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TECHNICAL MEMORANDUM

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SUBJECT: Estimation of Runoff and Storage Volumes for Use with Full Spectrum Detention

DATE: March 26, 2015

The purpose of this memorandum is to document the process used to develop new equations to estimate the runoff volumes and required storage volumes for use with full spectrum detention design. The concept of full spectrum detention is described in the Storage chapter of the *Urban Storm Drainage Criteria Manual* (USDCM) and other technical papers available for download at www.udfcd.org. The as-yet unpublished Storage chapter of the 2015 USDCM allows the use of simplified equations for determining full spectrum detention design volumes for watersheds less than 10 acres.

The runoff volume equations developed in this memorandum were based on Colorado Urban Hydrograph Procedure (CUHP 2005, v1.4.4) modeling and one-hour rainfall depths in the Rainfall chapter of the USDCM.

The runoff volume equations are only valid for one-hour rainfall depths between 0.94 and 3.4 inches as shown in Table 1. These one-hour rainfall depths were temporally distributed over a two-hour period to create design storms consistent with CUHP protocol for the 2-, 5-, 10-, 25-, 50-, 100, and 500-year return periods.

Table 1: Average one-hour rainfall depth in the Denver region, as a function of probability of occurrence.

Recurrence Interval (Years)	Probability of Occurrence	Rainfall Depth (Inch)
2	0.50	0.95
5	0.20	1.34
10	0.10	1.64
25	0.04	2.02
50	0.02	2.32
100	0.01	2.61
500	0.002	3.29

CUHP was used to evaluate 2,020 subcatchments from recent UDFCD master planning studies. Subcatchments having a width/length ratio, slope, or centroid length outside one standard deviation of the mean of the data set were discarded in order to limit data scatter, leaving 1,203 subcatchments for further evaluation. The CUHP model was run for all 1,203 subcatchments and return periods with the hydrologic parameters listed in Table 2. Watershed characteristics (e.g., size, shape, slope, location of centroid, and imperviousness) were taken directly from the master planning studies. Various combinations of Soil Type (A, B, and C/D) were evaluated for each subcatchment.

Table 2: hydrologic parameters used in the CUHP modeling.

Soil Group	**Historic Impervious Percentage (%)**	**Pervious Depression Storage (inch)**	**Impervious Depression Storage (inch)**	**Initial Infiltration Rate (in/hr)**	**Horton's Decay Coefficient ($second^{-1}$)**	**Final Infiltration Rate (in/hr)**
HSG A	2	0.35	0.1	5.0	0.0070	1.0
HSG B	2	0.35	0.1	4.5	0.0018	0.6
HSG C	2	0.35	0.1	3.0	0.0018	0.5

By performing a multiple regression analysis on those remaining CUHP subcatchments, equations were developed for the 2-, 5-, 10-, 25-, 50-, 100- and 500-yr return periods for each hydrologic soil group and combined to provide the following watershed runoff equations:

$$V_{Runoff\_2yr} = P_1 A[(0.084 I^{1.440})A\% + (0.084 I^{1.173})B\% + (0.084 I^{1.094})CD\%] \quad (1)$$

$$V_{Runoff\_5yr} = P_1 A[(0.084 I^{1.350})A\% + (0.077 I + 0.007)B\% + (0.070 I + 0.014)CD\%] \quad (2)$$

$$V_{Runoff\_10yr} = P_1 A[(0.085 I^{1.220})A\% + (0.069 I + 0.016)B\% + (0.061 I + 0.024)CD\%] \quad (3)$$

$$V_{\_Runoff\_25yr} = P_1 A[(0.082 I + 0.004)A\% + (0.055 I + 0.031)B\% + (0.048 I + 0.038)CD\%] \quad (4)$$

$$V_{Runoff\_50yr} = P_1 A[(0.078 I + 0.009)A\% + (0.049 I + 0.038)B\% + (0.044 I + 0.043)CD\%] \quad (5)$$

$$V_{Runoff\_100yr} = P_1 A[(0.073 I + 0.015)A\% + (0.043 I + 0.045)B\% + (0.038 I + 0.050)CD\%] \quad (6)$$

$$V_{Runoff\_500yr} = P_1 A[(0.064 I + 0.025)A\% + (0.036 I + 0.053)B\% + (0.031 I + 0.058)CD\%] \quad (7)$$

Where $V_{Runoff\_\#yr}$ is the runoff volume for the given return period (acre-feet), P_1 is the one-hour rainfall depth (inches), *A* is the contributing watershed area (acres), *I* is the percentage imperviousness (expressed as a decimal), and *A%*, *B%*, and *CD%* are the percent of each hydraulic soil group (also expressed as a decimal). It should be noted that these equations are a mix of linear and power functions. The CUHP Excel™ workbooks and multiple regression analysis files were saved in an archival folder named "*CUHP_Runoff_Volume_Equations.zip*" in the master planning reference library.

In order to develop estimated storage volume equations, the UD-FSD workbook was used to model full spectrum detention basins. UD-FSD was updated to v1.09 to include the runoff volume equations described above and the new EURV equation outlined in a Technical Memorandum dated March 23, 2015. UD-FSD v.1.09 was run for watershed areas of 5-, 10-, 20-, 40-, 60-, and 100-acres at 33%, 67%, and 100% imperviousness. Design storms included the 2-, 5-, 10-, 25-, 50-, and 100-year return period. Hydrologic soil groups A, B, and C/D were evaluated separately. WQCV drain times of 40 hours, 24 hours, and 12 hours were also evaluated resulting in a total of 972 model runs). The resulting maximum required storage volumes were divided by the corresponding runoff hydrograph volume and those ratios are shown in Tables 3 through 5 for the 40 hour WQCV drain time scenarios.

Table 3: UD-FSD Storage Volume Reduction Factors for HSG A Soils (40 hour drain time).

UD-FSD Model Results for HSG A Soils (40-hr drain time): V_{STORED} / V_{INFLOW}							
Watershed Area =	**5.00**	**10.00**	**20.00**	**40.00**	**60.00**	**100.00**	**AVG**
Watershed Imperviousness =	**33%**						
2-Year Ratio (A soils) =	94.6%	94.3%	93.9%	93.7%	93.5%	93.4%	**94%**
5-Year Ratio (A soils) =	95.2%	94.9%	94.5%	94.3%	94.1%	94.0%	**94%**
10-Year Ratio (A soils) =	95.4%	95.4%	95.0%	94.8%	94.6%	94.5%	**95%**
25-Year Ratio (A soils) =	64.6%	71.5%	70.7%	70.3%	69.9%	69.6%	**69%**
50-Year Ratio (A soils) =	59.4%	62.0%	61.9%	62.8%	63.6%	64.4%	**62%**
100-Year Ratio (A soils) =	59.6%	61.2%	61.3%	62.7%	63.6%	64.8%	**62%**
Watershed Imperviousness =	**67%**						
2-Year Ratio (A soils) =	96.2%	96.0%	95.9%	95.8%	95.7%	95.6%	**96%**
5-Year Ratio (A soils) =	96.8%	96.6%	96.3%	96.2%	95.9%	95.9%	**96%**
10-Year Ratio (A soils) =	97.2%	97.0%	96.7%	96.5%	96.3%	96.2%	**97%**
25-Year Ratio (A soils) =	82.8%	82.4%	81.7%	87.2%	86.2%	85.9%	**84%**
50-Year Ratio (A soils) =	76.1%	75.8%	75.5%	81.0%	79.6%	79.6%	**78%**
100-Year Ratio (A soils) =	74.4%	74.2%	74.2%	77.2%	77.0%	77.6%	**76%**
Watershed Imperviousness =	**100%**						
2-Year Ratio (A soils) =	95.9%	95.8%	95.7%	95.6%	95.5%	95.4%	**96%**
5-Year Ratio (A soils) =	96.7%	96.5%	96.3%	96.2%	96.0%	95.9%	**96%**
10-Year Ratio (A soils) =	97.1%	96.9%	96.7%	96.5%	96.3%	96.3%	**97%**
25-Year Ratio (A soils) =	90.9%	90.4%	89.8%	89.8%	92.4%	92.1%	**91%**
50-Year Ratio (A soils) =	85.9%	85.1%	83.9%	84.1%	88.0%	87.8%	**86%**
100-Year Ratio (A soils) =	82.0%	81.7%	81.2%	81.9%	84.3%	84.2%	**83%**

Table 4: UD-FSD Storage Volume Reduction Factors for HSG B Soils (40 hour drain time).

UD-FSD Model Results for HSG B Soils (40-hr drain time): V_{STORED} / V_{INFLOW}							
Watershed Area =	**5.00**	**10.00**	**20.00**	**40.00**	**60.00**	**100.00**	**AVG**
Watershed Imperviousness =	**33%**						
2-Year Ratio (B soils) =	95.0%	94.7%	94.4%	94.2%	94.0%	94.0%	**94%**
5-Year Ratio (B soils) =	88.0%	87.6%	86.9%	86.3%	85.7%	85.3%	**87%**
10-Year Ratio (B soils) =	70.1%	69.7%	68.6%	67.6%	66.4%	65.7%	**68%**
25-Year Ratio (B soils) =	52.6%	52.3%	51.1%	50.6%	50.6%	51.6%	**51%**
50-Year Ratio (B soils) =	49.0%	49.0%	48.6%	49.3%	49.7%	51.0%	**49%**
100-Year Ratio (B soils) =	50.3%	50.2%	50.0%	51.4%	52.5%	54.0%	**51%**
Watershed Imperviousness =	**67%**						
2-Year Ratio (B soils) =	96.2%	96.0%	95.7%	95.5%	95.3%	95.3%	**96%**
5-Year Ratio (B soils) =	96.0%	95.7%	96.1%	95.9%	95.6%	95.5%	**96%**
10-Year Ratio (B soils) =	81.7%	81.4%	85.8%	85.0%	84.3%	83.6%	**84%**
25-Year Ratio (B soils) =	67.3%	66.8%	73.6%	72.6%	71.5%	70.6%	**70%**
50-Year Ratio (B soils) =	61.4%	61.3%	66.4%	65.5%	65.1%	65.3%	**64%**
100-Year Ratio (B soils) =	60.4%	60.5%	62.9%	63.6%	63.9%	64.4%	**63%**
Watershed Imperviousness =	**100%**						
2-Year Ratio (B soils) =	95.8%	95.6%	95.3%	95.2%	95.0%	95.0%	**95%**
5-Year Ratio (B soils) =	96.5%	96.3%	96.0%	95.8%	95.6%	95.5%	**96%**
10-Year Ratio (B soils) =	89.3%	88.9%	88.4%	90.7%	90.4%	89.9%	**90%**
25-Year Ratio (B soils) =	79.7%	79.0%	78.0%	82.9%	82.3%	81.6%	**81%**
50-Year Ratio (B soils) =	73.2%	72.4%	71.2%	77.3%	76.5%	75.7%	**74%**
100-Year Ratio (B soils) =	69.4%	69.1%	68.5%	72.5%	72.2%	72.1%	**71%**

Table 5: UD-FSD Storage Volume Reduction Factors for HSG C&D Soils (40 hour drain time).

UD-FSD Model Results for HSG C&D Soils (40-hr draintime): V_{STORED} / V_{INFLOW}							
Watershed Area =	**5.00**	**10.00**	**20.00**	**40.00**	**60.00**	**100.00**	**AVG**
Watershed Imperviousness =				**33%**			
2-Year Ratio (C/D soils) =	94.9%	94.5%	94.1%	93.9%	93.7%	93.6%	**94%**
5-Year Ratio (C/D soils) =	75.2%	74.8%	73.6%	72.6%	71.6%	70.7%	**73%**
10-Year Ratio (C/D soils) =	58.8%	58.4%	57.1%	56.1%	54.8%	53.8%	**56%**
25-Year Ratio (C/D soils) =	46.2%	46.3%	45.8%	46.5%	46.8%	47.4%	**46%**
50-Year Ratio (C/D soils) =	45.9%	46.3%	46.3%	47.7%	48.5%	49.8%	**47%**
100-Year Ratio (C/D soils) =	47.3%	47.6%	47.6%	49.3%	50.2%	51.4%	**49%**
Watershed Imperviousness =				**67%**			
2-Year Ratio (C/D soils) =	96.1%	95.8%	95.5%	95.3%	95.1%	95.0%	**95%**
5-Year Ratio (C/D soils) =	86.2%	89.8%	89.1%	88.5%	87.9%	87.4%	**88%**
10-Year Ratio (C/D soils) =	72.1%	79.5%	78.1%	77.1%	75.9%	74.9%	**76%**
25-Year Ratio (C/D soils) =	59.4%	67.8%	66.2%	65.2%	63.6%	62.9%	**64%**
50-Year Ratio (C/D soils) =	56.9%	61.7%	60.6%	60.7%	60.6%	61.0%	**60%**
100-Year Ratio (C/D soils) =	56.8%	59.8%	59.0%	59.9%	60.4%	61.1%	**60%**
Watershed Imperviousness =				**100%**			
2-Year Ratio (C/D soils) =	95.6%	95.4%	95.1%	95.0%	94.7%	94.7%	**95%**
5-Year Ratio (C/D soils) =	92.9%	92.6%	94.3%	93.9%	93.4%	93.1%	**93%**
10-Year Ratio (C/D soils) =	82.9%	82.4%	86.6%	86.0%	85.0%	84.3%	**85%**
25-Year Ratio (C/D soils) =	72.7%	72.1%	78.5%	77.6%	76.1%	75.1%	**75%**
50-Year Ratio (C/D soils) =	66.7%	66.5%	72.9%	71.8%	70.1%	69.7%	**70%**
100-Year Ratio (C/D soils) =	65.5%	65.2%	68.5%	68.1%	67.9%	68.2%	**67%**

For each return period, the average storage/runoff ratio for all six areas was calculated as shown in the last column of Tables 3 through 5. The average storage/runoff ratio was plotted vs. imperviousness for each of the three hydrologic soil groups and a power regression was applied as shown in Figure 1 for the 100-year return period. Similar power regression plots were developed for the other five return periods also. The resulting storage/runoff ratio equations were then multiplied by the runoff volume equations (converted to watershed inches instead of acre-feet as expressed in Equations 1-6) to develop new storage volume equations. The resulting storage volume equations (in watershed inches) are shown in Equations 8 through 13. The same process was repeated for WQCV drain times of 24 hours and 12 hours. The results were almost identical since the WQCV is such a small percentage of the total detention volume. Therefore, the equations developed for the 40-hour WQCV drain time are considered suitable for all WQCV drain times.

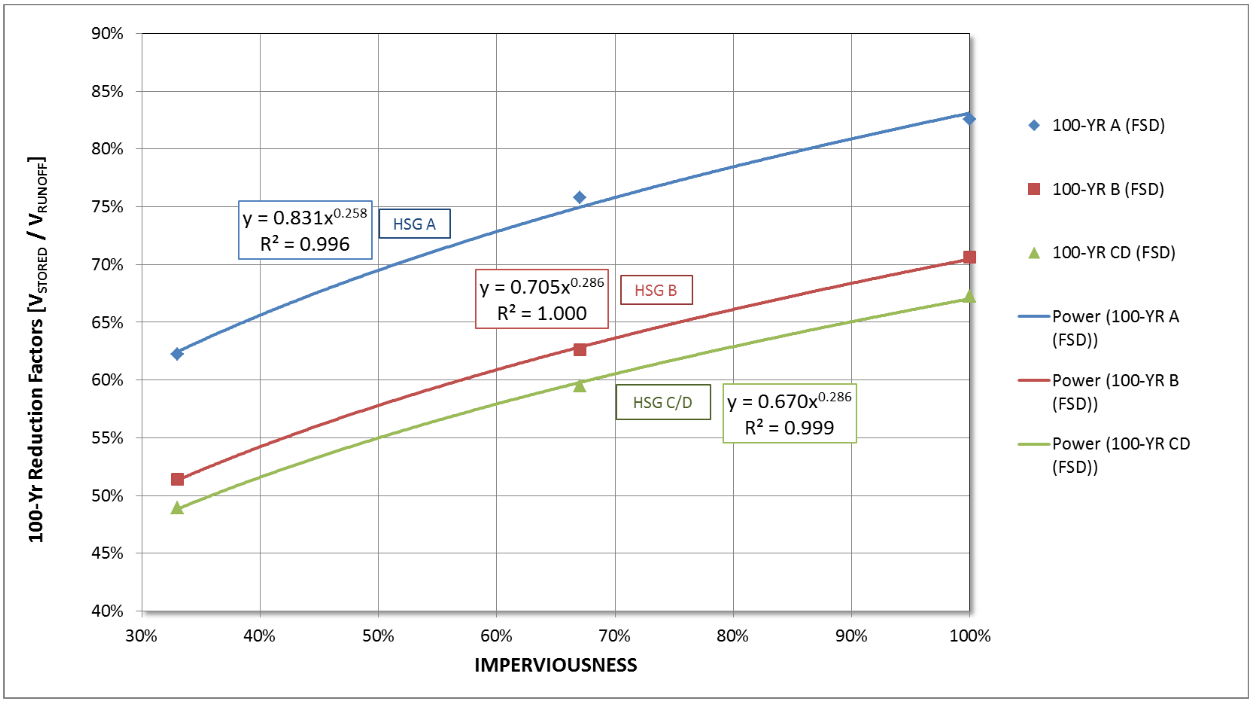

Figure 1: 100-yr Power regression equations for ratio of stored volume to runoff volume as a function of hydrologic soil group and imperviousness.

$$V_{Storage\_2yr}(in) = P_1[(0.968I^{1.458})A\% + (0.964I^{1.183})B\% + (0.962I^{1.104})CD\%] \quad (8)$$

$$V_{Storage\_5yr}(in) = P_1[(0.973I^{1.368})A\% + (0.900I^{1.098} + 0.082I^{0.098})B\% + (0.795I^{1.226} + 0.159I^{0.226})CD\%] \quad (9)$$

$$V_{Storage\_10yr}(in) = P_1[(0.988I^{1.237})A\% + (0.751I^{1.254} + 0.174I^{0.254})B\% + (0.630I^{1.371} + 0.248I^{0.371})CD\%] \quad (10)$$

$$V_{Storage\_25yr}(in) = P_1[(0.903I^{1.246} + 0.044I^{0.246})A\% + (0.538I^{1.409} + 0.303I^{0.409})B\% + (0.437I^{1.438} + 0.346I^{0.438})CD\%] \quad (11)$$

$$V_{Storage\_50yr}(in) = P_1[(0.810I^{1.291} + 0.093I^{0.291})A\% + (0.437I^{1.368} + 0.339I^{0.368})B\% + (0.366I^{1.346} + 0.358I^{0.346})CD\%] \quad (12)$$

$$V_{Storage\_100yr}(in) = P_1[(0.728I^{1.258} + 0.150I^{0.258})A\% + (0.364I^{1.286} + 0.381I^{0.286})B\% + (0.306I^{1.286} + 0.402I^{0.286})CD\%] \quad (13)$$

Where $Vstorage\_{\#yr}$ is the calculated storage volume (watershed inches), P_1 is the one-hour rainfall depth corresponding to the return period (inches), I is the percentage imperviousness (expressed as a decimal), and *A%*, B%, and C*D%* are the percent of each hydraulic soil group (expressed as a decimal). A comparison of the 100-yr runoff and storage volumes are shown in Figure 2.

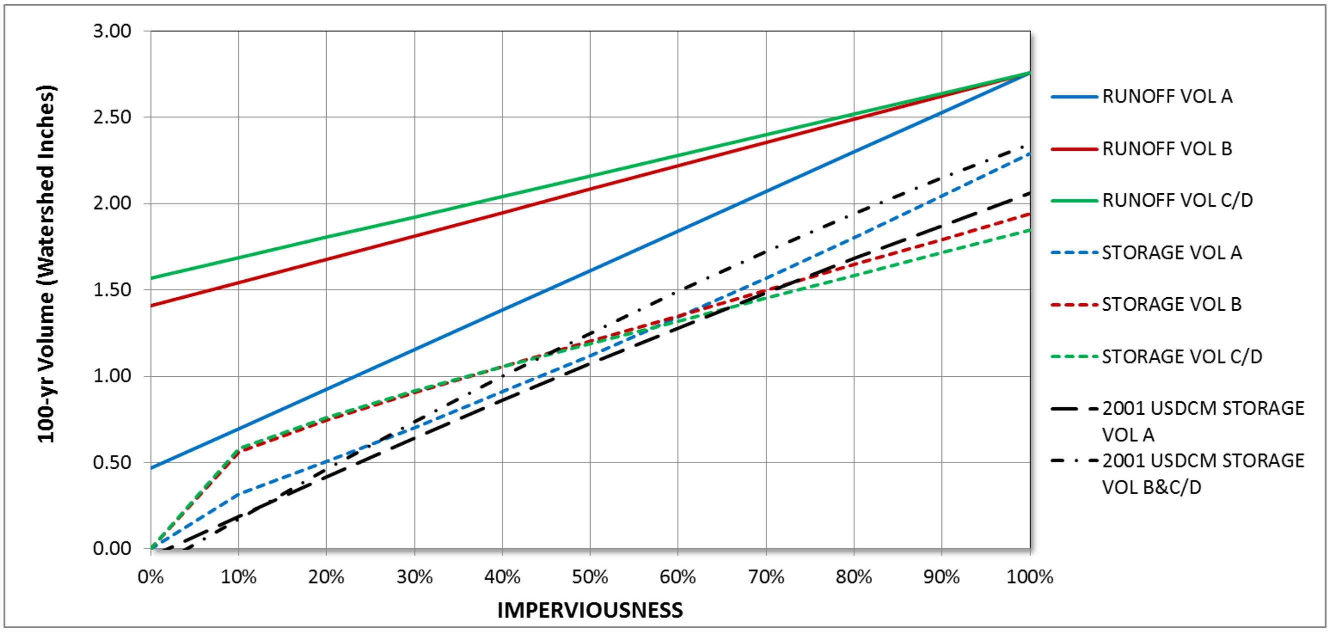

Figure 2: Plot of 100-yr runoff volumes and storage volumes.

Equations 8 through 13 can be expressed in acre-feet as shown in Equations 14 through 19.

$$V_{Storage\_2yr}(ac-ft) = P_1 A[(0.081I^{1.458})A\% + (0.080I^{1.183})B\% + (0.080I^{1.104})CD\%] \quad (14)$$

$$V_{Storage\_5yr}(ac-ft) = P_1 A[(0.081I^{1.368})A\% + (0.075I^{1.098} + 0.007I^{0.098})B\% + (0.066I^{1.226} + 0.013I^{0.226})CD\%] \quad (15)$$

$$V_{Storage\_10yr}(acft) = P_1 A[(0.082I^{1.237})A\% + (0.063I^{1.254} + 0.015I^{0.254})B\% + (0.052I^{1.371} + 0.021I^{0.371})CD\%] \quad (16)$$

$$V_{Storage\_25yr}(ac-ft) = P_1 A[(0.075I^{1.246} + 0.004I^{0.246})A\% + (0.045I^{1.409} + 0.025I^{0.409})B\% + (0.036I^{1.438} + 0.029I^{0.438})CD\%] \quad (17)$$

$$V_{Storage\_50yr}(ac-ft) = P_1 A[(0.067I^{1.291} + 0.008I^{0.291})A\% + (0.036I^{1.368} + 0.028I^{0.368})B\% + (0.031I^{1.346} + 0.030I^{0.346})CD\%] \quad (18)$$

$$V_{Storage\_100yr}(ac-ft) = P_1 A[(0.061I^{1.258} + 0.012I^{0.258})A\% + (0.030I^{1.286} + 0.032I^{0.286})B\% + (0.025I^{1.286} + 0.034I^{0.286})CD\%] \quad (19)$$

Where $V_{STORAGE\_\#yr}$ is the storage volume (acre-feet), P_1 is the one-hour rainfall depth corresponding to the return period (in), *A* is the watershed area in acres, *I* is the percentage imperviousness (expressed as a decimal), and *A%*, and *B&CD%* are the percent of each hydraulic soil group (expressed as a decimal).

<u>Example Problem 1:</u> An 18-acre Denver watershed is found to have the following characteristics: 50% imperviousness, 15% HSG A, 25% HSG B, and 60% HSG C&D. The 100-year one-hour rainfall depth is 2.6 inches.

Determine A) the estimated runoff hydrograph volume for the 100-year return period, and B) the estimated storage volume required for a full spectrum detention basin to accommodate the 100-year flood.

A) Analysis:

$$V_{Runoff_{100yr}} = P_1 A[(0.073I + 0.015)A\% + (0.043I + 0.045)B\% + (0.038I + 0.050)CD\%]$$

$$V_{Runoff\_100yr} = 2.6(18)[(0.073(0.5) + 0.015)(0.15) + (0.043(0.5) + 0.045)(0.25) + (0.038(0.5) + 0.050)(0.60)]$$

$$\boldsymbol{V_{Runoff\_100yr} = 3.08\ acre - feet.}$$

B) Analysis:

$$V_{Storage\_100yr} = P_1 A[(0.061I^{1.258} + 0.012I^{0.258})A\% + (0.030I^{1.286} + 0.032I^{0.286})B\% + (0.025I^{1.286} + 0.034I^{0.286})CD\%]$$

$$V_{Storage\_100yr} = 2.6(18)[(0.061(0.5)^{1.258} + 0.012(0.5)^{0.258})(0.15) + (0.030(0.5)^{1.286} + 0.032(0.5)^{0.286})(0.25) + (0.025(0.5)^{1.286} + 0.034(0.5)^{0.286})(0.6)]$$

$$\boldsymbol{V_{Storage\_100yr} = 1.77\ acre - feet.}$$

<u>Solution:</u> The 100-year required storage volume of 1.77 acre-feet is **<u>57%</u>** of the runoff hydrograph of 3.08 acre-feet.