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Finding "Maximized" Water Quality Capture Volume by Runoff Capture Ratio

by
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The 1987 Water Quality Act shifts the focus of storm water management in the United States from flood mitigation to stormwater quality control. The amount of runoff to be captured is a key factor in the design of storm-water quality enhancement facilities. When the design volume is too small, a large number of storm events exceed the facility's capacity. When it is too large, the smaller runoff events may flow through the facilities faster than desired for adequate removal of pollutants. In general, bigger is better. However, after a certain threshold size is reached, further removal of sedimentation becomes negligible.

Although drainage and flood control engineers often consider the 2-year storm event a small storm, it in fact produces runoff larger than 95 percent of the events that may occur in an urban catchment. Figure 1 shows an example distribution of storm numbers by depth for the Denver area. Here 94.1% of the storm events had a precipitation depth less than 0.95 inch which is equal to the one-hour, two-year storm depth in Denver. Although the skewness of the distribution varies with the region, the smaller events dominate all long term rainfall records.

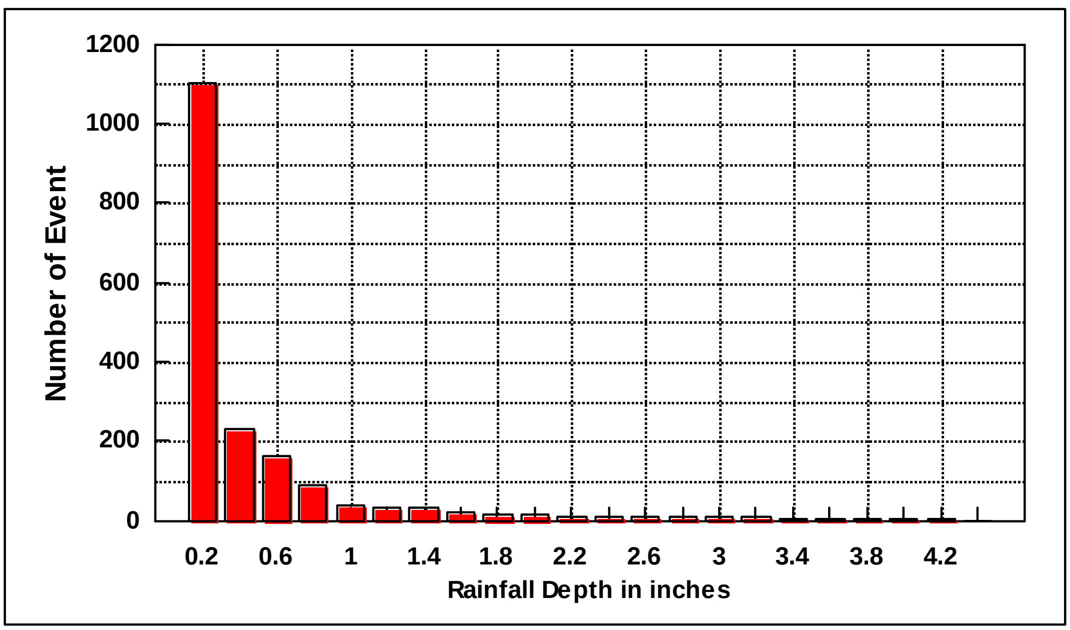

Figure 1 Rainfall Depth Distribution in the Denver Area, Colorado

There are many local recommendations and criteria that specify the minimum detention volume of a stormwater quality enhancement facility. For instance, Montgomery County in the State of Maryland (Maryland, 1986) requires the basin storage volume to be equal to 12.3 mm (0.5 inch) of runoff depth from the tributary watershed while the Maryland Water resources Administration suggests a volume equal to 2.5 times the runoff volume generated by the mean storm. Roesner et al. (1996), based on a review of runoff distribution from different areas of United States, suggested that a cost effective basin size should have a volume equal to runoff volume from a storm of 4-month return period. All of these criteria and suggestions tried to address a reasonable and what was believed to be an optimum detention volume for stormwater runoff quality management.

An effective stormwater enhancement facility has to balance the basin brim-full volume and its drain time. Occoquan Watershed Monitoring Laboratory came up with an estimate based on field observations that, on an average, 65 percent of the suspended sediment load found in urban runoff can be removed by a dry detention basin when its volume was equal to the average runoff event and the drain time of this volume was 12 hours. They also estimated that a removal rate of 82 percent was possible when this drain time was 40 hours (Washington, 1983).

Increasing the detention volume many not significantly increase its ability to remove the added sediment load since it is apparent that the volume and its drain time are both important in determining the sediment removal rate. Also, the engineer needs to consider the economics of each detention facility since larger facilities will cost more to construct and occupy larger tracts of land.

Detailed investigation based on calibrated long-term runoff simulations is the preferred method to determine the needed stormwater quality capture volume for a given site, stormwater drainage system, municipality or a region. A number of such initiatives have occurred in Europe, Australia and United States. Most of these investigations outside of United States were for the purpose of controlling combined sewer overflows. Regardless of the purpose, each of these initiatives required large commitments of fiscal resources that were justified by the multi-millions, or multi-billion, dollars costs of the facilities being installed in these combined sewer systems. All of these detailed studies needed initial estimates of detention volumes to initiate the modeling process, volumes often estimated using simplified methods. At the same time, the overwhelming majority of smaller municipalities in United States do not have the financial resources to perform detailed modeling studies. Therefore, estimates of storm water quality control volumes rely on rule-of-thumb, simplified guidelines. There is a need for simple and reliable procedures for estimating water quality detention volumes. At the same time, no simplified method can substitute for detailed investigations. Simplified techniques can help professionals estimate the water quality detention volumes during a preliminary planning phase of a project or make an initial estimate for clients to determine how much land will need to be set aside for storm water detention in development of a new subdivision.

This paper presents such a technique, showing that a stormwater quality detention basin size can be determined by finding a volume that, once exceeded, results in diminishing returns in capturing the percentage of storm runoff events or in the annual stormwater runoff volume. This capture volume is defined herein as "maximized" or "optimal" detention storage volume for treatment of stormwater runoff. Although the concept of this method appears simple, it provides a reliable and reasonable estimate of a detention storage volume for stormwater quality enhancement facilities. This method was applied to the hourly precipitation data recorded at the following seven first-order National Weather Service rain gages: Seattle WA, Sacramento CA, Cincinnati

OH, Boston MA, Phoenix AZ, Denver CO and Tampa FL. These data were used to find the maximized (optimal) volume for each of these sites. The findings were then used to derive a set of regression equations to correlate the maximized detention volume to the watersheds runoff coefficient, local mean precipitation, and drain time (i.e., the emptying time from a basin that has captured this volume).

RAINFALL DATA ANALYSIS

Pecher (1978) modified von den Herik's work (1976) that suggested how to convert a rainfall diagram to a runoff volume diagram. This method first requires that the individual storm events from a continuous rainfall record be defined by specifying a minimum inter-event time. The hourly precipitation records for the aforementioned seven cities were obtained from the National Climate Data Center, Asheville, NC and Table 1 summarizes the beginning and ending dates of each record. The average length of record was 25 years.

Table 1 Summary of one-hour Rainfall Records used in Study

Gage Location	Length of Record	
	Start	End
Seattle	Jan 1965	Dec. 1983
Sacramento	Dec. 1983	Jan 1990
Phoenix	Nov. 1953	Dec 1983
Denver	Aug. 1948	Feb 1978
Cincinnati	Aug. 1960	Dec 1983
Tampa	Jan. 1960	Dec 1983
Boston	May 1948	Dec 1983

A minimal amount of precipitation is required before runoff occurs. As a result, not every storm event produces runoff. The incipient runoff producing precipitation ranges from 0.06 to 1.2 inch (Markar and Ubonas, 1989). A value of 0.10 inch was used in this study. Three different storm event separation time periods, 6-, 12-, and 24-h were also investigated. The average precipitation values for each of the seven gage sites are summarized in Table 2 for three event separation times. Figure 2 presents the results of an EPA study on average producing rainfall depths, P_6, using an event separation time of six hours and an incipient runoff depth of 0.1 inch (Driscoll et al., 1989). Note that the values listed in the first column of Table 2 agree with Figure 2.

Table 2 Average Event Depth in inches for Various Separation Times at Selected Gages

Gage	Storm Separation Time		
Location	6-hr	12-hr	24-hr
Seattle	0.48	0.40	0.78
Sacramento	0.61	0.72	0.82
Phoenix	0.42	0.45	0.48
Denver	0.44	0.46	0.51
Cincinnati	0.58	0.66	0.73
Tampa	0.69	0.73	1.01
Boston	0.70	0.73	0.78

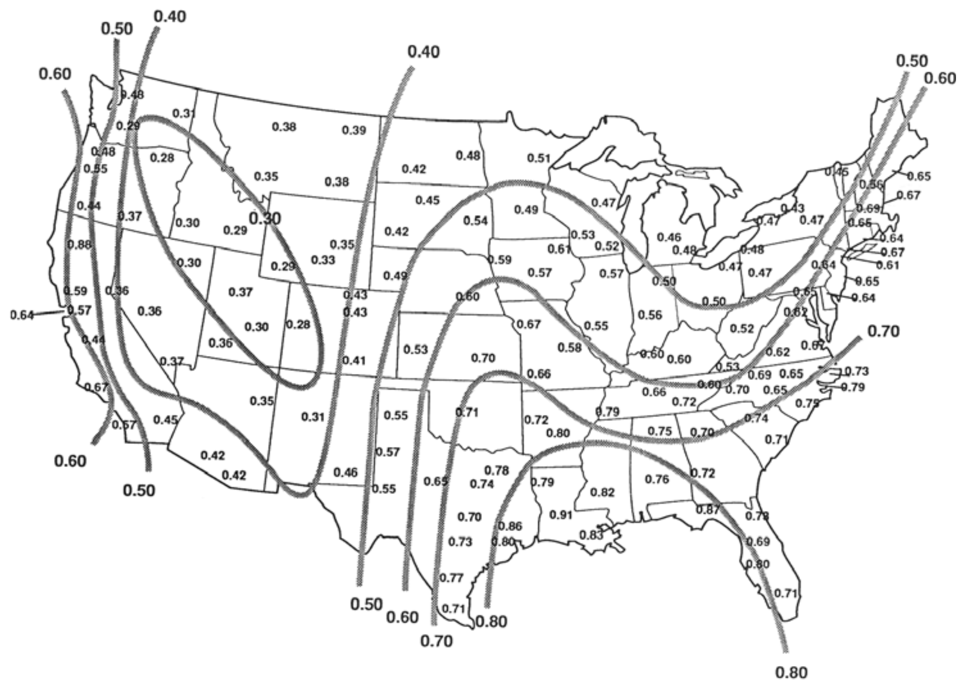

Figure 2 Distribution of Mean Precipitation, P_6, in inches for the United States

DETERMINATION OF RUNOFF CAPTURE RATE

For a single storm event, its rainfall depth can be converted to its runoff depth by watershed runoff coefficient as:

$$P_r = C\,(P_t - P_i) \qquad (1)$$

in which, P_r = runoff volume, C = watershed runoff coefficient, P_i = incipient runoff depth equal to 0.1 inch adopted in this study, and P_t = precipitation over tributary watershed. To estimate overflow runoff volume from a detention basin, it is assumed that the entire detention basin storage is available at the beginning of the storm. In practice, the drain time is determined by the required pollutant settling time. If sediment characteristics are not known, a 12-hour settling time for wet ponds and a 24-hour settling time for dry ponds are recommended for storm water quality control designs. The EPA study reported that about 80 to 90% sediment removal rate can be achieved using the above drain times. For a given detention basin that has a brim-full volume, P_p with an emptying (drain) time, T_e, its average release rate, q, is equal to:

$$q = P_p / T_e \qquad (2)$$

The maximum runoff volume, P_c, that can be potentially captured by the detention basin is equal to the basin volume plus the released runoff volume flowing through the detention basin during the storm event as:

$$P_c = P_p + q.T_d \quad (3)$$

The product, $q{\cdot}T_d$, represents the runoff volume beyond the brim-full volume that was captured as the result of the continuous release through the detention basin during the storm duration. If the runoff volume, P_r , is greater than the basin's maximum runoff capture capacity, P_c , the excess runoff volume, P_r-P_c , is assumed to overflow without any treatment. If the runoff volume, P_r , is less than the basin's maximum runoff capture volume, P_c , the runoff volume, P_r , for the event is entirely captured and treated. This assumption is considered conservative in storm water quality control management.

For a continuous record with a total of N runoff-producing storm events, adding the runoff volumes for all the storms occurring during the record period gives the total accumulated runoff volumes for the period of record. Thus, we have

$$P_{tr} = \sum_{j=1}^{j=N} P_{rj} \quad (4)$$

$$P_{to} = \sum_{j=1}^{j=N} (P_{rj} - P_{cj}) \quad \text{for } (P_{rj}\text{-}P_{cj}) > 0\text{, otherwise } (P_{rj}\text{-}P_{cj}) = 0 \quad (5)$$

in which P_{tr} = accumulated runoff volume through the record, P_{to} = accumulated overflow volume, and $j = j^{th}$ event in the record. The runoff volume capture ratio for the entire period of rainfall record is defined as

$$R_V = 1\text{-}\ P_{to} / P_{tr} \quad (6)$$

in which, R_V = runoff volume capture ratio for the rainfall record period, whose range is between zero and unity. Similarly, the runoff event capture ratio is defined:

$$R_n = 1\text{-}\ N_{to} / N \quad (7)$$

in which, R_n = runoff event capture ratio (*ECR*) for the period of rainfall record, N_{to} = number of runoff events that produced runoff volumes less than the facility's maximum capture capacity, and N = total number of runoff events.

MAXIMIZED DETENTION STOREAGE VOLUME

As discussed earlier, many storm water professionals are suggesting that dry ponds have a drain time of 24 to 48 hours and that wet ponds have a drain time of 12 to 24 hours. It is expected that a large detention volume draining in a short time will not sufficiently remove sediment. In fact, the predominant number of smaller storm events in a large basin will not be detained for sufficient time to permit the settling of smaller particles in storm water. For the purpose of this study, it is necessary to define how individual storms will be segregated from a continuous record. An earlier investigation (Urbonas et al., 1990) suggested that the storm event separation time be set at one-half of the brim-full drain time of a basin. After selecting the desired basin brim-full emptying times, individual storm events were identified by using storm event separation times equal to one-half the drain times. Next, all storms are converted to runoff depths by Eq 1 and then sorted in an ascending order. To avoid the few very large events from dominating the averages and the results, a value of runoff depth equal to 99.5 percentile runoff depth was selected as the maximum runoff depth, P_m, in this analysis. This maximum runoff depth was then used to screen out the extreme events and also to normalize the detention storage volume as:

$$P_{np} = P_p / P_m \qquad (8)$$

in which P_{np} = normalized storage volume normalized by P_{m}. To find the maximized detention storage volume, a series of incremental detention volumes were tested. For each selected storage volume, its runoff volume capture ratio, R_v, was determined by Equation 6.

Figure 3 presents an example plot of normalized detention storage volumes versus runoff volume capture ratios. The normalized runoff volume capture curve varies between zero and unity. The runoff volume capture ratio increases with respect to detention storage volume. However, the marginal increase along the curve in Figure 3 demonstrates a diminishing return when the basin storage volume continues increasing. As illustrated in Figure 3, the maximized detention storage volume is achieved at the point that has a slope of 1:1 tangent to the runoff volume capture curve. Any detention basin with a storage volume smaller than the maximized detention volume has an increasing return and any basin with a volume larger than the maximized one has a diminishing return. As a result, the maximized detention storage volume is recommended for storm water quality control designs. Cases investigated in this study indicate that the maximized storage volume captures 82 to 88% of runoff volumes.

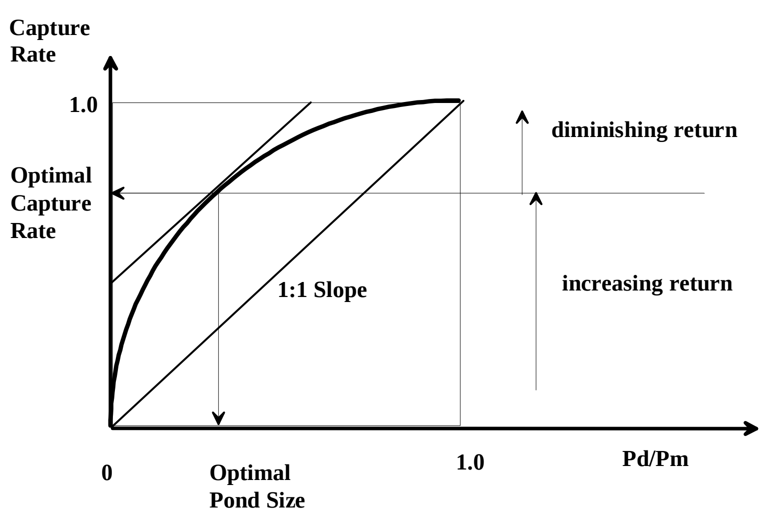

Figure 3. Determination of the Maximized Detention Size

Repeating the above process using the runoff event capture curve, another maximized detention volume can be derived as well. These two maximized storage volumes do not necessarily have the same runoff capture ratios, or R_v is not the same as R_n, and represents the percentage of total runoff volume captured, while R_n represents the percentage of the number of events captured. In design, the use of the runoff event capture ratio is similar in concept to what is used in combined sewer overflow control strategy (CSOCS). Namely, it is indicative of the annual average number of overflows in a combined sewer. Secondly, the use of runoff event capture ratio can avoid the long term analysis being dominated by very few extremely large rainfall events.

COMPUTER SOFTWARE PACKAGE - PONDRISK

PONDRISK is a computer model developed to determine the maximized detention storage volume by runoff capture rate. It contains five individual computer programs: PONDRISK, MAIN, PLINEAR, RISK, and NWSDATA. PONDRISK features menu driven with user interactions and on-screen data editing. To begin, type in "PONDRISK" and then press the RETURN key on the computer key board to continue:

C:\PONDRISK

The UP and DOWN ARROW keys are used to move the cursor on the screen. To select an option from a menu, the user enters a letter 'Y' and then presses the RETURN key to continue. To accept a default value, the user presses the RETURN key. Otherwise, the user types in a new value to replace the one on the screen. There are five options on the main menu. They are:

1. Documentation and Help
This option provides brief descriptions of PONDRISK.

2. Rainfall Statistic Analysis
This option analyzes a continuous one-hour rainfall record and divides it into individual events. It also creates a new file to save these rainfall events in a chronological sequence for later use of runoff capture and overflow analyses. This program requires the file names for input and output, interevent time in hours to separate adjacent storms, and incipient runoff depth in inches.

3. Overflow Risk Analysis for a Given Pond
This option examines the performance of an existing detention basin by its runoff capture rate and overflow risk. The program requests the input and output file names, runoff coefficient of the drainage basin, pond drain time in hours, and pond storage volume in acre-ft for a unit watershed area of 100 acres. For instance, a detention pond of 12 acre-ft for a drainage area of 200 acres will be entered with a storage volume of 6 acre-ft that covers a drainage area of 100 acres.

4. *Maximized Design Using Overflow Analysis*

This option assists the engineer to determine the maximized detention storage volume by examining the performance of a range of storage volumes. For each detention volume, the program calculates the cumulative runoff capture and overflow volume using the rainfall date file prepared in Option 2. The normalized runoff capture curve leads to the maximized detention storage volume.

5. Exit to DOS

This option allows the engineer to exit from the program.

NWSDATA is a rainfall data conversion tool developed to convert the continuous one-hour rainfall files with extension of PRN into the input format required by PONDRISK. Hourly precipitation records for rain gages can be obtained from

National Climatic Data Center E/CC42,
User Services Branch, Federal Building, Asheville, North Carolina 28801-2696.

A portion of an example data file received from NCDC is presented in Appendix A. Often the continuous rainfall record at a rain gage is divided into a series of PRN data files; for instance, PC67318A.PRN, PC67318B.PRN, PC67318C.PRN, PC67318D.PRN. Each file contains continuous hourly rainfall records for a period of time. NWSDATA is an independent program written in BASIC computer language. To run NSWDATA, the user types in

NWSDATA

On the screen, the first question asks for an output filename. The user must provide a file name, such as RAIN.DAT. The second question is how many PRN files for the gage station the user has. Using the previous example, there are four files from PC67138A.PRN to PC67138D.PRN; a number of four must be entered to this question. The third question is to enter the first rainfall data file name. The user types in PC67138A.PRN. And then press the return key to continue. NWSDATA transforms NCDC's data into the following data format which will be used in PONDRISK.

```
210019630128   0.04
220019630128   0.01
140019630129   0.01
150019630129   0.02
160019630129   0.11
170019630129   0.08
180019630129   0.07
190019630129   0.06
200019630129   0.05
210019630129   0.03
220019630129   0.01
230019630129   0.02
240019630129   0.05
 10019630130   0.01
 20019630130   0.01
 30019630130   0.02
```

40019630130 0.01
50019630130 0.03
60019630130 0.04
70019630130 0.05
80019630130 0.04

After having the first PRN data file successfully converted, NWSDATA asks for the second PRN file. After the second file name is given, NWSDATA repeats the same procedures to continue converting it. The user must follow the calendar sequence when providing the PRN files to the NSWDATA program. The output file from NWDATA consists of hourly precipitation depths. For instance, a line: "210019630128 0.04" indicates there was 0.04 inch precipitation recorded at 21:00 p.m. on January 28, 1963. The first two digits, 21, represent hours, the next two digits, 00, represent minutes, the next four digits, 1963, are for year, the next four digits, 0128, register month and date. The next seven digits are reserved for rainfall depth registered during the hour.

STUDY FOR SACRAMENTO, CA AREA

To develop the maximized water quality control storage volumes for the Sacramento, California, NWSDATA was executed to convert the rainfall record files obtained from the National Climatic Data Center into a data file, SACRA.DAT. The incipient runoff depth of 0.1 inch was adopted and subtracted from each rain storm to obtain its runoff-producing depth. Any rainfall event with a total precipitation less than or equal to 0.1 inch would be excluded from the analysis. The rainfall record in this study covered the period of time starting from January 28, 1963 to January 31, 1990. A total of 9502 hourly rainfall depths were identified during the analyses.

SACRA.DAT was used to produce the following data base files:

(1) To delineate storm events by different rainfall event separation times

Table 3 Example Data Files Generated for Sacramento Rain Gage

Option on Main Menu	Input File	Separation Time in Hours	Output File for Rainfall Statistics	Output File for Overflow Analysis
2	SACRA.DAT	6-hr	S6.OUT	S6.INP
2	SACRA.DAT	12-hr	S12.OUT	S12.INP
2	SACRA.DAT	24-hr	S24.OUT	S24.INP

These three separate computer runs resulted in six new files. Rainfall statistics such as mean, standard deviation, skewness coefficient, were tabulated in output files, S6.out, S12.out and S24.out, respectively for three rainfall separation times. A file with extension ".INP" contains all individual storm events identified by the rainfall event separation time. Such files can further be used to evaluate the performance of an existing pond or to develop the maximized storage volume.

(2) To develop maximized detention storage volume.

There are three different land uses being considered in this study. The corresponding runoff coefficients are 0.2, 0.6, and 0.9. The following separate computer runs were executed.

Table 4. Example File Names Used in Study for Sacramento Area.

Option on Main Menu	Input File	Runoff Coeff	Output File
4	S6.INP	0.2	R62.OUT
4	S6.INP	0.6	R66.OUT
4	S6.INP	0.9	R69.OUT
4	S12.INP	0.2	R122.OUT
4	S12.INP	0.6	R126.OUT
4	S12.INP	0.9	R129.OUT
4	S24.INP	0.2	R242.OUT
4	S24.INP	0.6	R246.OUT
4	S24.INP	0.9	R249.OUT

These nine computer runs generated nine output files that contain the analyses of runoff volume and event capture curves for a range of normalized pond sizes.

(3) Rainfall Statistics

A summary of rainfall statistics for the Sacramento area was given in Table 5.

Table 5 Rainfall Statistics for Sacramento Area by PONDRISK

Statistics	Rainfall	Separation	Time
	6-hr	12-hr	24-hr
Average Depth (inch)	0.61	0.72	0.82
Standard Deviation (inch)	0.62	0.76	0.92
Skewness Coef	2.96	3.50	3.44
Interevent Time (hour)	166.7	208.8	251.6

(4) Maximized Detention Volume

Figure 4 illustrates the runoff event capture curve computed for the Sacramento area using a rainfall event separation time of 12 hours and a watershed runoff coefficient of 0.5. The runoff event captured sharply increases with respect to the detention storage volume when the storage volume is less than 20% of P_m and then becomes slowly increased when the storage volume is greater than 30% of P_m. The maximized detention storage volume, P_o/P_m, is achieved by the point that has a tangent of 1:1 to the runoff event capture curve. As shown in Figure 4, the maximized point occurs when $P_o/P_m = 0.18$ and P_m in this case is equal to 3.855 inch per 100-acre watershed. For this case, the maximized detention volume would have captured 88 percent of the total number of runoff events that occurred during the period from 1963 to 1990 in the Sacramento area.

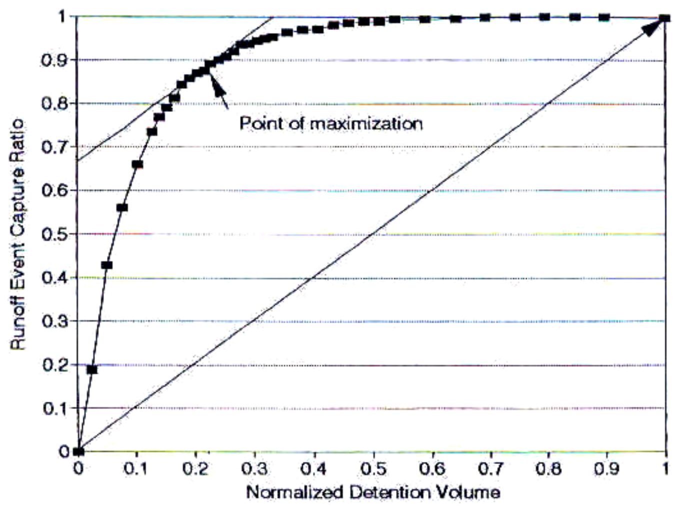

Figure 4 Sacramento Runoff Event Capture Curve for C=0.5 and Event Separation Time = 12 hr

Dricoll et al. (1989) found that a 6-hr event separation time produced most consistent statistical results when attempting to define rainfall event average values from continuous records. For convenience, the average event depth at the basin site is used to normalize the maximized detention volume as

$$\frac{P_o}{P_6} = \frac{P_o}{P_m}\frac{P_m}{P_6} \tag{9}$$

in which P_o = maximized detention volume, and P_6 = average event depth in Figure 2. Table 6 summarizes the maximized detention basin storage volumes with drain times of 12, 24 and 48 hours. The average runoff volume capture rate is about 82 to 88 percent. Figure 5 presents a design chart which correlates maximized detention volumes to watershed runoff coefficients.

Table 6 Maximized Detention Volumes, P_o/P_6, Developed for Sacramento Area

Runoff Coeff C	P_o/P_6 Drain Time in hours		
	12.000	24.000	48.000
0.200	0.187	0.271	0.458
0.500	0.526	0.784	1.229
0.700	0.737	1.096	1.712
0.950	1.004	1.497	2.312

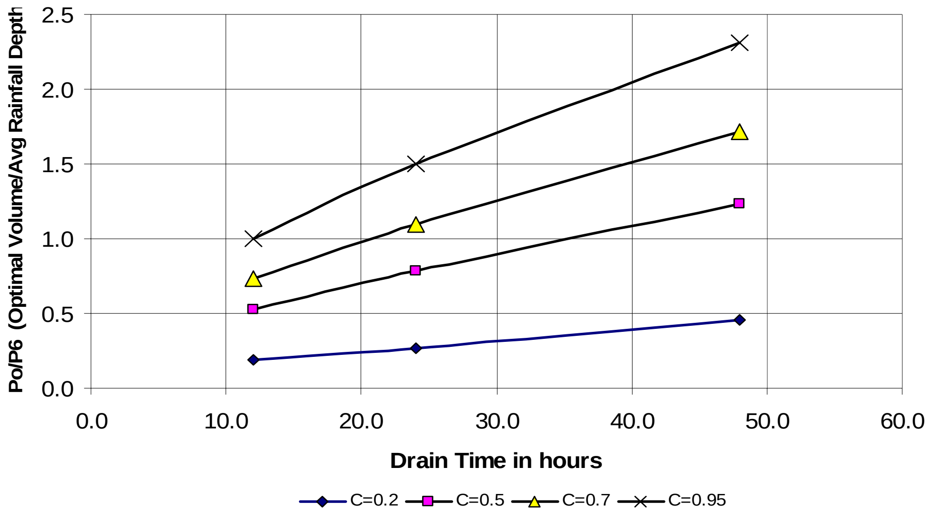

Figure 5 Maximized Detention Volumes for Storm Water Quality Control in Sacramento Area

In order to demonstrate how to use Figure 5 for detention basin design, a 10-acre watershed of multi-family in Sacramento area is used as an example. The runoff coefficient for the tributary watershed is 0.50. The proposed water quality basin drains in 24 hours. From Figure 5, the maximized size, P_o/P_6 = 0.75 for C=0.5 and drain time=24 hours. From Figure 2, P_6=0.61 inch for Sacramento area. As a result, the maximized detention volume is calculated as:

P_o = 0.75 * 0.61 = 0.49 inch for watershed area
Volume = 0.49/12 * 10 = 0.40 acre-ft for a watershed of 10 acres

A detention basin of 0.40 acre-ft is expected to capture approximately 82 to 88% of runoff volumes generated from the tributary watershed.

STUDY FOR SEVEN MAJOR METROPOLITAN AREAS

The computer model, PONDRISK (Guo, 1986), was used to cope with the large amount of continuous rainfall records. A continuous rainfall record was analyzed to general three data sets using the rainfall event separation times of 6, 12, and 24 hours. Next, these three data sets are loaded to a detention basin with a watershed runoff coefficient of 0.2, 0.5, 0.7 or 0.95. The maximized detention volumes were then determined from the runoff volume capture curve. Repeat the same procedure to produce the second set of maximized detention volumes using the runoff event capture curve. Tables 7 and 8 list the values of P_o/P_6 for all combinations among drain times, runoff coefficients, and storm event separation times.

Table 7 Maximized Detention Volumes for Runoff Volume Capture

Runoff Coef. *C*	Seattle	Sacramento	Phoenix	Denver	Boston	Tempa	Cincin
	12-hr Drain Time						
0.200	0.176	0.187	0.195	0.211	0.332	0.316	0.198
0.500	0.505	0.526	0.569	0.623	0.890	0.884	0.593
0.700	0.729	0.737	0.800	0.885	1.230	1.242	0.825
0.950	0.985	1.004	1.110	1.207	1.668	1.652	1.134
	24-hr Drain Time						
0.200	0.234	0.271	0.224	0.284	0.341	0.336	0.279
0.500	0.678	0.784	0.704	0.780	0.950	0.931	0.794
0.700	1.002	1.096	0.923	1.123	1.275	1.299	1.110
0.950	1.338	1.497	1.269	1.364	1.786	1.757	1.460
	48-hr Drain Time						
0.200	0.446	0.458	0.277	0.289	0.367	0.401	0.280
0.500	1.197	1.229	0.794	0.801	1.010	1.118	0.787
0.700	1.694	1.712	1.105	1.126	1.301	1.578	1.119
0.950	2.288	2.312	1.476	1.493	1.891	1.954	1.519

Table 8 Maximized Detention Volumes for Runoff Event Capture

Runoff Coef. *C*	Seattle	Sacramento	Phoenix	Denver	Boston	Tempa	Cincin
	12-hr Drain Time						
0.200	0.187	0.191	0.228	0.204	0.187	0.208	0.224
0.500	0.488	0.533	0.663	0.586	0.567	0.635	0.665
0.700	0.700	0.738	0.728	0.805	0.799	0.873	0.887
0.950	0.970	0.998	1.050	1.107	0.997	1.037	1.037
	24-hr Drain Time						
0.200	0.221	0.259	0.247	0.254	0.202	0.243	0.275
0.500	0.746	0.736	0.729	0.612	0.594	0.710	0.749
0.700	0.886	0.897	1.079	1.034	0.721	1.017	1.067
0.950	1.192	1.163	1.275	1.221	0.914	1.055	1.418
	48-hr Drain Time						
0.200	0.362	0.428	0.266	0.271	0.276	0.339	0.300
0.500	1.061	0.925	0.788	0.817	0.741	0.873	0.843
0.700	1.338	1.320	0.807	0.858	0.973	1.243	1.131
0.950	1.726	1.575	1.026	1.189	1.368	1.486	1.496

Using Tables 7 and 8 as the data base, an investigation on a statistically valid relationship was conducted between P_o/P_6, and C for a specified drain time as:

$$\frac{P_o}{P_6} = aC + b \tag{10}$$

Regression analyses were performed to determine the coefficients for Eq 10. Two sets of coefficients were developed: one for the runoff volume capture curve and another for the runoff event capture curve. Table 9 lists the constants, a, b in Eq 10 and correlation coefficient, r^2, as:

Table 9 Coefficients for Regression Analyses

Drain Time		Runoff	Volume		Runoff	Event
hours	*a*	*b*	r^2	*a*	*b*	r^2
12-hr	1.360	-0.034	0.80	1.096	0.010	0.97
24-hr	1.619	-0.027	0.93	1.256	0.030	0.91
48-hr	1.983	-0.021	0.84	1.457	0.063	0.85

For the seven gauging sites tested, the regression equation shows excellent correlation coefficients, r^2, ranging from 0.80 to 0.97. Generally the event capture ratios show higher correlation. At these seven test sites used in this study, Eq 10 results in a runoff capture ratio between 82 and 88 percent for a long term operation.

FIELD OBSERVATIONS IN DENVER AREA

In 1990, a pond followed by wetland system was installed in the Shop Creek watershed by the Cherry Creek Basin Water Quality Authority (CCBWQA) and the City of Aurora, Colorado. This system receives runoff from a 222.6 hectare (550-acre) watershed that has mostly single family residential land use. The total imperviousness of this watershed is approximately 40 percent. The system has a permanent pool volume of 5,900 cubic meters (4.8 acre-feet), namely 2.65 watershed millimeters (0.10 inches). Above the permanent pool the pond also has a brim-full surcharge detention volume of 11,230 cubic meters (9.1 acre-feet), namely 5.04 watershed millimeters (0.20 inches) that drains in 30 hours. For convenience, the runoff coefficients at various sites can be converted into the imperviousness percentage by the third order regression equation as

$$C = 8.58*10^{-7} I^3 - 7.80*10^{-5} I^2 + 7.74*10^{-3} I + 0.04 \qquad (11)$$

in which, C = runoff coefficient and I = percentage of watershed imperviousness. Equation 11 for this catchment having an imperviousness of 40% produces a C = 0.30.

Because this equation was derived using data collected nationwide over a two year period (EPA 1983), it may have broad applicability in United States for estimating the runoff coefficient for smaller storm events (i.e., 2-year and less). Also, since the predominant population of urban stormwater runoff events are smaller than the 2-year event, its use in determining the maximized detention volume is justified and probably more reliable than using published table values of runoff coefficients.

Next we proceed to find the maximized detention volume, P_o, for Shop Creek watershed using the event capture ratio approach. Using Figure 2 we find that P_6 = 10.9 mm (0.43 inches) for the Denver area. Using C = 0.30 in Eq 10, along with the values of *a* and *b* coefficients from Table 9 for runoff event capture, we find for a 24-hour drain time the maximized detention volume is:

$$\frac{P_o}{P_6} = 1.256 * C + 0.030 = 0.4068$$

$$P_o = 10.9 * 0.4068 = 4.43 \text{ watershed millimeters (0.174 inches)}$$

The Urban Drainage and Flood Control District, Denver, Colorado, in cooperation with the Cherry Creek Basin Water Quality Authority collected field data from this system since its installation in 1990. A total of 107 storm events occurred during the 1990, 1991 and 1992 monitoring seasons (i.e., May through September periods). Using these data, it was found that the average runoff coefficient for this watershed was $C = 0.29$. Using the aforementioned procedure, it was found that the maximized storm water quality control volume is determined at 85 to 88 percentile on the runoff event capture curve. At the same time, data collected at the Shop Creek site show that 87 percent of the observed 107 storm runoff events having a volume less than 4.43 watershed millimeters (0.174 inches). This amount of volume surcharges above the permanent pool and empties out through an orifice outlet in approximately 24 hours. Water quality data were also collected from 1990 through 1992 for a total of 36 storm events. It was found that 78% of total suspended solids were removed by the detention system during storm events versus the predicted removal rate of 77 percent when using the procedure developed by EPA (Driscoll et al 1989).

CONCLUSION

Design of a storm water quality control facility system has to be balanced between its runoff capture capability and cost effectiveness. The simple optimization techniques developed in this study estimates the required storm water quality detention volume that will on an average capture 82 to 88% of runoff volumes or events generated from the tributary watershed. The procedure based on runoff volume capture will yield a larger basin volume than that based on event capture. The latter is probably more representative of the frequency of impacts on the receiving systems and is similar to average annual overflows often cited when designing combined sewer overflow controls.

This procedure was one of several investigated by the Water Resources Division of the City and County of Sacramento, California. The result obtained using this method has been compared with rainfall/runoff continuous models. It was found that more detailed routing procedure yielded very similar results, yet required much more time and resources to use. As a result of this investigation, the above procedure has been adopted as a standard hydrologic procedure by the Water Resources Division, Sacramento, California for sizing on-site water quality detention facilities (Hydrology Standard 1994).

This method has also been evaluated by three-year field data collected from Shop Creek project by Urban Drainage and Flood Control District, Denver, Colorado. Comparison with the runoff volume distribution over 3-year monitoring period showed excellent agreement. Therefore, Eq 10 was then adopted for developing the minimum storm water capture volumes (*WQCV*) for on-site storm water quality control facilities by Urban Drainage and Flood Control District, Denver, Colorado. Various designs of storm water devices have been developed using Eq 10 for the Denver metropolitan area (UDFCD, 2001).

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