Chapter 2 – Rainfall

2.1 Purpose

This chapter presents the rainfall and snowfall design information needed for storm and snowmelt runoff analyses in the City of Aspen. Major subjects include:

- precipitation statistics for Aspen,
- IDF (intensity-duration-frequency) relationships for flood predictions from small watersheds,
- temporal rainfall distributions for flood flow simulation through large watersheds,
- snowmelt calculation methods, and
- the derivation of Water Quality Capture Volume (WQCV).

One of the most significant impacts of urbanization and development is the increase in peak flow rates, runoff volumes, and frequency of runoff from impervious areas. This increase in runoff can lead to severe stream erosion, habitat disruption, and increased pollutant loading in receiving waters. The increase in runoff from development is especially pronounced when drainage systems are designed to quickly 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 is reflected accurately by the hydrologic methods discussed herein.

With proper planning, the increased runoff volumes, rates, and pollutant loads can be managed and controlled in ways that mimic natural hydrology, reducing the impacts to the watershed. **The stormwater management policies of the City of Aspen strongly encourage methods to reduce runoff and increase infiltration to attenuate peak flood discharges and improve stormwater quality.** As a result, many of the drainage facilities are designed for watersheds smaller than 100 acres with a time to peak discharge of less than 30 minutes. This requires the use of rainfall patterns that are shorter than two-hour duration in the design of facilities. In this Chapter, the 2-, 5-, 10-, 25-, 50-, and 100-year 2-hr rainfall distribution curves are derived for the Aspen area based on the one-hr precipitation depth. However, **only the 5-, 10-, and 100-year storms are needed for drainage design at this time**. The information source for design storms presented in this Chapter is the Precipitation-Frequency Atlas of the United States, Midwestern States, NOAA Atlas 14, Volume 8 (NOAA 2013).

The continuous daily rainfall and snowfall data recorded at Aspen Weather Observation operated by the Water Department, City of Aspen was analyzed from 2006 to 2008 to derive the localized hydrologic parameters. The 29-year daily climate data collected at Station 050372 from 1980 through 2008 was used to derive the WQCV for the Aspen area (Station 050372, Western Regional Climate Center.)

The methodology used to generate the rainfall data for a project will depend on the size of the drainage basin being studied. The Rational Method for determining runoff, explained in Chapter 3, is widely accepted as providing a sufficient level of detail for generating runoff from relatively small basins and should be used for drainage basins with an area less than 90 acres. The Rational Method uses rainfall data in the form of intensity-duration (time)-frequency curves, discussed in Section 2.3.

Since the assumptions used in the Rational Method become less valid over larger areas, larger basins require a more rigorous analysis to generate runoff data. CUHP or SWMM designs, explained in Chapter 3, must be used for drainage basins with an area greater than 90 acres. CUHP and SWMM uses rainfall data in the form of depth ratios or depths, discussed in Section 2.4.

2.2 Overview

The climate in Aspen offers mild weather with low humidity and year-round sunshine. Summer weather in Aspen starts around June or July where temperatures reach 80°F during the day, although temperatures are much cooler during the night. The occasional summer shower can occur at any time, sometimes turning into thunderstorms. Autumn in Aspen is usually dry and warm and during September daytime temperatures can reach 70°F, but night temperatures can drop to freezing. Aspen is renowned for its warm winter sun. Winter daytime temperatures typically range from 20 to 40°F in the City and from 10 to 30°F on the mountain. Once the sun goes down, the temperature drops dramatically. **Table 2.1** presents monthly statistics for temperature, precipitation, snowfall, and snow depth in the Aspen area.

Table 2.1 Monthly Statistics for Temperature and Precipitation in Aspen

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	35	39	45	52	63	72	78	76	69	58	43	35	55.5
Average Min. Temperature (F)	9.1	12	20	26	35	41	47	46	39	30	19	9.7	27.7
Average Total Precipitation (in.)	1.7	2.1	2.7	2.5	2.1	1.4	1.8	1.6	2.1	2	2.6	1.9	24.37
Average Total Snowfall (in.)	25	27	28	20	7.8	1	0	0	1	11	28	25	173.8
Average Snow Depth (in.)	21	28	27	12	1	0	0	0	0	1	6	14	

(Source: Station 050372 at Aspen 1 SW, Colorado)

2.3 Rainfall Depth, Duration, Frequency, and Intensity

The rainfall intensity-duration-frequency (IDF) curve is a statistical formula to describe the relationship among the local rainfall characteristics and return periods. **The IDF curve is used in the Rational Method for peak runoff predictions of basins smaller than 90 acres.** Based on the NOAA Atlas Volume 3, the IDF curve for the City of Aspen can be derived according to the locality and elevation. The City of Aspen is located at approximately 39°11′32″N and 106°49′28″W, at an elevation of approximately 8,100 feet.

Based on depth and duration data (Appendix B, Table 1), rainfall intensities can be calculated for various frequencies. Rainfall intensity data, which form the basis of the Intensity-Duration-Frequency (IDF) curves in **Figure 2.1** are provided in **Table 2.2**.

Table 2.2 Rainfall Intensity-Duration-Frequency in Aspen, Colorado

Return Period	Rainfall Intensity in inch/hr for Various Periods of Duration								
	5-min	*10-min*	*15-min*	*30-min*	***1-hr (P1)***	*2-hr*	*3-hr*	*6-hr*	*24-hr*
2-yr	2.06	1.51	1.23	0.77	0.47	0.28	0.21	0.13	0.06
5-yr	2.98	2.17	1.77	1.09	**0.64**	0.36	0.26	0.16	0.07
10-yr	3.72	2.72	2.22	1.35	**0.77**	0.43	0.30	0.18	0.08
25-yr	4.75	3.47	2.82	1.71	0.95	0.53	0.36	0.21	0.09
50-yr	5.53	4.05	3.30	1.98	1.09	0.60	0.41	0.24	0.11
100-yr	6.32	4.63	3.76	2.24	**1.23**	0.67	0.45	0.26	0.12

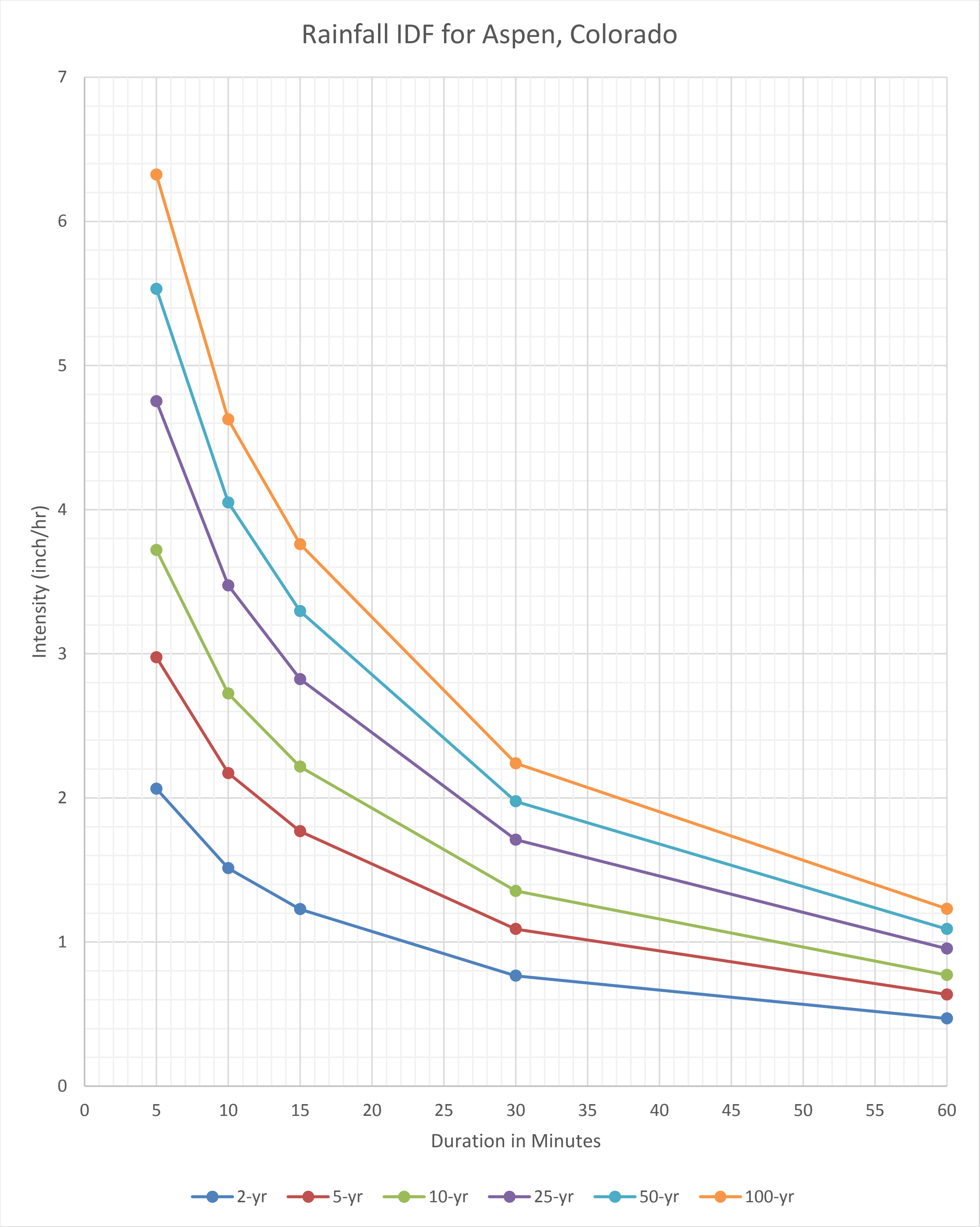
Using the data in **Table 2.2 (**derived from NOAA Atlas 14 Volume 8**)**, the following equation was derived that can be used to determine intensities not shown in the IDF table or curve:

$$I = \frac{88.8P_1}{(10+T_d)^{1.052}}$$ **(Equation 2-1)**

Where,
I = rainfall intensity (inch/hr),
P_1 = 1-hr rainfall depth (inches), and
T_d = duration or time of concentration (minutes).

This equation can be used in conjunction with the Rational Method in Chapter 3 of this Manual by setting T_d equal to the time of concentration of the watershed.

The coefficients within Equation 2-1 are applicable to UDFCD spreadsheets. UDFCD spreadsheet Runoff Analysis-UD-Rational v1.02a determines the time of concentration and peak runoff for a given drainage basin. The spreadsheet Detention Design - UD-Detention v2.34 utilizes various methods to determine required detention volume. The analysis is based off user input parameters for given drainage basin characteristics. The spreadsheets can be found at http://www.udfcd.org/downloads/down_software.htm.



Note: Accuracy is more reliable at 5 minute increments.

Figure 2.1 IDF Curves for Aspen, Colorado

2.4 Design Rainfall Distribution

For larger drainage areas (over 90 acres) or for sizing of facilities where a hydrograph must be analyzed, such as a detention pond, a temporal distribution must be assigned to a precipitation event for calculation of runoff. Characteristics of a temporal distribution include duration and distribution (depth at a certain time) of rainfall.

Very intense rainfall patterns resulting from convective storms or frontal stimulated convective storms typically drive flooding in small urban catchments like Aspen. These types of storms often have their most intense periods over duration of one or two hours or less, and they produce brief periods of high rainfall intensities. Analysis of the summer storms recorded at the Aspen rain gage revealed that an overwhelming majority of intense rainstorms produced their greatest intensities in the first hour of the storm. Based on this analysis, a 2-hour design storm with the “leading edge” of intensity in the first hour is recommended for watersheds less than or equal to 10 square miles in the Aspen area[1].

Depth ratios (or percentages) are input parameters for CUHP models. For this manual, another step was taken to derive distribution *depths* (these can also be input for CUHP models) for the 1-hr event in Aspen. Appendix B, Table 2 shows the incremental depths and Appendix B, Table 3 shows the cumulative depths. For areas outside of the City of Aspen, the depth ratios (percentages) in Appendix B, Table 4 should be used in CUHP to derive depths for those areas.

---

[1] The temporal distribution of rainfall must be adjusted for application to large watersheds (> 10 square miles). Since development projects in Aspen are typically ≤10 square miles, discussion of adjustment procedures for watersheds > 10 square miles is not included in this Manual. In cases where large watersheds are to be analyzed (i.e. the Roaring Fork River, Castle Creek or Maroon Creek) see the rainfall chapter of the UDFCD Urban Storm Drainage Criteria Manual for detailed discussion of adjustments (UDFCD 2001).

Table 2.3 Two-Hour Incremental Rainfall Depths for Aspen

Incremental Design Rainfall Distributions for Aspen Colorado

2-yr, 1 hour precipitation = 0.47
5-yr, 1 hour precipitation = 0.64
10-yr, 1 hour precipitation = 0.77
25-yr, 1 hour precipitation = 0.95
50-yr, 1 hour precipitation = 1.09
100-yr, 1 hour precipitation = 1.23

Time *minutes*	2-yr *(in)*	5-yr *(in)*	10-yr *(in)*	25-yr *(in)*	50-yr *(in)*	100-yr *(in)*
0	0.00	0.00	0.00	0.00	0.00	0.00
5	0.01	0.01	0.02	0.01	0.01	0.01
10	0.02	0.02	0.03	0.03	0.04	0.04
15	0.04	0.06	0.06	0.05	0.05	0.06
20	0.08	0.10	0.12	0.08	0.09	0.10
25	0.12	0.16	0.19	0.14	0.16	0.17
30	0.07	0.08	0.09	0.24	0.27	0.31
35	0.03	0.04	0.04	0.11	0.13	0.17
40	0.02	0.03	0.03	0.08	0.09	0.10
45	0.01	0.02	0.03	0.05	0.05	0.08
50	0.01	0.02	0.02	0.05	0.05	0.06
55	0.01	0.02	0.02	0.03	0.03	0.05
60	0.01	0.02	0.02	0.03	0.03	0.05
65	0.01	0.02	0.02	0.03	0.03	0.05
70	0.01	0.02	0.02	0.02	0.03	0.02
75	0.01	0.02	0.02	0.02	0.03	0.02
80	0.01	0.01	0.02	0.02	0.02	0.01
85	0.01	0.01	0.02	0.02	0.02	0.01
90	0.01	0.01	0.01	0.01	0.02	0.01
95	0.01	0.01	0.01	0.01	0.02	0.01
100	0.01	0.01	0.01	0.01	0.02	0.01
105	0.01	0.01	0.01	0.01	0.02	0.01
110	0.00	0.01	0.01	0.01	0.02	0.01
115	0.00	0.01	0.01	0.01	0.02	0.01
120	0.00	0.01	0.01	0.01	0.02	0.01

Table 2.4 Two-Hour Cumulative Rainfall Depths for Aspen

Cumulative Design Rainfall Distributions for Aspen Colorado						
2-yr, 1 hour precipitation = 0.47 5-yr, 1 hour precipitation = 0.64 10-yr, 1 hour precipitation = 0.77 25-yr, 1 hour precipitation = 0.95 50-yr, 1 hour precipitation = 1.09 100-yr, 1 hour precipitation = 1.23						
Time *minutes*	2-yr *(in)*	5-yr *(in)*	10-yr *(in)*	25-yr *(in)*	50-yr *(in)*	100-yr *(in)*
0	0.00	0.00	0.00	0.00	0.00	0.00
5	0.01	0.01	0.02	0.01	0.01	0.01
10	0.03	0.04	0.04	0.05	0.05	0.05
15	0.07	0.09	0.11	0.09	0.11	0.11
20	0.14	0.19	0.22	0.17	0.19	0.20
25	0.26	0.35	0.42	0.31	0.36	0.38
30	0.33	0.43	0.51	0.55	0.63	0.68
35	0.36	0.47	0.55	0.66	0.76	0.86
40	0.38	0.50	0.58	0.74	0.85	0.95
45	0.39	0.52	0.61	0.79	0.90	1.03
50	0.41	0.54	0.64	0.83	0.96	1.09
55	0.42	0.56	0.66	0.86	0.99	1.14
60	0.44	0.58	0.69	0.89	1.03	1.19
65	0.45	0.60	0.71	0.93	1.06	1.24
70	0.45	0.62	0.74	0.95	1.09	1.26
75	0.46	0.64	0.76	0.97	1.11	1.29
80	0.47	0.65	0.79	0.99	1.13	1.30
85	0.48	0.67	0.80	1.01	1.15	1.32
90	0.49	0.68	0.82	1.02	1.17	1.33
95	0.50	0.69	0.83	1.03	1.18	1.35
100	0.51	0.70	0.85	1.05	1.20	1.36
105	0.52	0.71	0.86	1.06	1.21	1.38
110	0.52	0.72	0.88	1.07	1.23	1.39
115	0.53	0.73	0.89	1.08	1.24	1.41
120	0.53	0.74	0.90	1.10	1.26	1.42

2.5 Snowmelt

The annual snowfall in the Aspen area can be as high as 150 to 200 inches. Snowmelt and refreezing can lead to many drainage problems in the winter and spring, including frost heave, freezing sewers, ice in street gutters, and inlet clogging. Therefore, **evaluation of snowmelt events can be helpful in selection of alternatives for snow management, determining snow storage, and is critical for determining capacities of stormwater quality controls**. However, snowmelt evaluations are not necessary at this time for development design in Aspen.

In some instances, it can be helpful to evaluate snowmelt with and without rainfall. Evaluation of snowmelt runoff depends on the snow-to-water ratio for fresh snow and the snow compact ratio for piled snow.

2.5.1 Snow Compact and Snow-to-Water Ratios

Once the snow is on the ground, it will settle under its own weight (largely due to differential evaporation) until its density is approximately 30% of water. Increases in density above this initial compression occur primarily by melting and refreezing, caused by temperatures above freezing or by direct solar radiation. The snow removal study for Berthoud Pass over Highway 40 reported that the compact ratio for piled snow is 43% (Guo 1999). Under different compact conditions, ten (10) inches of fresh snow can contain 0.10 to 4.0 inches of water, depending on crystal structure, wind speed, temperature, and other factors The Surface Drainage Master Plan for the City of Aspen suggests that **the snow-to-water ratio is set to be eleven (11) inches of fresh snow equivalent to one (1) inch of water** (Master Plan 2001).

2.5.2 Snowmelt Runoff Depth

For engineering practice, the energy budget equation is simplified to assume that daily snowmelt is proportional to the difference between the representative daily temperature and a base temperature (Viessman et. al. 1997).

$$P_s = K_s (T_m - 32)$$ **(Equation 2-2)**

Where,

P_s = snowmelt depth (inches of water),

K_s = degree-day snowmelt coefficient (inch/day-^{o}F) = 0.011 inch/day-^{o}F, and

T_m = maximum daily temperature (^{o}F).

To determine an appropriate value for Ks, analysis was conducted to calibrate Eq. 2-2 using the 3-year daily snow data recorded at the City of Aspen (Aspen Weather Observation, 2006 to 2008). The best-fitted value for Ks was found to be 0.011 inch/day-oF when using the daily maximum temperature.

2.6 Hydrology for Stormwater Quality

In 1972, the Federal Clean Water Act established the National Pollutant Discharge Elimination System (NPDES) program. Since 2000, the EPA has expanded the NPDES program to cover stormwater discharges. Since 1994, the City of Aspen has conducted sporadic water quality tests in the Roaring Fork River and increased enforcement of any illegal dumping into the river (Roaring Fork River Report 2008). Chapter 8 of this manual further explains how to prevent stormwater pollutants from reaching receiving waters in the City of Aspen.

There are a number of different types of precipitation/runoff events that have the potential to affect stormwater quality in Aspen. Typical types of events include:

- Summer rainfall/runoff event—consists of runoff, primarily from impervious surfaces during rainfall events that occur from May to October.
- Mid-winter snowmelt—Aspen can experience significant diurnal temperature fluctuations, even in winter, with temperatures far below freezing at night, warming to above the freezing point during the day. These events can be problematic from both flooding and water quality perspectives when inlets are obstructed by snow and ice or when little infiltration is possible due to frozen or saturated ground conditions. Water quality best management practices (BMPs) only function and provide treatment at a fraction of their full capability during winter.
- Spring runoff—generally beginning in April and progressing into May and June. The annual melting of the snowpack accumulated over the winter can produce large peak flows, especially given the significant snow-covered ski area south of the City, and snow stored in town along streets and in snow storage areas.
- Rain on snow—These events are more commonly evaluated for flooding potential rather than for water quality purposes; however, there are important water quality considerations for these events. When rain on snow occurs, performance of BMPs may be compromised if there is snow stockpiled in BMPs and/or because of saturated or frozen ground conditions.

In practice, the settlement process in a storage basin is the most economic and effective means to improve stormwater quality. Therefore the City has determined a volume of water that must be held in order to settle out pollutants. The water quality capture volume (WQCV) is defined as the detention storage volume to capture 80% of annual runoff volumes generated from the tributary catchment (ASCE WEF 1998). WQCV varies with respect to catchment imperviousness and rainfall patterns (Guo and Urbonas 2002). In preparation of this manual, the Western Climate Center provided the continuous daily snow-rainfall data recorded at the City of Aspen. The WQCV for the Aspen area was derived based on the analysis of more than 10,000 precipitation (rain and snow) events from January 1980 through December 2008.

The WQCV for Aspen ranges from 0.05 watershed inches (approximately 180 ft^3/acre) for a catchment with imperviousness of 20 percent up to 0.26 watershed inches (approximately 950 ft^3/acre) for imperviousness of 100 percent. The complete design chart illustrating the WQCV as a function of catchment imperviousness is provided in Chapter 8 - Water Quality.

2.7 References

ASCE WEF (1998). *Urban Runoff Quality Management.* WEF Manual of Practice No. 23, Water Environment Federation (WEF) and American Society of Civil Engineers Manual and Report on Engineering Practice No. 87. 1998.

Aspen Weather Observation (2006 to 2008), Daily Precipitation Record, Water Department, City of Aspen, from January 2006 through December 2008. www.aspenpitkin.com/depts/58/

Guo, James C.Y. and Harrigan, Kelly (2009). "*Conservative Design Rainfall Distribution*", ASCE J. of Hydrologic Engrg. Volume 14, Issue 5, pp. 528-530 (May 2009)

Guo, J. C.Y. (1999). "*Sand Recovery for Highway Drainage Designs,*" ASCE J. of Drainage and Irrigation Engineering, Vol 125, No 6, Nov.

Guo, J. C.Y. and Urbonas, B. (2002). "Runoff Capture and Delivery Curves for Storm Water Quality Control Designs," ASCE J. of Water Resources Planning and Management, Vol 128, Vo. 3, May/June.

Master Plan (2001), “Surface Drainage Master Plan for the City of Aspen, Colorado”, prepared by WRC Engineering, Inc. November

Station 050372 at Aspen 1 SW, Colorado, Daily Precipitation Record from January 1980 through December 2008, Western Regional Climate Center, Desert Research Institute 2215 Raggio Parkway, Reno, NV 89512, http://www.wrcc.dri.edu

Hansen, E.M., F.K. Schwarz, and J.T. Riedel (1977). “Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages, Hydrometeorological Report No. 49,” National Weather Service, National Oceanic and Atmospheric Administration, Department of Commerce, Washington, DC., U.S. Government Printing Office.

NOAA (2013), “Precipitation-Frequency Atlas of the United States, Midwestern States, NOAA Atlas 14, Volume 8,” National Oceanic and Atmospheric Administration, Washington, D.C.: U.S. Department of Commerce, National Weather Service.

Western Regional Climate Center, Station 050372 at Aspen 1 SW, Colorado, Daily Precipitation Record from January 1980 through December 2008, Western Regional Climate Center, Desert Research Institute 2215 Raggio Parkway, Reno, NV 89512, http://www.wrcc.dri.edu

Urban Drainage and Flood Control District (2001), “Urban Storm Drainage Criteria Manual, Volume 1, Rainfall Chapter,” Urban Drainage and Flood Control District, Denver, Colorado.

Viessman, W. and Lewis, G. L., (1977), “Introduction to Hydrology”, Happer and Row, New York.

Wikipedia Encyclopedia *(2009), Chapter Snow, http://en.wikipedia.org/wiki/Wikipedia*

Wright Water Engineers, Inc. (2014), “City of Aspen Detention Analysis”