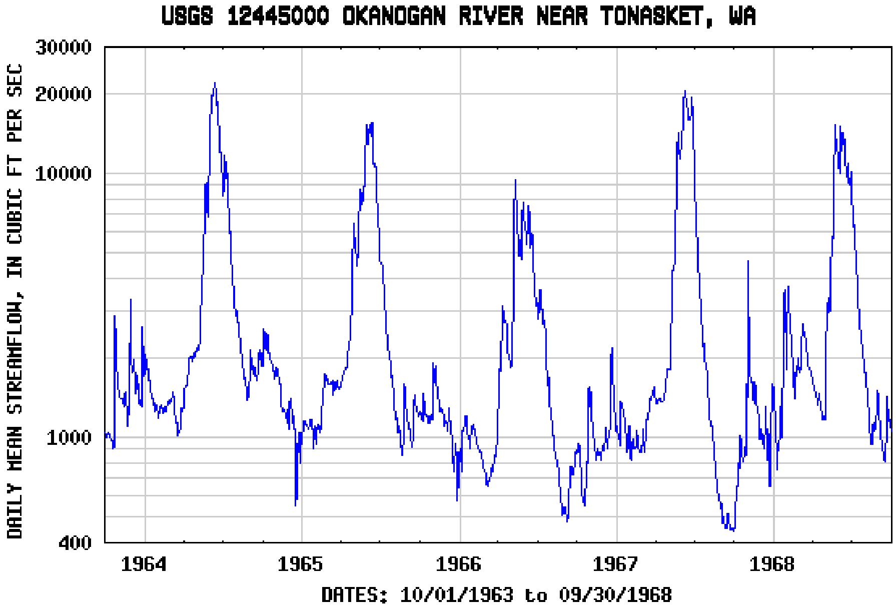
1.3 Hydrographs

Rain-dominated or rain-on-snow stream flow events (where rain and snowmelt simultaneously contribute to stream flow) appear on annual hydrographs as "spikes" extending over one-to-three days as shown below. These events are typical in western Washington streams.



Hydrology Figure 6: Rain-dominant hydrograph, 1964-1968. Deschutes River. Source: USGS. Water Resources of Washington. [6]

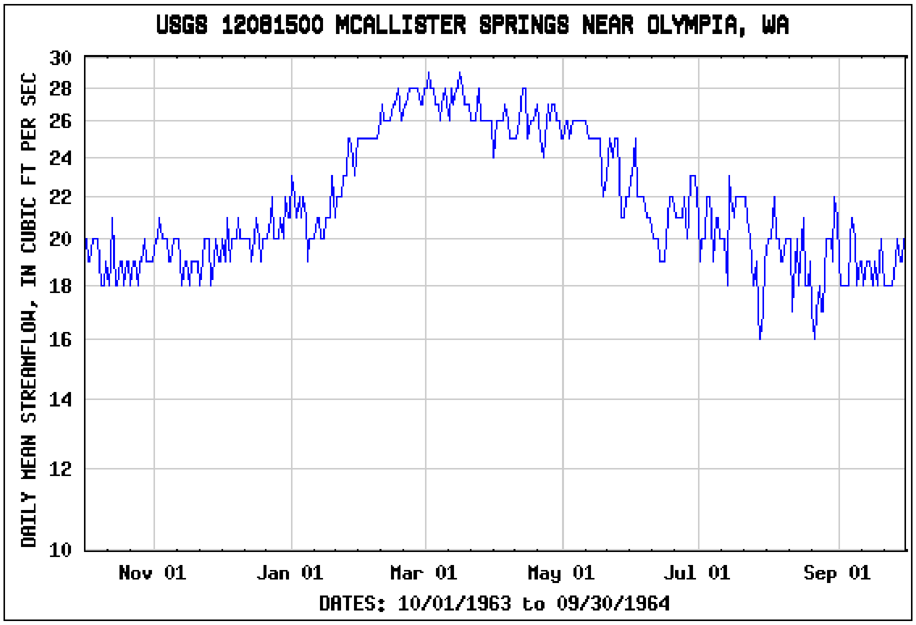
Stream flow from melting deep, high-elevation snowpacks typically creates a broader, smoother curve extending over weeks or months as shown below. This type of event is common in streams draining the east slope of the Cascades and the west slope of the Rocky Mountains in eastern Washington.



Hydrology Figure 7: Snowmelt-dominant hydrograph, 1964-1968. Okanogan River.

Source: USGS. Water Resources of Washington.

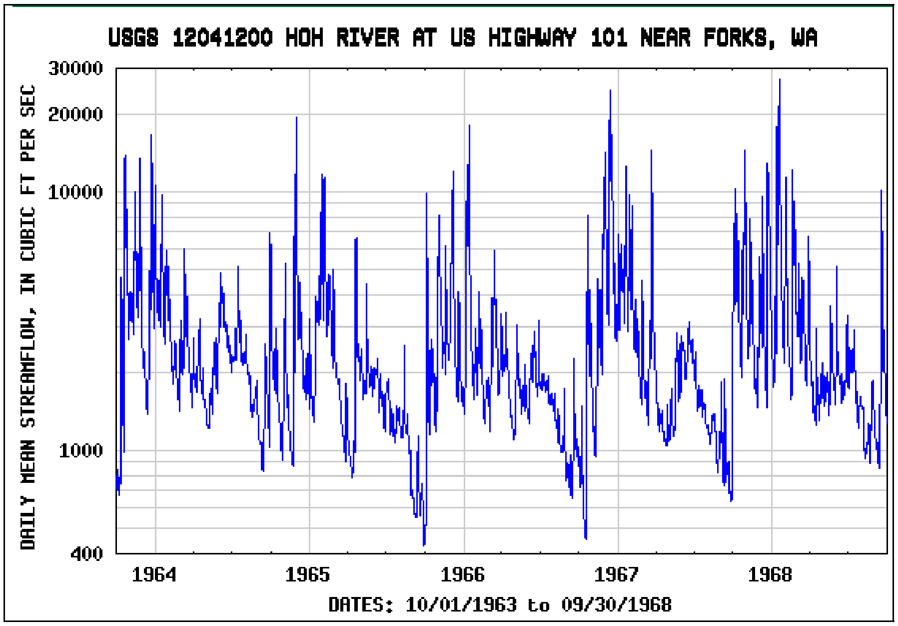
A stream that originates primarily from groundwater will have a moderated hydrograph indicative of sustained base flow, as shown below. Groundwater discharge may rise and fall in response to seasonal precipitation patterns.



Hydrology Figure 8: Groundwater-dominant hydrograph, 1964-1968. McAllister Springs.

Source: USGS. Water Resources of Washington.[6]

Stream flow influenced by glacial melt may still rise and fall daily during the summer months, as shown below.

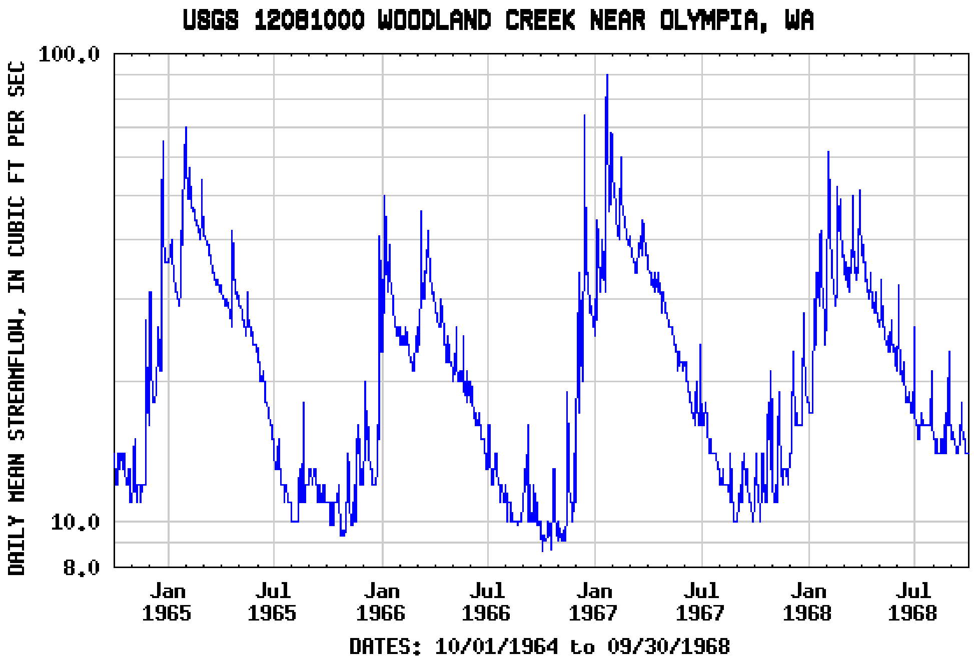


Hydrology Figure 9: Rainfall-dominant with glacial melt hydrograph, 1964-1968. Hoh River. Source: USGS. Water Resources of Washington. [6]

1.4 Hydrologic Regimes

1.4.1 Natural Hydrologic Regimes

A hydrologic regime is the sequence or pattern of low flows and high flows in a hydrograph. Hydrologic regimes are combinations of flow events (such as low flows, moderate high flows, and flood flows) and when they occur (fall rains, spring snowmelt) for annual hydrographs described in Section 1.3, *Hydrographs*. The magnitude, duration, frequency, and sequencing of variable flows can influence the physical and biological characteristics of a stream in several ways. Larger (flood) flows deliver energy and materials that create and maintain a channel's geometric form. Lower flows define the physical limits of aquatic and riparian habitats and are an important factor in a stream's ability to moderate heat and pollutant inputs. The hydrologic regime of a stream is a key element in planning, design, and evaluation of stream habitat restoration and stream bank protection projects. Note the pattern of summer low flows, moderate spring and fall high flows, and winter flood flows in the rainfall dominant hydrologic regime shown below.



Hydrology Figure 10: Natural hydrologic regime. 1964-1968. Woodland Creek.
Source: USGS. Water Resources of Washington.

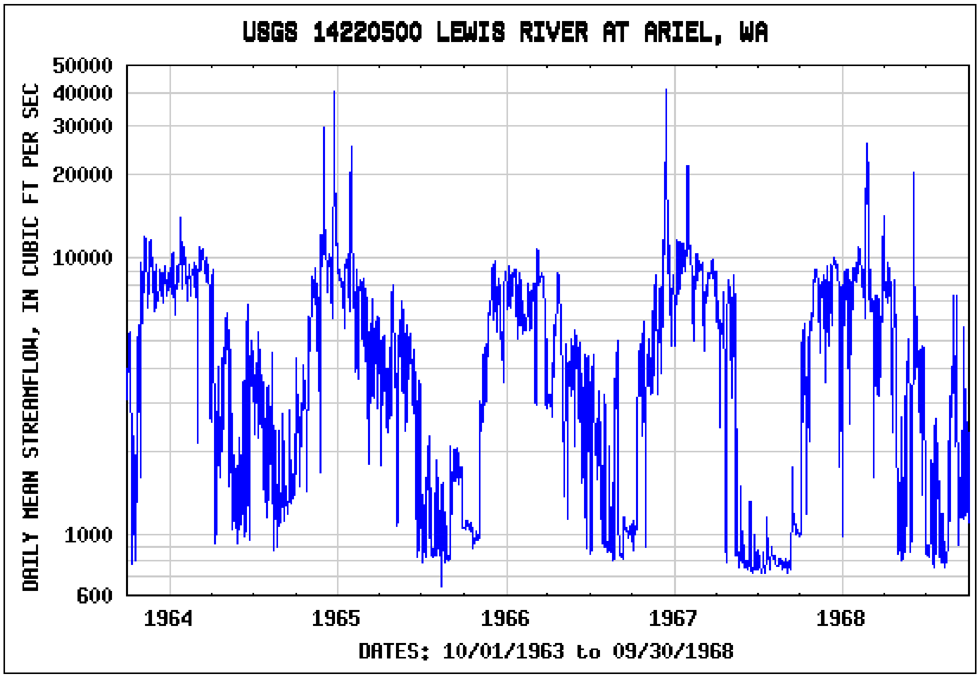
1.4.2 Regulated Hydrologic Regimes

Few major drainages in Washington are free of human influence. Many streams are affected by flow regulation that impounds, diverts, augments or modifies the natural flow. It is necessary to account for human-induced changes to a hydrologic regime when examining a hydrologic record in a regulated stream, Separating differences in the flow regime from pre-dam to post-dam conditions is necessary to plan and anticipate future conditions. Alteration of flow regimes during urbanization should also be evaluated for project assessments in urban areas.

Dams are built and operated for many uses, including hydroelectric power generation, storage for agricultural, industrial, and municipal use, flood control, and recreation. Regardless of the purpose of the dam, the effects of dams on a hydrologic regime can be dramatic. Some dams store large quantities of water and reduce stream flow during periods of high runoff. When stored water is released and used within a basin, flows may increase downstream due to return flows from water users.

Storing storm runoff reduces downstream peak flows. This effect is most pronounced for smaller to medium flood events and tends to diminish with larger events. The cyclic rise and fall of flow associated with storage and releases of water can affect channel morphology by altering erosion, deposition, and sediment transport. It can impact the presence, distribution, and survival of aquatic biota and riparian vegetation. In some cases, juvenile fish in the stream during summer low flows may be stranded or washed downstream by sudden flow releases.
Dams for hydroelectric power generation produce a highly variable hydrograph over short periods of time (a few hours to a few days) due to the release of stored water to meet demands

for electricity, as shown below. Once the demand is met, spring and summer flows are rapidly reduced which can strand fish and other aquatic organisms in the channel.



Hydrology Figure 11: Hydropower regulated hydrologic regime, 1964 – 1968. Lewis River.
Source: USGS. Water Resources of Washington.

Agricultural diversions typically reduce stream flow and aquatic habitat during the irrigation season. Annual flow is generally decreased due to both increased evaporation from reservoir and soil surfaces and transpiration from crops. Peak water demand normally coincides with the summer low-flow period, creating conflicts between aquatic resources and agricultural requirements. In the extreme, streams can be completely dewatered during summer. Stream temperature problems are exacerbated by reduced flows, especially where groundwater pumping and loss of stream/floodplain connectivity has reduced or eliminated groundwater contribution to surface flows.

Municipal and industrial diversions do not usually exhibit the seasonal variability typical of irrigation diversions. Municipal uses are more year-round but may peak in the summer months due to extensive lawn and landscape watering. During a drought or in the driest months of the year, diversions may dewater a stream without in-stream flow requirements.

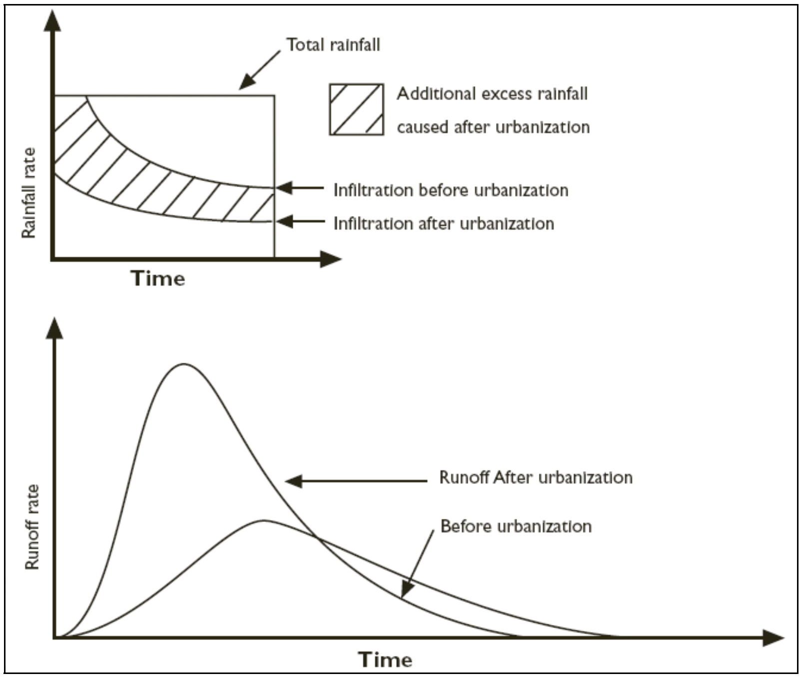
Flow augmentation is often practiced where the demand for water exceeds the natural supply. Augmentations take water from one drainage basin and divert it to another basin through tunnels, aqueducts, or open ditches. The discharge is usually to a natural stream channel or directly into a reservoir. Flow augmentations occur during spring and early summer runoff when water is abundant and reservoirs are filling. A watershed can show a dramatic increase in the magnitude, duration and frequency of flows if it is being augmented.

Channelization and construction of dikes, levees and other flood control works protect human infrastructure (roads, buildings, utilities, etc.) when a river or stream inundates its floodplain. Channelization is “the deliberate alteration of one or more of the interdependent hydraulic variables of channel slope, width, depth, roughness, or size of sediment load”. It typically includes such activities as channel widening, deepening, straightening, bank stabilization, and removal of live and dead vegetation from the channel and banks. Channelization may reduce the frequency and duration of overbank flooding through the channelized reach by increasing flow velocities through a straightened and shortened reach (as a result of increased slope) and by increasing the capacity of the main channel.

This effect is often obtained at the expense of non-channnelized areas downstream. These areas tend to experience increased magnitude and frequency of flooding due to more rapid delivery of flow and reduced flood storage. Channelization and levee construction often cause increased channel erosion, excessive deposition of bedload, and loss of channel capacity.

1.4.3 Urbanization

Urbanization of a watershed can have a profound impact on hydrographs as shown below.



Hydrology Figure 12: Conceptual hydrograph changes due to urbanization.
Source: Source: Chow, V. T., D. R. Maidment and L. W. Mays. 1988. Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering.[5]

Increased area of impervious surface is a common cause of increased peak flow and reduced base flow. Impervious surfaces such as paved streets, parking lots, and roofs, can decrease soil infiltration, increase storm runoff and decrease groundwater recharge. As runoff in urban channels increases, the duration of high flows decreases because groundwater is no longer a major contributor to flow. New channels, curbs, gutters, and storm sewers create smoother conveyance and increase hydraulic efficiency of the drainage system. Runoff can reach the channel more quickly when it travels over smooth, hard surfaces and the lag time between rainfall and runoff is decreased. Increased peak flows result in more hydraulic force acting on a stream channel and increased bed and bank erosion. Storm flows may be captured in one watershed and released in a nearby watershed, changing watershed boundaries and runoff hydrographs. Storm flows captured in detention facilities and gradually released can reduce magnitude and increase lag time of peak flows in urban channels. Flow duration increases over that found in rural drainages and base flow may not be restored.

2 HYDROLOGIC ANALYSIS

Quantifying stream flow and evaluating frequency and duration of flows are two types of hydrologic analyses relevant to instream projects. Project designs are typically based on specific flow criteria such as low flows, dominant discharge, or flood flows. A number of methods can be used to quantify flow depending on available data and site information. These include direct measurements, estimates using Manning’s equation, regional regression analysis, hydraulic models, and runoff simulation models.

Frequency analysis is a method of interpreting records of hydrologic events to determine future probabilities of occurrence. It is often the basis for planning and designing aquatic habitat and streambank protection projects. The method may be direct or indirect and depends on available data. For example, peak flow data may be used directly if a project has a record of flood measurements. In other cases, data from neighboring stations can be regionalized and applied at a non-gaged site.

2.1 Stream flow measurements

Historic stream flow measurements at a gage can be used for hydrologic analysis if the period of record is long enough to be statistically significant or if any portion of the period of record is relevant. Gage data are usually reported as mean daily flows. Instantaneous peak flows rather than mean daily flows are used for deriving peak flow statistics if the project is an urbanized or suburbanized basin, or on a first- or second-order stream. Only a short period of record is usually relevant in an urban environment because rapid development and changing hydrologic conditions tends to make historic data obsolete. Segmenting data to represent existing or future conditions may be necessary but also may leave only a small amount of data to work with.

The United States Geological Survey (USGS) provides flow measurements for hydrologic analyses. USGS gaging stations are found on major drainages and can be important sources of flow data and information. Instantaneous maximum and minimum daily flow values are also reported for some gages. Historic records may be the only flow measurements available for a particular river where gaging stations are no longer in operation. Flow measurements for gaging stations are available from the USGS website. The USGS office may also help obtain more recent or historic data. State and local agencies, federal agencies (e.g., U.S. Forest Service, U.S. Fish and Wildlife Service, Bureau of Land Management, and Bureau of Reclamation), municipal water suppliers, and power companies are other sources of hydrologic data.

2.2 Stream flow estimates

Stream flow can be estimated for ungaged streams by using the following methods:

1. *Manning's equation*. Manning's equation is commonly used to calculate flow in a channel using channel geometry and other characteristics. The application of Manning's equation is detailed in the *Hydraulics* appendix.

2. *Regional Regression Analysis.* Regional regression equations relate discharge to channel dimensions and watershed characteristics. Where gage data are insufficient, hydrologic parameters can be derived through analysis of precipitation events using data from other stations in the region. Regional analysis for non-gaged sites works well for flood-frequency correlated with meteorological or physiographic parameters. Floods at non-gaged sites can then be estimated from rainfall and size of the basin. This method assumes similar meteorological and physiographic conditions for a region and flood-frequency curves of approximately the same slope. Regional regression equations are available from the USGS and common regression variables include basin area, mean basin elevation, and average annual rainfall.

3. *Hydraulic models.* Hydraulic models calculate flow in a channel using input parameters and equations discussed in the *Hydraulics* appendix. Most hydraulic models are based on Manning's equation and require many of the same input values. Field measurements of discharge, based on channel dimensions and the Manning's equation, can be used to calibrate hydraulic models.

4. *Runoff and Stream flow Simulation Models.* Runoff and stream flow simulation models predict streamflow based on simulated runoff from storm events and other inputs. They are useful where there are no established streamflow gauges. They are most relevant in urbanized watersheds with hydrologic alteration due to impervious areas, flood control, and storm flow detention.

2.3 Stream Flow Calculations

2.3.1 Flow Frequency

Floods occur when stream flows exceed the capacity of the channel and overtop the channel banks. Incised channels often have significantly more capacity than natural channels and may contain the high flows. Aggraded channels have flood flows at greater frequency than non-aggraded channels. A 10-year, 50-year, and 100-year return period flow is often used in streambank protection designs. A 100-year flow channel design is often used for protection of infrastructure or public safety. Channel design projects may not be permitted if they increase the water surface elevation of the 100-year flood.

Flood flows may be reported as annual maximum flows with a return interval of a certain number of years (for example 10-, 20-, or 100-years). The probability of occurrence in any year is the inverse of the return interval. For example, the probability of occurrence of the 100-year flood in any year is 1/100 = 0.01 = 1%. The *annual maximum series* consists of maximum annual flood events. A *partial-duration series* consists of all peaks of record greater than some base magnitude during the year. The recurrence interval for a partial-duration series is based on the frequency of occurrence of floods of a given size. It is the occurrence of flows that equal or exceed a given discharge[9]. A partial-duration series or annual maximum series may be used for greater than the 10-year event.

Log Pearson Type 3 analysis is the federal standard for determining flood frequency. A complete discussion and reference for performing Log Pearson Type 3 analyses is available in Water Resources Bulletin 17B. Precipitation events of a certain probability do not necessarily result in stream flow of the same probability. A 10-year rainstorm may not produce a 10-year stream flow.

2.3.2 Flow Duration

Flow duration is the length of time a flow occurs. Flow-duration statistics based on frequency of occurrence are useful for projects that include habitat objectives for a specified life stage for target species. Flow-duration statistics require gage data for a specific season for which the design is relevant although USGS-derived flow-duration statistics are not generally season specific. Flow-duration statistics should be based on daily-flow data collected during fish spawning if a design objective is to sustain sufficient flows for fish spawning, Further information regarding derivation of flow-duration statistics is available in Dunne and Leopold.

2.3.3 Low Flows

Low flows typically reflect base flow conditions. An active low flow channel with sustained base flows may have distinct geomorphic features such as riffles and pools. The water level in a low-flow channel is important for revegetation or habitat projects. The survival and passage of fish and other aquatic species may depend on the depth and velocity of low flows. Survival of riparian plant communities and deep-rooted species is essential to habitat restoration and bank protection. Vegetation planted at the proper bank elevation can use soil moisture maintained during the growing season by base flows in the low-flow channel.

2.3.4 Dominant Discharge

This discussion of dominant discharge, effective discharge, and bankfull discharge is provided for informational purposes. Use of these geomorphic measurements is not recommended without careful study of their applicability on particular streams. Dominant discharge and related approximations are frequently uncertain distinctions on dynamic, alluvial-bedded streams of the Pacific Northwest.

Dominant discharge is defined as flow that produces the greatest morphologic effect over an extended period of time. It would control the shape and function of the channel in equilibrium (i.e., during periods the channel is not recovering from large floods or other severe disturbances) but it is frequently more concept than quantifiable value. Three methods commonly used to approximate dominant discharge are effective discharge, bankfull discharge, and return-period discharge. Each has limitations as to appropriate applications. Dominant discharge could be used for design of channel dimensions including cross-section, slope, and planform when a project goal is to mimic natural channel conditions although safety and property protection may require consideration of a larger design flow.

2.3.4.1 Effective discharge

Effective discharge is believed to transport the most bed load over time and is commonly viewed as a reasonable approximation of dominant discharge[10] [11]. Effective discharge is quantified with a channel sediment budget and flow duration analysis. A sediment budget can be complex, difficult, and expensive to develop and may be inappropriate for many projects. Flow duration refers to the time stream flows exceed a threshold value capable of moving various sediment sizes as determined through sediment transport analyses. Flow duration analysis requires gaged flow records of daily mean flows in non-urban channels or instantaneous discharges in urbanized channels. A detailed methodology for calculation of effective discharge is provided in Biedenharn et al (2000).

2.3.4.2 Bankfull discharge

"Bankfull stage" is the water level at which a stream overflows the floodplain. It is defined as the elevation of a stream channel that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels"[12]. It is hard to determine floodplain and channel boundaries in streams with numerous side channels and indistinct banks. Incised channels also do not have bank heights that relate to "bankfull" discharges[13] and where bankfull flow may significantly exceed dominant discharge. Guidelines for identifying bankfull indicators are provided in Dunne and Leopold (1978). A discussion of bankfull discharge and its relation to channel geometry in the Pacific Northwest is also provided in Castro and Jackson (2001).

Bankfull discharge can be approximated in some cases by using Manning's equation and field measurements of channel cross-section as detailed in the *Hydraulics* appendix. Measurement of channel width is discussed in detail in the <u>Design of Road Culverts for Fish Passage</u>[14] guideline. It is important to consider that channel geometry represents current hydrologic and geologic conditions. Prolonged dry periods with low peak flows tend to narrow channels as vegetation progressively colonizes and stabilizes the bed and banks. Measuring channel geometry under these conditions would indicate a much smaller cross-section than would be found under a wetter regime. Catastrophic floods and debris flows change equilibrium channels and may also obscure historical geometry[15].

2.3.5 Return-Interval discharge

Discharge with a given return interval may approximate dominant discharge when effective discharge cannot be calculated or when bankfull discharge is inappropriate due to an unstable channel or altered watershed. Recurrence intervals of 1.5 years or 2 years are commonly applied[16] . Studies have found some consistency between dominant discharge, bankfull discharge, and the 1- to 2-year recurrence interval discharge[9] [12]. More recent work focusing on the Pacific Northwest indicates that average bankfull discharges have recurrence interval ranges from 1.2 to 1.5 years (with standard deviation of 0.5) depending on ecoregion. When data are stratified by ecoregion, humid areas of western Oregon and Washington have a mean value of 1.2 years, while dryer areas of Idaho and eastern Oregon and Washington have a mean value of 1.4 to 1.5 years. Recurrence interval discharges can be calculated using gauge data or regional regression analysis on non-gauged steams[17] [18].

2.3.6 Ordinary High Water Line

"Ordinary high water line" (OHWL) is defined in state law as "the mark on the shores of all waters that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual and so long continued in ordinary years, as to mark upon the soil or vegetation a character distinct from that of the abutting upland". It is a legal definition that does not always serve design needs well. The distance between ordinary high water marks on the bank is considered to be the ordinary high water width. It is similar to active channel width. A calculated discharge below OHWL can be used to approximate dominant discharge using Manning's equation and field measurement of channel cross-sections as detailed in the *Hydraulics* appendix.

2.4 Stream Flow Models

2.4.1 Single-Event Runoff Models

Most stormwater and flood models are single-event runoff models. They model direct runoff by simulating rainfall events for certain conditions of precipitation intensity, infiltration rate, time of concentration, and time of travel, without antecedent soil-moisture conditions. These models are usually used for determining peak discharge on small, urbanized watersheds with assumed uniform basin characteristics.

Examples of single-event runoff models include:

- The US Army Corps of Engineers, HEC-1 model[19],
- The US Natural Resources Soil Conservation Service, Project Formulation-Hydrology model (Technical Release No. 20)[20]; and
- The US Natural Resources Soil Conservation Service, Urban Hydrology for Small Watersheds (Technical Release No. 55)

HEC-1 develops a series of interconnected sub-basins with hydrologic and hydraulic components of surface runoff, a stream channel, or a reservoir. HEC-1 calculates discharge but stage can be indirectly calculated from additional user input. The result of the model is a hydrograph at a specified location.

NRCS Technical Release 20 (TR-20) provides analysis of flood events. TR-20 was formulated to develop runoff hydrographs; route hydrographs through both channel reaches and reservoirs, and combine or separate hydrographs at confluences. This model is applied to watersheds with peak flows from thunderstorms or high-intensity, short-duration rainfall.

NRCS Technical Release 55 (TR-55) presents simplified procedures to calculate storm runoff volume, peak discharge, hydrographs, and storage volumes for floodwater reservoirs. These procedures are applicable in small urbanizing watersheds. The program provides peak runoff computations using a Graphical Peak Discharge Method, Tabular Peak Discharge Method, and Temporary Storage.

2.4.2 Continuous-Flow Simulation Models

Continuous-flow simulation models account for changes in stream flow resulting from changes in flow inputs. They are valuable for estimating discharges from a series of precipitation events, particularly in urban environments, and for determining frequency and probability of discharge resulting from various precipitation events.

1. The U. S. Environmental Protection Agency, Storm Water Management Model (SWMM)[21] can simulate precipitation and transport of water and pollutants through pipe and channel networks, storage treatment units, and receiving waters. It simulates both single event and continuous flows in storm sewers and natural drainage. It is used for prediction of flow, stage, and pollutant concentration.

2. The Hydrological Simulation Program – FORTRAN (HSPF)[22] simulates runoff, streamflow, and water quality. HSPF uses the Stanford Watershed Model and input data such as precipitation, potential evapotranspiration, and snowmelt. The model considers four storage zones for precipitation (upper-zone storage, lower-zone storage, groundwater, and snowpack). It routes overland flow, infiltration, interflow, base flow, and flow-to-groundwater within the upper and lower zones to the watershed outlet. It simulates both single event and continuous flows. Typically three to six years of rainfall-runoff data are necessary to calibrate the various parameters, and adjustments are made until an acceptable level of agreement between simulated and recorded flows is established.

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