Chapter 6
Hydrology

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1.0 Introduction

This chapter describes hyrdologic methods for determining design flows and volumes for the planning and design of stormwater management facilities in the City of Woodland Park. The development of appropriate hydrology for a project should be one of the first steps in the planning and design process. Accurately estimating design flows and volumes is critical to the proper functioning of facilities. Depending on the size of the drainage basin and the type of project, different hydrologic methods may be appropriate. In some cases, flow estimates may be available from previous studies, and these should be considered and evaluated, especially when new hydrologic analysis results in significant changes to previous estimates.

A general discussion of the overall process of developing plans and analyzing drainage systems can be found in the UDFCD Storm Drainage Criteria Manual (UDFCD Manual) Volume 1, Planning Chapter. The UDFCD Runoff Chapter and Volume 3 also provide valuable background on hydrologic methods for water quality and flood control that should be used when more complex analysis is required. The Colorado Springs Drainage Criteria Manual (Colorado Springs Manual) (2013) also provides useful information, and should be used for guidance when analyses using the Natural Resources Conservation Service (NRCS) Curve Number method are necessary.

Design flows for stormwater facilities are primarily based on rainfall events, and a range of possible storm events must be considered. In Woodland Park, snowmelt is a significant source of runoff and streamflow and must be accounted for in planning and design. Other sources of runoff such as nuisance flows can affect a project design and must also be identified. Anticipated changes to drainage area characteristics, especially due to development, must be fully considered for facilities to function as intended.

Average annual precipitation in Woodland Park is approximately 24 inches. The wettest months are March through August, with an average August precipitation depth of approximately 4.4 inches. The first frost typically occurs in September, and the last frost is typically in late May or early June. The City receives approximately 140 inches of snow in an average winter, and the ground remains frozen for extended periods. A summer monsoon often brings heavy rainfall in July and August, which typically are the two wettest months. Short-duration thunderstorms (cloud bursts) occur frequently during the monsoon and can produce intense rainfall/runoff and flash flooding. Rainstorms of greatest significance have historically occured between the months of May and September.

Urbanization can have a significant impact on runoff by increasing peak flow rates, runoff volumes, and the frequency of runoff. This increase in runoff can lead to stream erosion, habitat degradation, and increased pollutant loading. However, with proper planning, increased runoff can be managed to create or supplement existing wetland areas or riparian habitats, which may provide significant benefits to the watershed. The increase in runoff from development is especially pronounced when drainage systems are designed to quickly and “efficiently” convey runoff from paved areas and roofs directly into inlets and storm sewers, discharging eventually into drainageways that are typically designed to convey flows at maximum acceptable velocities. Whether for one site or for a whole watershed, this increase in runoff and acceleration of flood peaks can be estimated by the hydrologic methods discussed herein.

Projects in the City of Woodland Park include both new development and redevelopment. Upcoming post-construction stormwater regulations from EPA that are currently in the rulemaking process are likely to include more stringent stormwater requirements for redevelopment and may include expansion of Municipal Separate Storm Sewer System (MS4) coverage to smaller communities such as Woodland Park. By implementing measures to shift hydrology back toward a more natural state, redevelopment projects will help improve the drainageways in Woodland Park and downstream communities. Detention and water quality, in accordance with this Manual, are to be provided for all new development.

In addition to increased runoff, the reduction of available sediment due to urbanization has a destabilizing effect on downstream channels. When the natural sources of sediment are eliminated by paving, building structures or stabilized channels, runoff will tend to replace the natural sediment supply with new sources. Therefore, even an effective reduction in developed runoff to levels approximating historic rates will probably not eliminate the need for the stabilization of downstream systems.

In terms of stormwater quality management, hydrology is fundamental because increased flow rates and volumes of runoff, especially from frequently occurring storms, have the potential to affect receiving waters and aquatic resources. Effective stormwater management seeks to disconnect impervious surfaces, decrease flow velocities, and convey runoff over vegetated ground surfaces, leading to filtering, infiltration, and attenuation of flows. These principles can also be reflected in the hydrologic variables discussed in this chapter, yielding longer times of concentration and reduced runoff peaks and volumes.

1.1 Watersheds

The dividing line between the Fountain Creek Watershed and the Upper South Platte Watershed runs right through the center of Woodland Park. Fountain Creek, with its headwaters beginning in Woodland Park, drains south into the Arkansas River at Pueblo, Colorado. The Fountain Creek Watershed is approximately 927 square miles and is characterized by "extremes in temperature and precipitation, large elevation changes, steep gradients, diverse ecosystems, and a multitude of water uses" (Fountain Creek Watershed Flood Control and Greenway District). The Upper South Platte Watershed is expansive, covering roughly 2,600 square miles from the Continental Divide to Strontia Springs Reservoir. The Upper South Platte Watershed also varies greatly in elevation and gradient and encompasses five major municipal reservoirs as well as several smaller reservoirs. Streams within the Upper South Platte Watershed that traverse parts of the City of Woodland Park include Trout Creek and Loy Gulch.

1.2 Design Flows

A broad range of storm events pass through stormwater facilities and natural drainageways. These range from those producing little or no runoff prior to development to extensive and extreme storm events that produce life threatening and destructive floods. To effectively and efficiently analyze even a small percentage of all possible events is time and cost prohibitive. Therefore, to efficiently plan and design stormwater facilities, "design flows" have been established to represent events that are typical or representative of the range of runoff events that can occur. In most cases, projects can be adequately designed using estimates of these representative flows. Depending on the type of project, design flows may include "baseflows," "low flows," "minor flows," "major flows" and "flood flows." For site design, minor (5-year) and major (100-year) flows are of greatest interest and typically will be calculated using the Rational Method as described in this chapter. Baseflows, low flows and flood flows must also be considered for projects involving channel design. A description of each of these types of flows is provided below and methods for estimating these design flows are described later in this chapter.

1. <u>Baseflows</u>. Baseflow estimates (sometimes referred to as "trickle flows") are used to account for flows that may not be directly related to storm events but may be created by groundwater recharge of streams, wastewater return flows, excess irrigation, water system losses, and other urban water uses. Baseflows are the flows that can be observed in streams and engineered drainageways during dry weather. Channel improvements must account for these flows to address erosion potential in the lower portion of channel sections. The presence of these flows in historically dry basins can also interfere with the growth of certain types of vegetation.

However, these same flows can provide water to sustain vegetation along low-flow channel banks or in channels with wetland bottoms where vegetation was not previously supported.

2. Low Flows. Low flows are used primarily for open channel design and are defined as those flows resulting from relatively frequent storm events that are contained within a well-defined or main channel portion of the floodplain (sometimes these are referred to as “bankfull flows” or “channel forming flows” for natural streams). Flows greater than the low-flow event begin to flow beyond the main channel into the overbank or floodplain portion of natural channels. It is generally accepted that the bankfull discharge has a return period that is in the 1-year to 2-year range, but this value can change significantly, especially when there is urbanization in a basin. “Low flows” should not be confused with “minor flows” which are associated with a specific recurrence interval, as described below, and are generally greater than “low flows” for natural channels.

3. Minor Flow. Minor flows are defined as those flows resulting from relatively frequent storm events that are contained within a portion of the conveyance system such as gutters and storm sewers and are typically defined by a specific return period. Flows greater than the minor flow event typically exceed storm drain capacity and begin to interfere with human activity, such as traffic and pedestrian access. For the purposes of this Manual, the minor flow is defined by the 5-year storm runoff event.

4. Major Flow. Major flows must be conveyed to avoid safety hazards, undue interference with human activity, damage to adjacent structures and damage to conveyance systems. The 100-year runoff event has been identified as the major flow that must be safely conveyed according to this Manual. This design flow is typically used to determine maximum street capacities and to size certain facilities such as culverts. While the 100-year flood is the basis for floodplain regulation for most areas in Woodland Park, larger flood events can and will occur.

5. Flood Flows. In this Manual the term “flood flows” is used to refer to any flows that exceed the low-flow channel, whether natural or engineered. Flood flows must be conveyed to avoid safety hazards, damage to adjacent structures and damage to conveyance systems. Flood flows are typically used to design open channels, size detention ponds and to delineate floodplains. Flooding is often associated with rather extreme events, but is actually defined by any event that causes flows to spill from the low-flow channel onto the overbank or floodplain area of a channel. The 100-year runoff event has been identified as the major flood event that defines the regulatory floodplain according to this Manual. However, flood studies typically include evaluation of other events such as the 10-, 25-, 50- and 500-year events. In some cases, it may be necessary to evaluate lesser flows, such as the 2-year or 5-year flow, to consider critical hydraulic conditions. In some situations, it may be appropriate to address more severe flows, such as the 500-year flow. For instance, drop structures may be largely submerged during the 100-year event, with critical hydraulic conditions occurring during lesser floods. Also, where critical infrastructure, including hospitals, emergency response facilities, etc. may be at risk, State and local floodplain regulations may require evaluation of less frequent (more extreme) events such as the 500-year flood.

Prudent management of upstream land uses and the implementation of runoff reducing practices such as Low Impact Development (LID) and/or Full-Spectrum Detention (FSD), described in detail in the UDFCD Manual, have the potential to reduce the volume and rate of runoff for design flows received by downstream systems. These effects are generally most significant for frequently occurring events. How design flows are affected by upstream basin conditions (under future “build out” conditions) must be fully considered.

1.3 Sources of Design Flows and Types of Hydrologic Analyses

Estimates of runoff are required for a variety of purposes in stormwater management analyses. In some cases, previously completed analyses may be available for the project area. When gauge data are available over an extended period of record, they typically are the most reliable source of flow estimates. However, in headwaters areas, stream gauges with extended periods of record are limited, and calculations are commonly used to define hydrology (with field checking for reasonableness based on observed events). Designers should consult with the City to determine applicability of master plans in the area. However, it is often necessary to complete new analyses that more accurately represent project conditions and provide estimates where they are needed to complete the project. Whenever new analyses are needed, they shall be completed based on the methodologies described in this Manual.

To provide plans and designs that are appropriate for current and future conditions, hydrologic analyses must include various scenarios. Scenarios will typically include multiple runoff events, changes in land uses and alternative system plans such as for transportation. Each scenario must be identified and properly described so that the drainage system plan and possible alternatives can be adequately evaluated.

1.3.1 Published Hydrologic Information

The 1996 *Woodland Park Stormwater Management Plan* was prepared for many of the Woodland Park drainage basins. This plan contains information regarding hydrology for a range of storm events at numerous design points within the study watersheds. This study contains information about watershed and sub-watershed boundaries, soil types, percent imperviousness, and rainfall. When published flow rates are available, these values shall be used for design unless they are considered to be inaccurate or unreliable due to physical changes in the drainage basin or in criteria. The need for additional evaluation and the use of other values shall be approved in writing in advance of any related planning or design work. Note: The City of Woodland Park is currently in the process of creating a city-wide drainage master plan that will supersede the 1996, so applicants are advised to consult with the City to be sure that hydrology is consistent with ongoing planning efforts.

Published hydrologic information for major drainageways can also be found in Federal Emergency Management Agency (FEMA) Flood Insurance Studies (FIS). For all FEMA-related projects, the FEMA hydrologic data shall be consulted. Flow rates published in FEMA FIS studies typically represent existing conditions at the time the study was completed and generally do not incorporate any future development.

1.3.2 Statistical Methods

In some situations, statistical analysis of measured stream flow data provides an acceptable means of determining design flows. Statistical analyses for larger, less-frequent storm events are to be limited to drainageways with a long period of reliable flow data that had no significant changes occur in land uses within the tributary watershed during the flow record. A minimum period of record of 30 years is recommended for statistical analysis of events up to and including the 100-year event; however, when performing statistical analysis for frequently occurring events, such as a 2- or 5-year event, a shorter period of record may be acceptable.

Statistical analyses of gage data should be completed using the Log-Pearson Type III analysis as performed by programs such as the U.S. Geological Survey (USGS) PeakFQ analysis tool. The gage identification and location should be indicated on all calculation sheets and model output.

1.3.3 Rainfall/Runoff Methods

It is typically necessary to estimate runoff for a project when no previous estimates have been provided, especially for lot or multi-lot redevelopment projects and new development projects. The most common method for making these estimates is by converting rainfall (using intensity, depth and temporal and spatial characteristics) to runoff by representing basin characteristics that affect the volume and rate of runoff expected. There are numerous methods that can be applied; however, in most cases in Woodland Park, the Rational Method will prove sufficient for small to medium sized development and redevelopment projects. Generally, best results will be obtained using smaller catchment sizes in the Rational Method, and in no case should the Rational Method be applied for drainage areas larger than 130 acres or when routing is required.

For larger projects and projects involving major drainageways, more complex methods involving models to generate hydrographs are appropriate. These methods are documented in detail in the UDFCD and Colorado Springs Manuals. The method selected will depend on the purpose of the analysis and the scale of the project, but for most projects in Woodland Park, the Rational Method is appropriate. This manual intentionally provides flexibility for the engineer to choose the rainfall-runoff modeling method that is most appropriate for the goal of the project. The modeling upon which the FIS is based was conducted using the NRCS curve number method, with 24-hour SCS rainfall distributions for model input (SCS Type II for Trout Creek and SCS Type IIA for Fountain Creek). When the NRCS method is used for rainfall and runoff modeling, these same distributions are recommended for application for consistency with the FIS. In some cases, however, other models may be more suitable than an NRCS curve number-based model for evaluating hydrology. For example, in areas with significant storm sewer networks, where pressurized flow occurs in the major event, a model such as the EPA Stormwater Management Model (SWMM) may have better capabilities to analyze the system. While many of the hydrologic calculations in the City can be accomplished using the Rational Method, when hydrograph-based modeling is necessary, the applicant should consult with the City to determine the most applicable loss method and routing model to use for the situation being analyzed. The Colorado Springs Manual provides guidance on the NRCS method, and the UDFCD Manual provides guidance on EPA SWMM.

1.4 Data Requirements

Prior to commencing a hydrologic analysis the designer must research and collect the necessary data to provide inputs for the hydrologic method to be used. These data may be available from existing sources or may need to be created for the project at hand. These data will typically include: topographic mapping, existing and future land use conditions for each scenario to be evaluated, an inventory of existing and proposed structures (in waterways and other structures associated with development) within the study area, soil types, ground cover types, groundwater conditions, site location information (horizontally and vertically), previous studies, and any other documents that can provide needed background information. It is the responsibility of the designer to identify and collect the most appropriate and accurate data available to complete the analysis. Some useful sources of information include previous major drainage planning studies, NRCS Soil Surveys, USGS mapping (detailed survey data are needed for design), the USGS StreamStats program, nearby rain gages and stream gages, storm sewer mapping, historic and current aerial photography, and other sources.

1.5 Selecting Hydrologic Methods

The Rational Method shall be the default hydrologic method for drainage analysis for development and redevelopment projects in the City. It is most applicable to development and redevelopment projects in Woodland Park given the fact that the City is largely developed and sits at the headwaters of two major watersheds. The Rational Method is a relatively simple approach where only peak flows are required and a hydrograph is not required also making it well suited for use in Woodland Park. The 1996 *Woodland Park Stormwater Management Plan* included watershed and sub-watershed level hydrology and routing and established reliable hydrology for major drainageways in Woodland Park. The plan should be consulted for work in drainageways as well as analysis of drainage areas and runoff characteristics for off site analysis. While this chapter provides guidance on the Rational Method, for larger development projects and projects involving work on major drainage ways, more complex modeling methods may be required, including the NRCS Curve Number Loss Method and unit hydrograph as implemented in USACE HEC-HMS model or the U.S. Environmental Protection Agency Stormwater Management Model (EPA SWMM) as conditions warrant. For documentation and guidance on application of these methods, consult with the Colorado Springs Manual for the NRCS Curve Number method and the UDFCD Manual for EPA SWMM.

For runoff volume estimates, the Water Quality Capture Volume (WQCV) is calculated using an empirical equation provided in this chapter. For detention sizing, the Rational Formula-Based Modified Federal Aviation Administration (FAA) Method (FAA 1966, sometimes referred to as the “FAA Procedure”), as modified by Guo (1999a), provides a reasonable estimate of storage volume requirements. This method, provided in the Storage Chapter, and/or empirical equations are appropriate for detention sizing for most applications in Woodland Park. For larger facilities, hydrograph-based design may be required using procedures from the UDFCD and/or Colorado Springs Manual, depending on the hydrologic method used.

2.0 Rainfall

This section describes rainfall characteristics for use with the above mentioned hydrologic methods in determining design flows and volumes. Rainfall data to be used are based on National Oceanic and Atmospheric Administration, *Precipitation-Frequency Atlas of the United States, Midwestern States, Volume 8, Version 2.0* (NOAA Atlas 14), updated in 2013. Precipitation depth maps in the NOAA Atlas can be used to determine 6-hour and 24-hour point rainfall values and to determine rainfall depths and intensities for other durations. NOAA Atlas 14 data are also available online. The online version of the data allows for determination of precipitation statistics at a specific point location, accounting for some spatial variability of rainfall. Applicants can use the tables and figures included in this manual, which represent typical conditions throughout the City, or they may use the online tool based on the specific project location. Any major differences between depths and intensities found online versus those provided in this manual should be carefully evaluated in conjunction with the City Engineer.

For modeling of large watersheds (generally greater than 10 square miles), depth area reduction factors (DARFs) are typically applied to account for an aerial reduction of point precipitation estimates. Since much of the hydrologic analysis in Woodland Park can be accomplished using the Rational Method and because there are few subwatersheds that begin to reach the size where a DARF would be applied, DARFs are not included in this manual. If an applicant is modeling a watershed with an area greater than 10 square miles and wishes to apply a DARF, the applicant shall consult with the City Engineer to determine the appropriate adjustment factor based on the DARF recommendations in the Colorado Springs Manual.

2.1 Rainfall Depths and Intensities

Rainfall depths must be determined based on the duration and return period of the design storm. Depths can be derived by the methods described in the NOAA Atlas. The depths reported in the NOAA Atlas represent probable total depths for each duration and return period at a point on the ground. The NOAA

Atlas has recently been updated and new rainfall mapping has been published. This chapter is based on the updated NOAA mapping, and the updated NOAA mapping shall be used as the basis for hydrologic design in Woodland Park. As discussed above, the primary hydrologic method that will apply to most development and redevelopment projects in Woodland Park is the Rational Method. Therefore this section presents depth-duration-frequency and intensity-duration-frequency tables and figures (Tables 6-1 and 6-2 and Figures 6-1 and 6-2). In cases where hydrograph analysis is needed, the reader should refer to the storm depths in Table 6-1 and Figure 6-1, along with the NOAA Atlas, to determine appropriate point precipitation depths that can be applied to the design storm distribution methods in the UDFCD (Colorado Urban Hydrograph Procedure) and Colorado Springs Manuals (SCS). The most up-to-date mapping from NOAA (NOAA Atlas 14) is available online (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=co).

Table 6-1. Depth-Duration-Frequency Relationships for Woodland Park, Colorado

Duration	Precipitation Depth in Inches for Range of Recurrence Intervals							
(minutes)	1-year	2-year	5-year	10-year	25-year	50-year	100-year	500-year
5	0.23	0.28	0.36	0.43	0.55	0.64	0.74	1.01
10	0.34	0.41	0.53	0.64	0.80	0.94	1.09	1.48
15	0.41	0.50	0.64	0.78	0.98	1.15	1.33	1.81
30	0.52	0.63	0.81	0.98	1.24	1.45	1.68	2.28
60	0.64	0.76	0.97	1.17	1.48	1.75	2.03	2.80

Table 6-2. Intensity-Duration-Frequency Relationships for Woodland Park, Colorado

Duration	Precipitation Intensity in Inches Per Hour for Range of Recurrence Intervals							
(minutes)	1-year	2-year	5-year	10-year	25-year	50-year	100-year	500-year
5	2.77	3.32	4.31	5.21	6.56	7.70	8.93	12.10
10	2.03	2.44	3.16	3.82	4.81	5.64	6.54	8.89
15	1.65	1.98	2.57	3.10	3.91	4.59	5.32	7.22
30	1.05	1.25	1.63	1.96	2.47	2.90	3.36	4.57
60	0.64	0.76	0.97	1.17	1.48	1.75	2.03	2.80

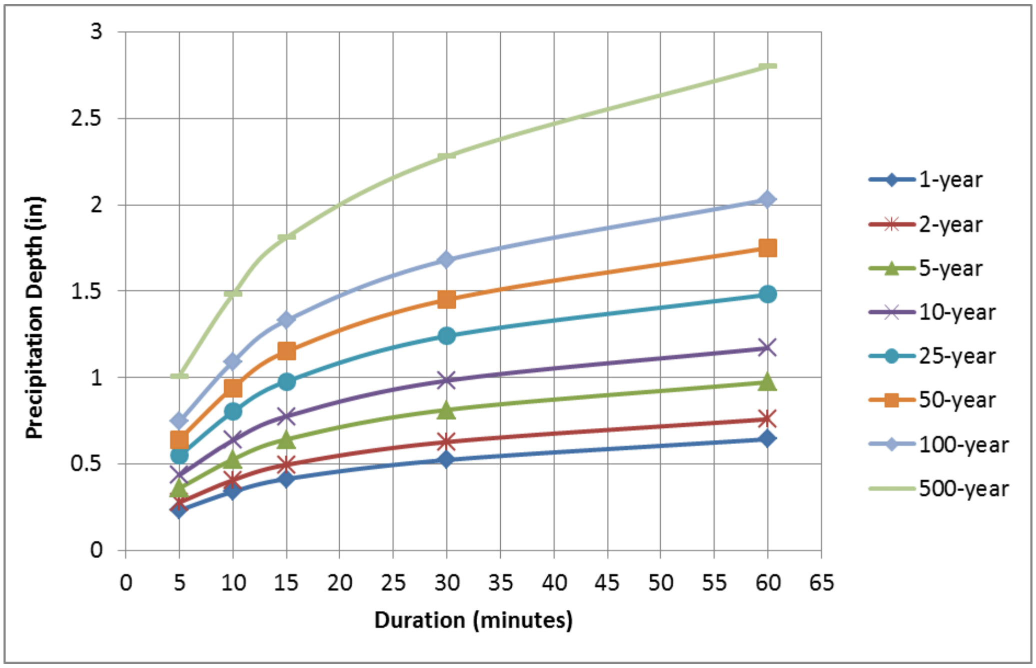

Figure 6-1. Depth-Duration-Frequency Relationships for Woodland Park, Colorado (from NOAA Atlas 14)

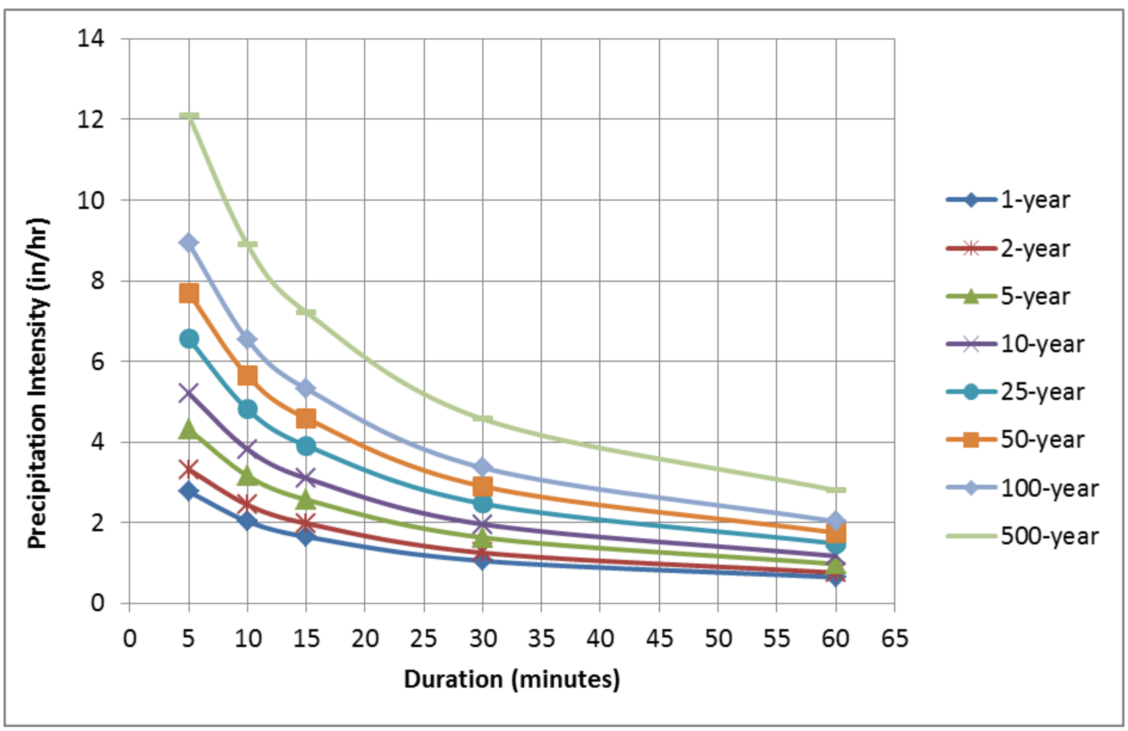

Figure 6-2. Intensity-Duration-Frequency Relationships for Woodland Park, Colorado (from NOAA Atlas 14)

2.2 Hydrologic Basis of Design for Water Quality—Water Quality Capture Volume (WQCV)

The hydrologic basis of design for water quality in Woodland Park is retention of 75% of the 2-year runoff volume, which is roughly equivalent to the WQCV defined by UDFCD. The primary difference between the Woodland Park criterion for 75% of the 2-year runoff volume and the WQCV used by UDFCD is that the Woodland Park criterion requires retention of the capture volume, while the UDFCD criterion allows for slow release. Retention of 75% of the 2-year runoff volume is the standard for the City of Woodland Park. In areas where soils are not suitable for infiltration or where infiltration of the retention volume could cause problems for adjacent structures, the WQCV, with a slow release in accordance with the UDFCD Manual may be used in place of the 75% of the 2-year runoff volume criterion. Applicants wishing to use the WQCV with slow release criterion as a substitute for the retention criterion should consult with the City Engineer to explain why retention/infiltration is infeasible for a given project site.

While guidance in the preceding sections focuses on the hydrologic events related to flood control and conveyance facilities, small frequently occurring events form the basis of design for water quality facilities. The WQCV, corresponding to roughly an 85th percentile event, defines storage volume requirements for stormwater best management practices (BMPs) and is roughly equivalent to 75% of the 2-year runoff volume. The basis for establishing the 85th percentile event and guidance for implementing water quality facilities is described in Volume 3 of the UDFCD Manual. Because of a limited period of record for hourly precipitation data suitable for analysis to determine the WQCV specific to Woodland Park, the WQCV procedure from the UDFCD Manual shall be used to determine the WQCV in Woodland Park, with an adjustment to account for orographic effects. The following equation shall be applied:

$$WQCV = 1.15 \cdot a \cdot (0.9 \cdot I^3 - 1.19 \cdot I^2 + 0.78 \cdot I) \qquad \text{Equation 6-1}$$

Where:

WQCV = Water Quality Capture Volume (watershed inches)

a = Coefficient corresponding to WQCV drain time (Table 6-3)

I = Imperviousness (must be expressed as a decimal [%/100] and not a percent).

Table 6-3. Drain Time Coefficients for WQCV Calculations

Drain Time (hrs)	**Coefficient, *a***
12 hours (sand filters, bioretention, retention ponds)	0.8
24 hours (constructed wetland basins)	0.9
40 hours (Extended dry detention)	1.0

3.0 Snow

Snow is significant in Woodland Park, with approximately 140 inches falling in a typical winter. However, due to the timing of intense rainfall later in the summer (typically during the monsoon in July and August) peak flow rates for stormwater design are typically the result of rainfall events rather than snowmelt or rain on snow events.

Although snowmelt may not drive the sizing for drainage and water quality infrastructure, snowmelt and freezing conditions must be factored into design to account for:

- Baseflows from melting in the spring;
- Frozen ground through most of the winter that limits infiltration potential;
- Snow storage areas near detention facilities;
- Water quality practices and other drainage infrastructure;
- Maintenance requirements due to sanding
- Other factors.

Table 6.4 identifies a number of challenges associated with Woodland Park's cold climate and setting.

Table 6-4. Cold Climate and Physiographic Design Challenges (adapted from Center for Watershed Protection 1997)

Condition	Design Challenge
Cold Temperatures	• Pipe freezing, in some cases even at locations where there is flowing water that is slowed by a transition such as a bend • Ice-cover on permanent water surfaces • Reduced biological activity • Reduced oxygen levels during ice cover • Reduced settling velocities • Diurnal cycle of melting and freezing in winter and spring • Mid-winter warm ups and runoff
Deep Frost Line	• Frost heaving • Reduced soil infiltration
Short Growing Season	• Short time period to establish vegetation • Different plant species appropriate to cold climates than to moderate climates
Significant Snowfall	• High runoff volumes during snowmelt and rain-on-snow • High pollutant loads during spring melt • Sand applied to some roads and walks for improved traction • Snow management may affect BMP storage
Sanding Practices	• Heavy sediment load
Steep Slopes	• Rapid runoff • Potentially high "background" levels of erosion • Potential for mudflows and debris flows

4.0 Rational Method

The Rational Method is used to determine runoff peak discharges for drainage basins up to and including 130 acres in size and when hydrologic routing is relatively simple. However, the drainage area should be divided into sub-basins that represent homogeneous land uses, soil types or land cover. The Rational Method is most typically applied for site-level development projects and sizing of inlets and storm drains. The Rational Method is based on the relationship between rainfall intensity and runoff, and is expressed by the following equation:

$$Q = C \cdot I \cdot A \qquad \text{(Eq. 6-2)}$$

In which:

Q = the maximum rate of runoff (cubic feet per second [cfs])

C = the runoff coefficient that is the ratio between the runoff volume from an area and the average rainfall depth over a given duration for that area

I = the average intensity of rainfall for a duration equal to the time of concentration (in/hr)

A = basin area (acres).

The assumptions and limitations of the Rational Method are described in the UDFCD Manual, Volume 1, Runoff Chapter. Standard Form 1 (SF-1) and Standard Form 2 (SF-2) are provided at the end of this chapter as Figure 6-4 and Figure 6-5, respectively, to provide a standard format for Rational Method calculations. The SF-1 Form is used for calculating the time of concentration, and the SF-2 form is used to estimate accumulated peak discharges from multiple basins as storm runoff flows downstream in a channel or pipe. Results from the Rational Method calculations shall be included with the drainage report submittal. As an alternative to SF-1 and SF-2, the UD-Rational spreadsheet can be used to document basin parameters and calculations or other spreadsheets or programs can be used as long as the information and format is the similar to that shown in these standard forms.

4.1 Rational Method Runoff Coefficient (C)

The runoff coefficient represents the integrated effects of infiltration, detention storage, evaporation, retention, flow routing, and interception, all of which affect the time distribution and peak rate of runoff. Runoff coefficients are based on the imperviousness of a particular land use and the hydrologic soil type of the area and are to be selected in accordance with Table 6-5.

The procedure for determining the runoff coefficient includes these steps:

1. Categorize the site area into one or more similar land uses and drainage areas, each with a representative imperviousness.

2. Based on the dominant hydrologic soil type in the area, use Table 6-5 to estimate the runoff coefficient for the particular land use category for the design storms of interest.

3. Calculate an area-weighted average runoff coefficient for the site based on the runoff coefficients from individual land use areas of the site.

When analyzing an area for design purposes, urbanization of the full watershed, including both on-site and off-site areas, shall be assumed.

Gravel parking areas, storage areas, and access drives shall be analyzed based on an imperviousness of 80%. This is due to the potential for gravel areas being paved over time by property owners and the resulting adverse impacts on the stormwater management facilities and adjacent properties.

There are some circumstances where the selection of impervious percentage values may require additional investigation due to unique land characteristics (e.g., recent burn areas). When these circumstances arise, it is the designer's responsibility to verify that the correct land use assumptions are made.

When multiple sub-basins are delineated, a composite C value can be calculated:

$$C_c = (C_1A_1 + C_2A_2 + C_3A_3 + \ldots C_iA_i) / A_t \qquad \text{(Eq. 6-3)}$$

Where:

C_c = composite runoff coefficient for total area

C_i = runoff coefficient for subarea corresponding to surface type or land use

A_i = area of surface type corresponding to C_i (units must be the same as those used for total area)

A_t = total area of all subareas for which composite runoff coefficient applies

i = number of surface types in the drainage area.

Table 6-5. Runoff Coefficients for Rational Method (UDFCD 2001)

Land Use or Surface Characteristics	Percent Impervious	Runoff Coefficients											
		2-year		5-year		10-year		25-year		50-year		100-year	
		HSG A&B	HSG C&D	HSG A&B	HSG C&D	HSG A&B	HSG C&D	HSG A&B	HSG C&D	HSG A&B	HSG C&D	HSG A&B	HSG C&D
Business													
Commercial Areas	95	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.87	0.87	0.88	0.88	0.89
Neighborhood Areas	70	0.45	0.49	0.49	0.53	0.53	0.57	0.58	0.62	0.60	0.65	0.62	0.68
Residential													
1/8 Acre or less	65	0.41	0.45	0.45	0.49	0.49	0.54	0.54	0.59	0.57	0.62	0.59	0.65
1/4 Acre	40	0.23	0.28	0.30	0.35	0.36	0.42	0.42	0.50	0.46	0.54	0.50	0.58
1/3 Acre	30	0.18	0.22	0.25	0.30	0.32	0.38	0.39	0.47	0.43	0.52	0.47	0.57
1/2 Acre	25	0.15	0.20	0.22	0.28	0.30	0.36	0.37	0.46	0.41	0.51	0.46	0.56
1 Acre	20	0.12	0.17	0.20	0.26	0.27	0.34	0.35	0.44	0.40	0.50	0.44	0.55
Industrial													
Light Areas	80	0.57	0.60	0.59	0.63	0.63	0.66	0.66	0.70	0.68	0.72	0.70	0.74
Heavy Areas	90	0.71	0.73	0.73	0.75	0.75	0.77	0.78	0.80	0.80	0.82	0.81	0.83
Parks and Cemeteries	7	0.05	0.09	0.12	0.19	0.20	0.29	0.30	0.40	0.34	0.46	0.39	0.52
Playgrounds	13	0.07	0.13	0.16	0.23	0.24	0.31	0.32	0.42	0.37	0.48	0.41	0.54
Railroad Yard Areas	40	0.23	0.28	0.30	0.35	0.36	0.42	0.42	0.50	0.46	0.54	0.50	0.58
Undeveloped Areas													
Historic Flow Analysis--Greenbelts, Agriculture	2	0.03	0.05	0.09	0.16	0.17	0.26	0.26	0.38	0.31	0.45	0.36	0.51
Pasture/Meadow	0	0.02	0.04	0.08	0.15	0.15	0.25	0.25	0.37	0.30	0.44	0.35	0.50
Forest	0	0.02	0.04	0.08	0.15	0.15	0.25	0.25	0.37	0.30	0.44	0.35	0.50
Exposed Rock	100	0.89	0.89	0.90	0.90	0.92	0.92	0.94	0.94	0.95	0.95	0.96	0.96
Offsite Flow Analysis (when landuse is undefined)	45	0.26	0.31	0.32	0.37	0.38	0.44	0.44	0.51	0.48	0.55	0.51	0.59
Streets													
Paved	100	0.89	0.89	0.90	0.90	0.92	0.92	0.94	0.94	0.95	0.95	0.96	0.96
Gravel	80	0.57	0.60	0.59	0.63	0.63	0.66	0.66	0.70	0.68	0.72	0.70	0.74
Drive and Walks	100	0.89	0.89	0.90	0.90	0.92	0.92	0.94	0.94	0.95	0.95	0.96	0.96
Roofs	90	0.71	0.73	0.73	0.75	0.75	0.77	0.78	0.80	0.80	0.82	0.81	0.83
Lawns	0	0.02	0.04	0.08	0.15	0.15	0.25	0.25	0.37	0.30	0.44	0.35	0.50

4.2 Time of Concentration

One of the basic assumptions underlying the Rational Method is that runoff is a function of the average rainfall rate during the time required for water to flow from the hydraulically most remote part of the drainage area under consideration to the design point. However, in practice, the time of concentration can be an empirical value that results in reasonable and acceptable peak flow calculations.

For urban areas, the time of concentration(t_c) consists of an initial time or overland flow time (t_i) plus the travel time (t_t) in the storm sewer, paved gutter, roadside drainage ditch, or drainage channel. For non-urban areas, the time of concentration consists of an overland flow time (t_i) plus the time of travel in a concentrated form, such as a swale or drainageway. The travel portion (t_t) of the time of concentration can be estimated from the hydraulic properties of the storm sewer, gutter, swale, ditch, or drainageway. Initial time, on the other hand, will vary with surface slope, depression storage, surface cover, antecedent rainfall, and infiltration capacity of the soil, as well as distance of surface flow. The time of concentration is represented by Equation 6-4 for both urban and non-urban areas.

$$t_c = t_i + t_t \qquad \text{(Eq. 6-4)}$$

Where:

t_c = time of concentration (min)

t_i = overland (initial) flow time (min)

t_t = travel time in the ditch, channel, gutter, storm sewer, etc. (min).

4.2.1 Overland (Initial) Flow Time

The overland flow time, t_i, may be calculated using Equation 6-5.

$$t_i = \frac{0.395(1.1 - C_5)\sqrt{L}}{S^{0.33}} \qquad \text{(Eq. 6-5)}$$

Where:

t_i = overland (initial) flow time (min)
C_5 = runoff coefficient for 5-year frequency (see Table 6-4)
L = length of overland flow (300 ft maximum for non-urban land uses, 100 ft maximum for urban land uses)
S = average basin slope (ft/ft).

Note that in some urban watersheds, the overland flow time may be very small because flows quickly concentrate and channelize.

4.2.2 Travel Time

For catchments with overland and channelized flow, the time of concentration needs to be considered in combination with the travel time, t_t, which is calculated using the hydraulic properties of the swale, ditch, or channel. For preliminary work, the overland travel time, t_t, can be estimated with the help of Figure 6-3 or Equation 6-6 (Guo 1999).

$$V = C_v S_w^{0.5} \qquad \text{(Eq. 6-6)}$$

Where:

V = velocity (ft/s)

C_v = conveyance coefficient (from Table 6-6)

S_w = watercourse slope (ft/ft).

Table 6-6. Conveyance Coefficient, C_v

Type of Land Surface	C_v
Heavy meadow	2.5
Tillage/field	5
Riprap (not buried)*	6.5
Short pasture and lawns	7
Nearly bare ground	10
Grassed waterway	15
Paved areas and shallow paved swales	20

*For buried riprap, select C_v value based on type of vegetative cover.

The travel time is calculated by dividing the flow distance (in feet) by the velocity calculated using Equation 6-6 and converting units to minutes.

The time of concentration (t_c) is then the sum of the overland flow time (t_i) and the travel time (t_t) per Equation 6-4.

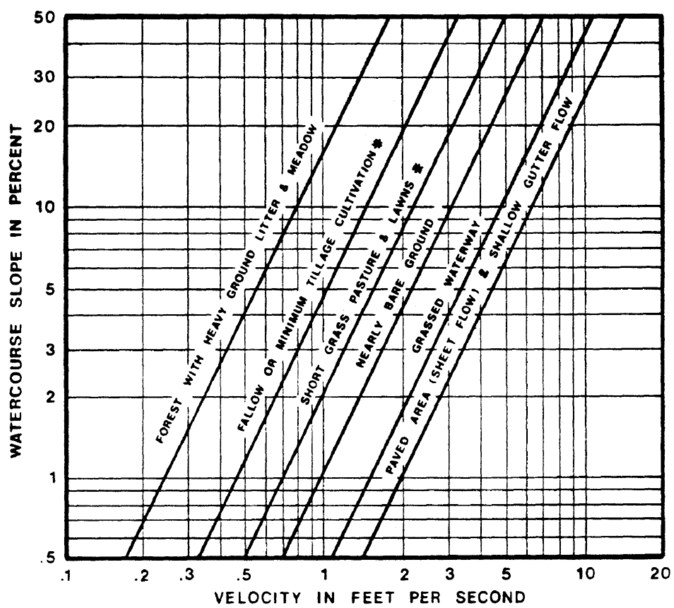

Figure 6-3. Estimate of Average Overland Flow Velocity for use with the Rational Formula

4.2.3 First Design Point Time of Concentration in Urban Catchments

Using this procedure, the time of concentration at the first design point (typically the first inlet in the system) in an urbanized catchment should not exceed the time of concentration calculated using Equation 6-7. The first design point is defined as the point where runoff first enters the storm sewer system.

$$t_c = \frac{L}{180} + 10 \qquad \text{(Eq. 6-7)}$$

Where:

t_c = maximum time of concentration at the first design point in an urban watershed (min)

L = waterway length (ft)

Equation 6-7 was developed using rainfall-runoff data collected in the Denver region and, in essence, represents regional “calibration” of the Rational Method. Normally, Equation 6-7 will result in a lesser time of concentration at the first design point and will govern in an urbanized watershed. For subsequent design points, the time of concentration is calculated by accumulating the travel times in downstream drainageway reaches.

4.2.4 Minimum Time of Concentration

If the calculations result in a t_c of less than 10 minutes for undeveloped conditions, it is recommended that a minimum value of 10 minutes be used. The minimum t_c for urbanized areas is 5 minutes.

4.2.5 Post-Development Time of Concentration

As Equation 6-5 indicates, the time of concentration is a function of the 5-year runoff coefficient for a drainage basin. Typically, higher levels of imperviousness (higher 5-year runoff coefficients) correspond to shorter times of concentration, and lower levels of imperviousness correspond to longer times of concentration, all other factors being equal. Although it is possible to calculate a longer time of concentration for a post-development condition versus a pre-development condition by increasing the length of the flow path, this is often a result of selecting unrealistic flow path lengths. As a matter of practice and for the sake of conservative design, it is required that the post-development time of concentration be less than or equal to the pre-development time of concentration. As a general rule and when sufficiently detailed development plans are not available, the post-development time of concentration can be estimated to be about 75% of the pre-development value.

4.2.6 Common Error in Calculating Time of Concentration

A common error in estimating the time of concentration occurs when a designer does not check the peak runoff generated from smaller portions of the catchment that may have a significantly shorter time of concentration (and, therefore, a higher rainfall intensity) than the drainage basin as a whole. Sometimes calculations using the Rational Method for a lower, urbanized portion of a watershed will produce a higher peak runoff than the calculations for the drainage basin as a whole, especially if the drainage basin is long or the upper portion has little or no impervious cover.

4.3 Rainfall Intensity (I)

The average rainfall intensity (I), in inches per hour, by recurrence interval, can be found from the Intensity-Duration-Frequency curves and data in Figure 6-2 and/or Table 6-2. The value for I is based on the assumption that the peak runoff will occur when the duration of the rainfall is equal to the time of concentration. For example, Figure 6-2 indicates a rainfall intensity of approximately 5.2 inches/hour for the 100-year event for a catchment with a time of concentration of 15 minutes. These curves are based on the rainfall depths from the 2013 update of NOAA Atlas 14 mapping for Woodland Park.

4.4 Basin Area (A)

The size of a drainage basin contributing runoff to a design point, in acres, is used to calculate peak runoff in the Rational Method. Accurately delineating the area contributing to each design point is one of the most important tasks for hydrologic analyses since the estimated runoff is directly proportional to the basin area. The area may be determined through the use of planimetric-topographic maps, supplemented by field surveys where topographic data has changed or where the contour interval is too great to distinguish the direction of flow. The drainage basin lines are determined by the natural topography, pavement slopes, locations of downspouts and inlets, paved and unpaved yards, grading of lawns, and many other features found on the urban landscape. In areas where there are storm drains, the entire contributing drainage area can sometimes be greater than the drainage area determined by topographic analysis of the ground surface, due to storm drains collecting runoff from areas that lie outside of the surface topographic extent of the basin.

5.0 Runoff Reduction Methods

Conventional methods for evaluating increased runoff volume and peak flows associated with urbanization make certain assumptions about the relationship between impervious surfaces and their effect on runoff. A primary assumption of many conventional methods is that the impervious surfaces are directly connected to the drainage features receiving the runoff. In reality, this connection is not always so direct, and adjusting land use planning and design practices to "disconnect" impervious areas (i.e. route flows from impervious areas to pervious areas rather than the gutter and street inlets), can reduce the rate and volume of runoff downstream. Many of the same practices that have been developed for improving water quality are also beneficial for reducing runoff volumes and peak flows. These practices can generally be referred to as Best Management Practices (BMPs), Low Impact Development (LID) and Green Infrastructure (GI) approaches. The effects of urbanization, the selection of BMPs, the implementation of LID approaches and their potential for reducing runoff are discussed in detail in Volume 3 of the UDFCD Manual. Key concepts associated with these practices are briefly summarized below with regard to their implications for estimating runoff.

5.1 Four Step Process

UDFCD has long recommended a "Four Step Process" for receiving water protection that focuses on reducing runoff volumes, treating the WQCV, stabilizing drainageways, and implementing long-term source controls. The Four Step Process pertains to management of smaller, frequently occurring events, as opposed to larger storms for which drainage and flood control infrastructure are sized. The Four Step Process is summarized as follows:

1. Step 1: Reduce runoff by disconnecting impervious area, eliminating "unnecessary" impervious area and encouraging infiltration into soils that are suitable.

2. Step 2: Retain 75% of 2-year runoff volume (when conditions are not suitable for retention and infiltration, the WQCV, with a slow, controlled release per the UDFCD Manual may be considered).

3. Step 3: Stabilize stream channels.

4. Step 4: Implement source controls.

Benefits of implementing the complete process can include improved site aesthetics through functional landscaping features that also provide water quality benefits. Additionally, runoff reduction can decrease required storage volumes, increasing developable land and reducing the size of downstream facilities. A detailed description of the Four Step Process, which includes BMP selection tools and quantitative procedures for completing these steps,is provided in Volume 3 of the UDFCD Manual.

There are two primary approaches to reducing runoff volume and peak flows provided in this Manual. The first is to represent runoff reduction practices in the standard methods by converting the effects of these practices into a reduced value for imperviousness on a basin or sub-basin level. The second is to more directly represent the physical impacts of the BMPs and LID practices through modeling each of the elements at a sub-basin level. There is a significant difference in the level of detail and expertise required in the application of these two approaches. Most situations can be reasonably addressed through the application of an adjusted value for imperviousness, or "effective imperviousness."

5.2 Effective Imperviousness

Volume 3 of the UDFCD Manual and the Colorado Springs Manual both provide methods that allow for adjustments to runoff calculations to account for disconnected impervious area and LID practices. The UDFCD Impervious Reduction Factor method, described in Volume 3, can be applied at a site development scale to determine adjustments in imperviousness for a range of storm return frequencies. The effective imperviousness determined using these methods (which will always be less than or equal to total imperviousness of the site) can be used in Rational Method calculations to account for the effects of runoff reduction practices, using Table 6-5 to determine runoff coefficients based on adjusted imperviousness values. The effects of volume reduction generally diminish with increasing storm frequency, and unless practices provide significant storage above and beyond the WQCV requirement, reductions in runoff coefficients for large storm events will be minimal.

6.0 Design Hydrology Based on Future Development Conditions

6.1 On-site Flow Analysis

Full site development shall be considered when the design engineer selects runoff coefficients or impervious percentage values and performs the hydrologic analyses for on-site areas. Changes in flow patterns and sub-basin boundaries due to site grading and proposed street and roadway locations must be considered. Time of concentration calculations must reflect increased surface flow velocities and velocities associated with proposed runoff conveyance facilities.

6.2 Off-site Flow Analysis

Fully developed conditions shall be considered when the design engineer selects runoff coefficients or impervious percentage values and performs the hydrologic analyses for off-site areas. Where the off-site area is undeveloped, fully developed conditions shall be projected using the best available land use information, current zoning, or approved land use applications. The City shall be consulted to verify all assumptions regarding future development in off-site areas.

Where the off-site area is fully or partially developed, the hydrologic analysis shall be based on existing platted land uses, constructed conveyance facilities, and developed topographic characteristics. Consideration of potential benefits related to detention provided in off-site areas depends on the type of detention provided and whether or not the detention is publicly owned and/or maintained.

In general, the detention effects of on-site or multi-lot detention practices on private property will not be considered when determining off site flows and flood flows for downstream drainageways because they are not publicly owned and maintained. In some cases at the discretion of the City, detention effects of these types of facilities may be accounted for provided there is a drainage easement and agreement allowing the City to maintain the drainage facilities if the owner does not.

Standard Form SF-1. Time of Concentration

PROJECT ______________________

PREPARED BY ______________________ DATE ____________

Sub-Basin Data			Initial/Overland Time (t_i)			Travel Time (t_t)				t_c Check (Urbanized Basins)		Final t_c	Remarks
DESIGN	C_5	AREA (A) acres	LENGTH (L) feet	SLOPE (S) %	t_i minutes	LENGTH (L) feet	SLOPE (S) %	Velocity (V) ft/sec	t_t minutes	TOTAL LENGTH (L) feet	t_c=(L/180)+10 minutes	$t_c = t_i + t_t$ minutes	

Figure 6-4. Standard Form SF-1, Time of Concentration

Standard Form SF-2. Storm Drainage System Design (Rational Method Procedure)

CALCULATED BY:	JOB NO.:
DATE:	PROJECT:
CHECKED BY:	DESIGN STORM:

STREET	DESIGN POINT	AREA DESIGN	DIRECT RUNOFF						TOTAL RUNOFF				STREET		PIPE			TRAVEL TIME			REMARKS
			AREA (A)	RUNOFF COEFF. (C)	t_c	CA	I	Q	t_c	Σ(CA)	I	Q	SLOPE	STREET FLOW	DESIGN FLOW	SLOPE	PIPE SIZE	LENGTH	VELOCITY	t_t	
			ac		min		in/hr	cfs	min		in/hr	cfs	%	cfs	cfs	%	in	ft	ft/sec	min	

Figure 6-5. Standard Form SF-2, Rational Method Calculations