CHAPTER 6

EXAMPLE PROBLEMS

Example 6.1

HYDROLOGY

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EXAMPLE 6.1

INTRODUCTION

Example 6.1 (referred to as **Example 1** in **Chapter 5** develops the hydrology of a 25-acre watershed drained by two distinct channels. A study point is established at the confluence of these channels. The proposed development disturbs 11.9 acres.

Several design elements are illustrated in this problem. **Example 6.1A** uses SCS TR-55 methodology for determining the peak discharge from the watershed. It also shows the impact of the time of concentration, t_c , on the peak discharge.

Example 6.1B uses the Rational Method* for determining the peak discharge from the same watershed described in **6.1A**.

Example 6.1C uses the SCS Tabular Method and divides the watershed into sub-watersheds. The watershed analyzed in this example is simple, but it serves to illustrate the conditions where a development may be large enough or diverse enough to warrant the use of sub-watersheds.

Example 6.1D uses the Rational Method to determine the peak discharge from the sub-watersheds described in **6.1C**.

* *Note that the 25-acre drainage area exceeds the Rational Method's recommended limit of 20 acres, but the method is still used in this example for comparison purposes.*

EXAMPLE 6.1A

Example 6.1A uses SCS TR-55 for the hydrologic analysis of the 25-acre watershed, which is considered homogeneous. The critical design decision is the selection of the post-developed time of concentration, t_c, flow path. Typically, the pre-developed condition t_c flow path is the path from the most hydrologically distant point. The post-developed condition flow path, however, should represent the peak discharge. Note that if the watershed has more than one flow path, the longest one may not be the most representative of the watershed's peak. Therefore, engineering judgement may be required to select the appropriate path. This example highlights the effect that the t_c flow path can have on the peak discharge.

Given:

A 25-acre watershed consisting of woods and agricultural lands. Two channels drain the 25 acres to the study point. The study point is at the confluence of these two channels. The proposed development disturbs 11.9 acres. Refer to **Figure 6-1** for a schematic drawing of the pre- and post-developed condition watershed.

Find:

The pre- and post-developed peak discharges from the watershed using SCS methods. The pre-developed t_c flow path should be the flow path from the most hydrologically distant point to the watershed study point. The selected post-developed t_c flow path should be the path that is most representative of the proposed development and the associated increase in peak discharge.

Solution:

Pre- and post-developed peak discharges for the watershed, as shown in **Figure 6-1**, can be calculated using the SCS TR-55 Graphical Peak Discharge Method or the Tabular Peak Discharge Method. For this example, the watershed is considered homogeneous, so the Graphical Peak Discharge Method will be used. The effect of the selected t_c flow path on the peak discharge is summarized in **Table 6-1**. TR-55 worksheets are included at the end of this example.

FIGURE 6.1 - 1a,b
Example 1 - 25-Acre Watershed Pre- and Post-developed Condition

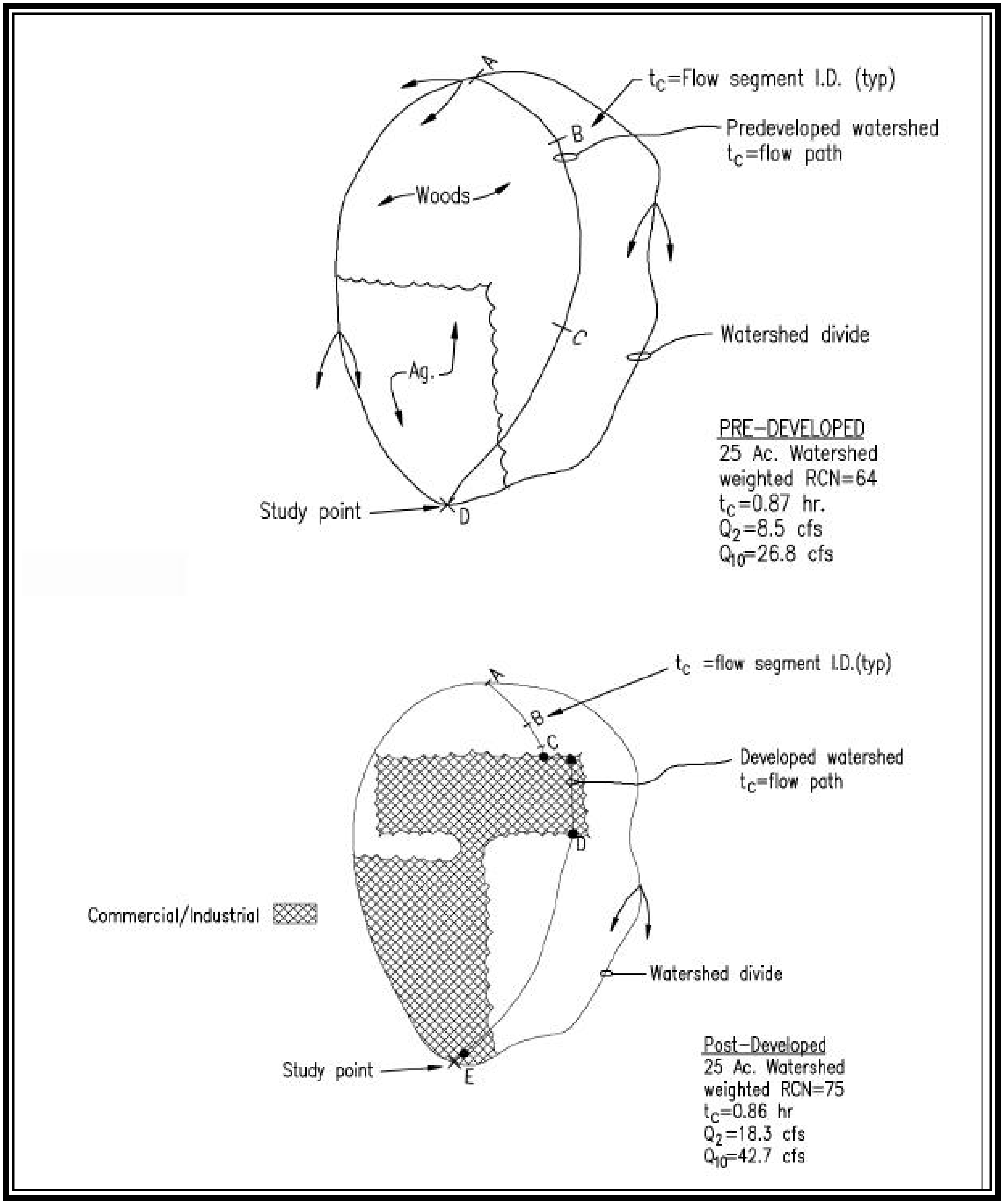


FIGURE 6.1-1c

Example 1 - 25-Acre Watershed Post-developed Condition - Most Representative t_c Flow Path

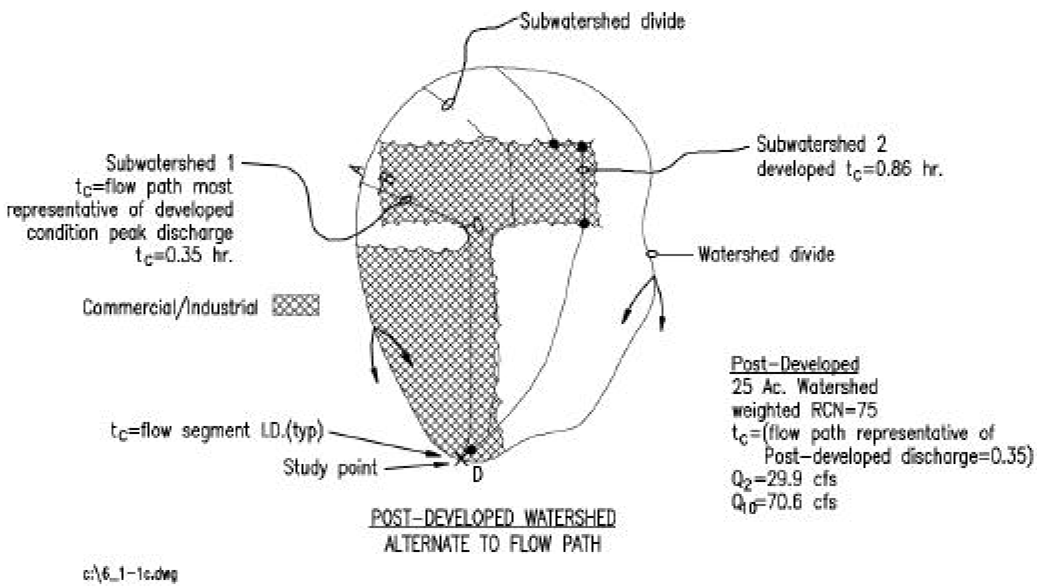


TABLE 6.1 - 1
Hydrologic Summary - Full Watershed, Example 6.1A
TR-55 Graphical Peak Discharge Method

Condition	Area (ac.)	RCN	t_c (hrs.)	Q_2 (cfs)	Q_{10} (cfs)	Remarks
Pre-developed	25	64	0.87	8.5	26.8	Longest t_c path (a)
Post-developed	25	75	0.86	18.3	42.7	Longest t_c path (b)
Post-developed	25	75	0.35	29.9	70.6	Most representative t_c path (c)

By using the flow path that best represents the developed area, a significant increase in the design peak discharge occurs. To prove that this higher discharge is more accurate, the watershed can be divided into two sub-watersheds that are analyzed independently using the Tabular Peak Discharge Method (which allows for analysis of heterogeneous sub-watersheds). The discharge hydrographs from each sub-watershed are then added at the watershed study point. See **Example 1.6C** for this solution.

Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1 A By TSB Date 5-96

Location ______ Checked ______ Date ______

Circle one: Present Developed ENTIRE 25 acre watershed

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	Fig. 2-3	Fig. 2-4	Area ☐ acres ☐ mi^2 ☐ %	Product of CN x area
B	Woods - good condition	55			12.75	701.25
C	Woods - good condition	70			6.0	420.0
B	Agriculture - SR + CR good Condition	75			6.25	468.75
				Totals =	25.0	1590.0

1/ Use only one CN source per line.

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{1590}{25} = 63.6$; Use CN = $\boxed{64}$

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	2	10	
Rainfall, P (24-hour)	in	3.5	5.5	
Runoff, Q .... (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	in	0.70	1.91	

Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1A By TSB Date 5-96

Location ______ Checked ______ Date ______

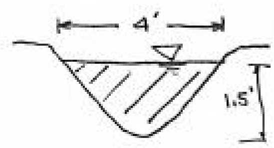
Circle one: Present Developed ENTIRE 25 acre watershed

Circle one: T_c T_t through subarea - longest flow path

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)	Segment ID	AB			
1. Surface description (table 3-1)		woods - light			
2. Manning's roughness coeff., n (table 3-1) ..		0.40			
3. Flow length, L (total L ≤ 300 ft)	ft	300			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.025			
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute T_t	hr	0.75	+		= 0.75
Shallow concentrated flow	Segment ID	BC			
7. Surface description (paved or unpaved)		unpaved			
8. Flow length, L	ft	600			
9. Watercourse slope, s	ft/ft	.045			
10. Average velocity, V (figure 3-1)	ft/s	3.4			
11. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.05	+		= 0.05
Channel flow	Segment ID	CD			
12. Cross sectional flow area, a	ft^2	3.0			
13. Wetted perimeter, p_w	ft	5.0			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft	0.6			
15. Channel slope, s	ft/ft	.045			
16. Manning's roughness coeff., n		.05			
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V	ft/s	4.7			
18. Flow length, L	ft	1200			
19. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.07	+		= 0.07
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19)	hr				0.87



SEGMENT CD

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Worksheet 4: Graphical Peak Discharge method

Project EXAMPLE 6.1A By TSB Date 5-96

Location ______ Checked ______ Date ______

Circle one: Present Developed ENTIRE 25 acre watershed

1. Data:

Drainage area .... A_m = .039 mi^2 (acres/640)

Runoff curve number .... CN = 64 (From worksheet 2)

Time of concentration .. T_c = 0.87 hr (From worksheet 3)

Rainfall distribution type = II (I, IA, II, III)

Pond and swamp areas spread throughout watershed ...... = — percent of A_m (____ acres or mi^2 covered)

		Storm #1	Storm #2	Storm #3
2. Frequency	yr	2	10	
3. Rainfall, P (24-hour)	in	3.5	5.5	
4. Initial abstraction, I_a .... (Use CN with table 4-1.)	in	1.125	1.125	
5. Compute I_a/P		0.32	0.20	
6. Unit peak discharge, q_u .... (Use T_c and I_a/P with exhibit 4-____)	csm/in	310	360	
7. Runoff, Q .... (From worksheet 2).	in	0.70	1.91	
8. Pond and swamp adjustment factor, F_p .... (Use percent pond and swamp area with table 4-2. Factor is 1.0 for zero percent pond and swamp area.)		—	—	
9. Peak discharge, q_p .... (Where $q_p = q_u A_m Q F_p$)	cfs	8.5	26.8	

Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1 A By TSB Date 5-96

Location ______ Checked ______ Date ______

Circle one: Present Developed ENTIRE 25 acre watershed

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	Fig. 2-3	Fig. 2-4	Area ☐acres ☐mi² ☐%	Product of CN x area
B	Woods - Good Condition	55			7.1	390.5
C	Woods - Good Condition	70			6.0	420.0
B	Commercial/Industrial 78% IMP.	90			11.9	1071.0
				Totals =	25.0	1881.5

1/ Use only one CN source per line.

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{1881.5}{25.0} = $ 75.3 ; Use CN = 75

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	2	10	
Rainfall, P (24-hour)	in	3.5	5.5	
Runoff, Q .... (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	in	1.30	2.85	

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Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1 A By JSB Date 5-96

Location ______ Checked ____ Date ____

Circle one: Present Developed ENTIRE 25 acre watershed

Circle one: T_c T_t through subarea - longest flow path

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)

	Unit			
Segment ID		AB		
1. Surface description (table 3-1)		Woods light		
2. Manning's roughness coeff., n (table 3-1)		0.40		
3. Flow length, L (total L ≤ 300 ft)	ft	300		
4. Two-yr 24-hr rainfall, P_2	in	3.5		
5. Land slope, s	ft/ft	.025		
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ Compute T_t	hr	0.75	+	= 0.75

Shallow concentrated flow

	Unit			
Segment ID		BC		
7. Surface description (paved or unpaved)		unpaved		
8. Flow length, L	ft	100'		
9. Watercourse slope, s	ft/ft	.045		
10. Average velocity, V (figure 3-1)	ft/s	3.4		
11. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.01	+	= 0.01

Channel flow

	Unit			
Segment ID		CD	DE	
12. Cross sectional flow area, a	ft^2	PIPE	3.0	
13. Wetted perimeter, p_w	ft	FLOW	5.0	
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft		0.6	
15. Channel slope, s	ft/ft		.045	
16. Manning's roughness coeff., n			.05	
17. $V = \frac{1.49\,r^{2/3}\,s^{1/2}}{n}$ Compute V	ft/s	AVG. 5.3	4.7	
18. Flow length, L	ft	500	1200	
19. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.03	+ 0.07	= 0.10

20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) .... hr 0.86

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Worksheet 4: Graphical Peak Discharge method

Project EXAMPLE 6.1 A By TSB Date 5-96

Location ______ Checked ____ Date ______

Circle one: Present **Developed** ENTIRE 25 acre watershed (longest flow path)

1. Data:

Drainage area .... A_m = .039 mi^2 (acres/640)

Runoff curve number .... CN = 75 (From worksheet 2)

Time of concentration .. T_c = 0.86 hr (From worksheet 3)

Rainfall distribution type = II (I, IA, II, III)

Pond and swamp areas spread throughout watershed ...... = — percent of A_m (____ acres or mi^2 covered)

		Storm #1	Storm #2	Storm #3
2. Frequency	yr	2	10	
3. Rainfall, P (24-hour)	in	3.5	5.5	
4. Initial abstraction, I_a .... (Use CN with table 4-1.)	in	0.667	0.667	
5. Compute I_a/P		0.19	0.12	
6. Unit peak discharge, q_u .... (Use T_c and I_a/P with exhibit 4-____)	csm/in	360	385	
7. Runoff, Q .... (From worksheet 2).	in	1.30	2.85	
8. Pond and swamp adjustment factor, F_p .... (Use percent pond and swamp area with table 4-2. Factor is 1.0 for zero percent pond and swamp area.)		—	—	
9. Peak discharge, q_p .... (Where $q_p = q_u A_m Q F_p$)	cfs	18.3	42.7	

Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1 A By TSB Date 5-96

Location ______ Checked ____ Date ____

Circle one: Present **Developed**

Circle one: T_c T_t through subarea

ENTIRE 25 acre watershed flow path representative of peak.

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)	Segment ID	AB			
1. Surface description (table 3-1)		woods light			
2. Manning's roughness coeff., n (table 3-1) ..		0.40			
3. Flow length, L (total L ≤ 300 ft)	ft	100			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.035			
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute T_t	hr	0.27	+		= 0.27
Shallow concentrated flow	Segment ID	BC			
7. Surface description (paved or unpaved)		Paved			
8. Flow length, L	ft	460			
9. Watercourse slope, s	ft/ft	0.03			
10. Average velocity, V (figure 3-1)	ft/s	3.5			
11. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.04	+		= 0.04
Channel flow	Segment ID	CD			
12. Cross sectional flow area, a	ft^2	Pipe			
13. Wetted perimeter, p_w	ft	Flow			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft				
15. Channel slope, s	ft/ft				
16. Manning's roughness coeff., n					
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V	ft/s	Avg. 4.7			
18. Flow length, L	ft	700			
19. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.04	+		= 0.04
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19)	hr				0.35

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Worksheet 4: Graphical Peak Discharge method

Project EXAMPLE 6.1 A By ____ Date ________

Location ______________________ Checked ____ Date ________

Circle one: Present Developed ENTIRE 25 acre watershed using most representative t_c flow path.

1. Data:

Drainage area .... A_m = .039 mi^2 (acres/640)

Runoff curve number .... CN = 75 (From worksheet 2)

* Time of concentration .. T_c = 0.35 hr (From worksheet 3) *

Rainfall distribution type = II (I, IA, II, III)

Pond and swamp areas spread throughout watershed ...... = — percent of A_m (____ acres or mi^2 covered)

		Storm #1	Storm #2	Storm #3
2. Frequency	yr	2	10	
3. Rainfall, P (24-hour)	in	3.5	5.5	
4. Initial abstraction, I_a .... (Use CN with table 4-1.)	in	0.667	0.667	
5. Compute I_a/P		0.19	0.12	
6. Unit peak discharge, q_u .... (Use T_c and I_a/P with exhibit 4-____)	csm/in	590	635	
7. Runoff, Q .... (From worksheet 2).	in	1.30	2.85	
8. Pond and swamp adjustment factor, F_p .... (Use percent pond and swamp area with table 4-2. Factor is 1.0 for zero percent pond and swamp area.)				
9. Peak discharge, q_p .... (Where $q_p = q_u A_m Q F_p$)	cfs	29.9	70.6	

EXAMPLE 6.1B

The Rational Method can be applied to any given watershed to find the peak discharge at a desired study point. As discussed in **Chapter 4**, the Rational Method is most accurate for watersheds having drainage areas of 20 acres or less and t_c flow paths of 20 minutes or less. The watershed in this example will be analyzed using the Rational Method, although it exceeds these limits, to provide a comparison to the SCS Methods of **Part A**. The decision to use a particular method is based on the watershed conditions (size, type of land cover, etc.) and the desired output (the peak rate of runoff, or a runoff hydrograph). For further discussion of the various methods, see **Chapter 4**.

Given:

The watershed in **Part A** of this example, as presented in **Figure 6.1-1a,c**.

Find:

The pre- and post-developed peak discharge using the Rational Method and the post-developed time of concentration flow path as described in **Part A** of this example.

Solution:

The rational method is applied to the 25-acre watershed as follows:

Pre-developed weighted runoff coefficient C:

Land Use	**Area *A* (*ac.*)**	**Runoff Coefficient *C***	***C x A***
Agriculture	6.25	0.6	3.75
Woods	18.75	0.3	5.63
TOTAL	25.0		9.38

$$\text{Weighted runoff coefficient } C = \frac{9.38}{25.0} = 0.38$$

<u>Post-developed</u> weighted runoff coefficient C:

Land Use	**Area *A* (*ac.*)**	**Runoff Coefficient *C***	***C x A***
Industrial/ Commercial	11.9	0.9	10.71
Woods	13.1	0.3	3.93
TOTAL	25.0		14.64

Weighted runoff coefficient $C = \frac{14.64}{25.0} ' \ 0.59$

TABLE 6.1 - 2
Hydrologic Summary - Full Watershed, Example 6.1B
Rational Method Peak Discharge, Q=CIA

Condition	**Area *A* (*ac.*)**	**Runoff Coefficient *C***	**t_c* (*min.*)**	***I*** (*in/hr*)**	**Q_2*** (*cfs*)**	**Q_{10}*** (*cfs*)**
Pre-developed	25.0	0.38	52 .87 *hr.*	I_2 = 1.8 I_{10} = 2.5	17	24
Post-developed	25.0	0.59	21 .35 *hr.*	I_2 = 3.3 I_{10} = 4.4	49	65

* *t_c based on SCS methods, Part A*
** *Intensity from Richmond area IDF curve*
*** *Rational Method equation: Q=CIA*

Comparing these results with those using SCS methods for the same watershed [**Table 6.1-1**, Post Developed t_c Path (b)], the Rational Method gives a significant increase in the 2-year pre- and post-developed peak discharges but gives similar discharges for the 10-year storm.

EXAMPLE 6.1C

Example 6.1C divides the given 25-acre watershed into two sub-watersheds. The TR-55 Tabular Method is used to generate their hydrographs, which are then added at the study point.

Given:

The proposed development disturbs 11.9 acres. Ten acres drain through subwatershed 1 and 1.9 acres drain through subwatershed 2.

Find:

The peak discharge from the watershed by adding the runoff hydrographs from the two sub-watersheds at the study point.

Solution:

The 25-acre watershed is divided into Sub-watersheds 1 and 2 based on pre- and post-developed land uses and drainage divides, as shown in **Figure 6.1-2**. To obtain the peak discharge from the total watershed, hydrographs must be generated for each sub-watershed and then added at the study point. The SCS Tabular Method (or any other hydrologic computer program that generates a runoff hydrograph) should be used.

The results, using the SCS TR-55 Tabular Hydrograph Method, are summarized in **Table 6.1-3**. Completed TR-55 worksheets are included at the end of this example.

Referring to the TR-55 Tabular Method Worksheets, note that the peak discharge obtained from adding the two hydrographs is less than the sum of their individual peaks. This is due to the timing effect of the peak flow through the watershed. Sometimes, the peak discharge will decrease with development because of the decreased flow time. Also note that the peak discharge hydrograph for the developed area travels through the study point before discharge from the other subwatershed(s). For additional examples and discussion on the Tabular Method, refer to TR-55.

TABLE 6.1 - 3
Hydrologic Summary - Sub-watersheds, Example 6.1C
SCS TR-55 Tabular Hydrograph Analysis

Sub-watershed 1					
Condition	**Area (*ac.*)**	**RCN**	**t_c (*hrs.*)**	**Q_2 (*cfs*)**	**Q_{10} (*cfs*)**
Pre-developed	9.5	68	.74	4.7	14.4
Post-developed	12.0	84	.35	21.9	42.0
Sub-watershed 2					
Condition	**Area (*acres*)**	***RCN***	**t_c (*hrs.*)**	**Q_2 (*cfs*)**	**Q_{10} (*cfs*)**
Pre-developed	15.5	61	.87	4.8	13.9
Post-developed	13.0	67	.86	5.9	18.2
Sub-watershed 1 and 2 Composite Hydrograph					
Condition	-			**Q_2 (*cfs*)**	**Q_{10} (*cfs*)**
Pre-developed	-			9.5	27.8
Post-developed	-			24.2	53.4

FIGURE 6.1-2a
Example 6.1C Sub-watersheds 1 & 2 Pre-developed Condition

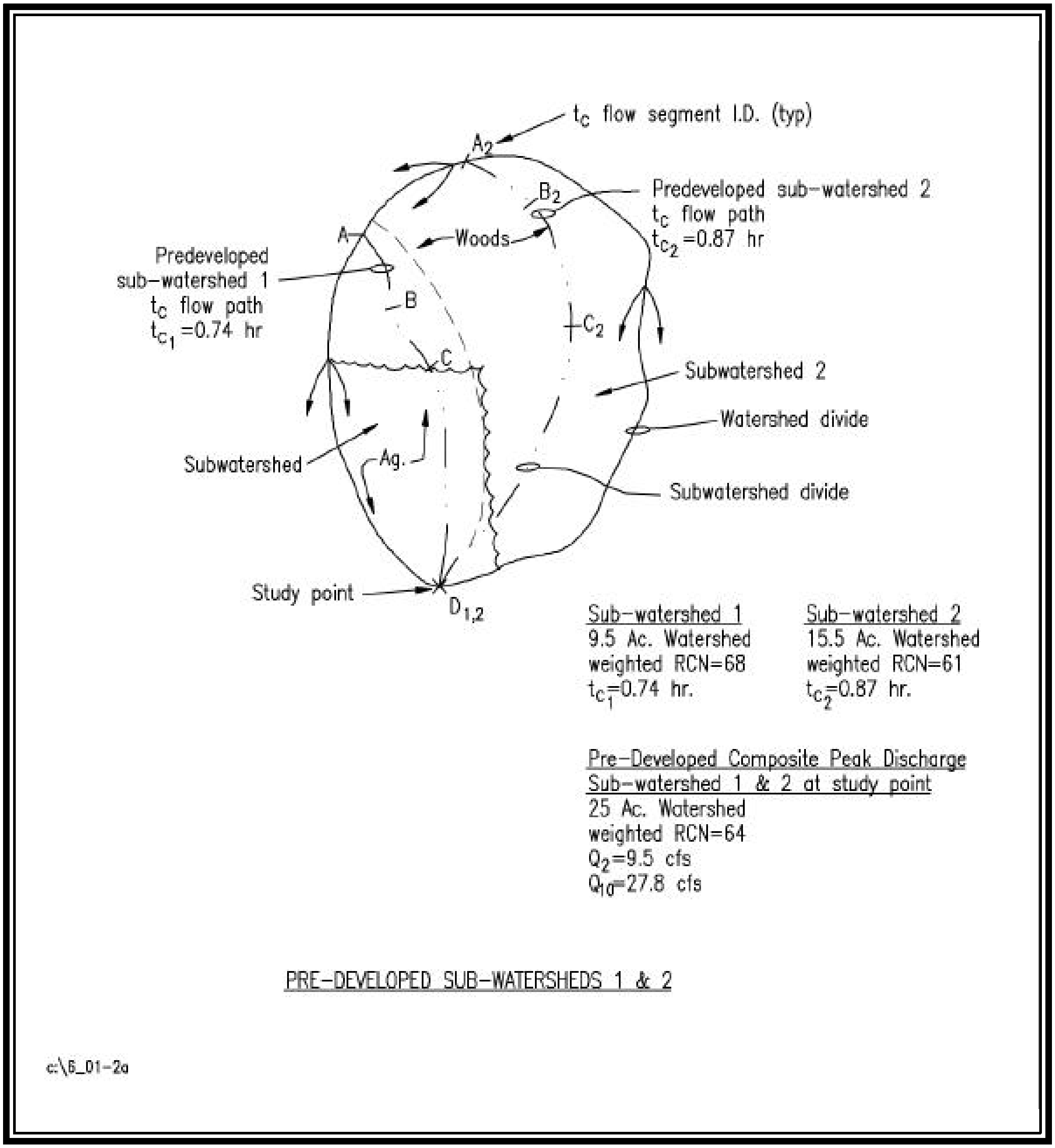
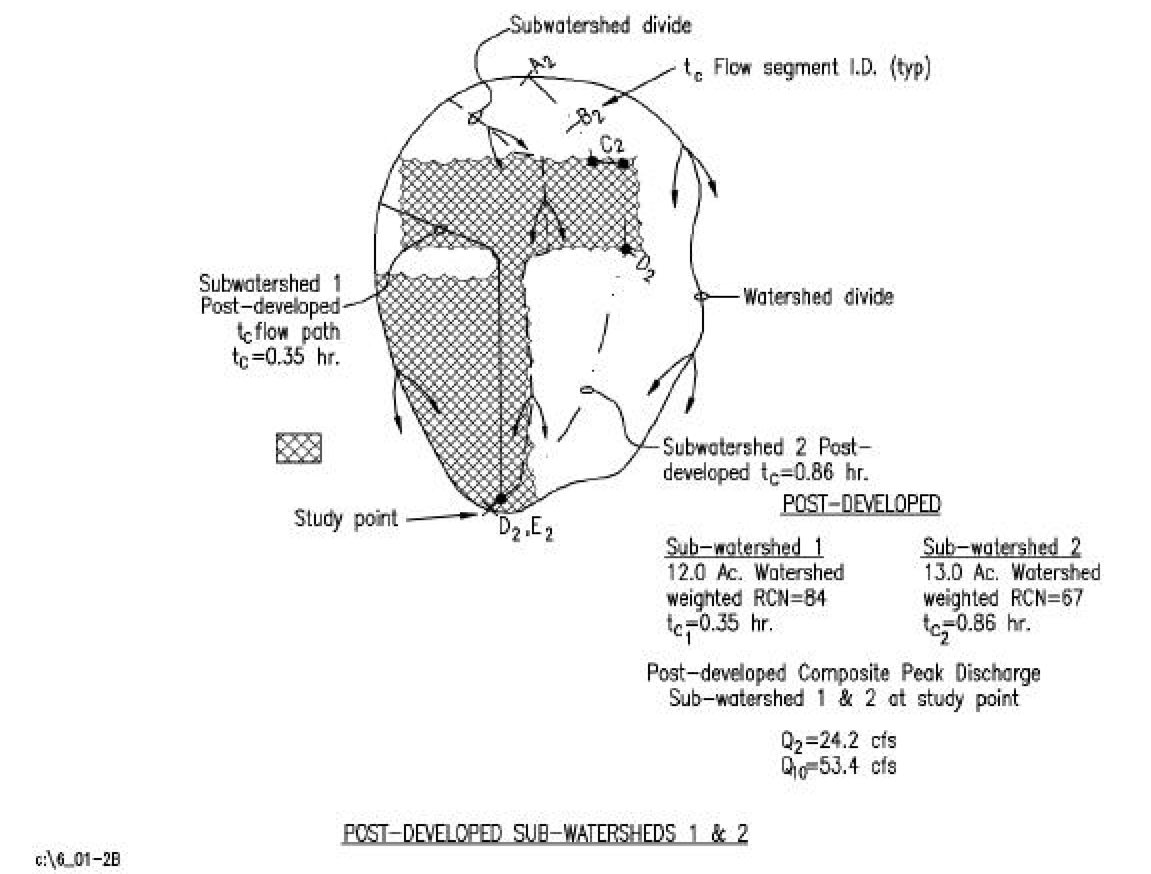


FIGURE 6.1-2b
Example 6.1C Sub-watersheds 1 & 2 Post-developed Condition



Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1C By TSB Date 5-96

Location ______ Checked ____ Date ____

Circle one: Present Developed Sub-watershed 1

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/			Area ☐acres ☐mi² ☐%	Product of CN x area
		Table 2-2	Fig. 2-3	Fig. 2-4		
B	Woods - good Condition	55			3.25	178.75
B	Agriculture - SR + CR good Condition	75			6.25	468.75
				Totals =	9.5	647.5

1/ Use only one CN source per line.

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{647.5}{9.5} = 68.1$; Use CN = $\boxed{68}$

2. Runoff

	Storm #1	Storm #2	Storm #3
Frequency ... yr	2	10	
Rainfall, P (24-hour) ... in	3.5	5.5	
Runoff, Q ... in (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	0.90	2.24	

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Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1C By TSB Date 6-96

Location ______ Checked ______ Date ______

Circle one: Present Developed Sub-watershed 2

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	CN 1/ Fig. 2-3	CN 1/ Fig. 2-4	Area ☐acres ☐mi² ☐%	Product of CN x area
B	Woods-good condition	55			9.5	522.5
C	Woods-good condition	70			6.0	420.0
				Totals =	15.5	942.5

1/ Use only one CN source per line.

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{942.5}{15.5} = 60.8$; Use CN = $\boxed{61}$

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	2	10	
Rainfall, P (24-hour)	in	3.5	5.5	
Runoff, Q .... (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	in	0.57	1.68	

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Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1C By TSB Date 6-96

Location ______ Checked ______ Date ______

Circle one: Present Developed Sub-watershed 1

Circle one: T_c T_t through subarea

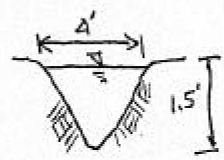
NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)	Units	Segment ID AB			
1. Surface description (table 3-1)		Woods light			
2. Manning's roughness coeff., n (table 3-1) ..		0.40			
3. Flow length, L (total L ≤ 300 ft)	ft	300			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.035			
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ Compute T_t	hr	0.66	+		= 0.66

Shallow concentrated flow	Units	Segment ID BC			
7. Surface description (paved or unpaved)		unpaved			
8. Flow length, L	ft	260			
9. Watercourse slope, s	ft/ft	.035			
10. Average velocity, V (figure 3-1)	ft/s	3.0			
11. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.04	+		= 0.04

Channel flow	Units	Segment ID CD			
12. Cross sectional flow area, a	ft^2	3.0			
13. Wetted perimeter, p_w	ft	5.0			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft	0.6			
15. Channel slope, s	ft/ft	.045			
16. Manning's roughness coeff., n		.05			
17. $V = \frac{1.49\,r^{2/3}\,s^{1/2}}{n}$ Compute V	ft/s	4.7			
18. Flow length, L	ft	700			
19. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.04	+		= 0.04



20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) .... hr 0.74

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Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1 C By TSB Date 6-96

Location ______ Checked ____ Date ______

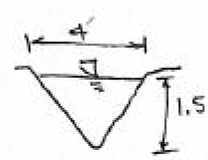
Circle one: Present Developed Sub-watershed 2

Circle one: T_c T_t through subarea

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only) Segment ID		AB			
1. Surface description (table 3-1)		woods light			
2. Manning's roughness coeff., n (table 3-1) ..		0.40			
3. Flow length, L (total L $\leq$ 300 ft)	ft	300			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.025			
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute T_t	hr	0.75	+		= 0.75
Shallow concentrated flow Segment ID		BC			
7. Surface description (paved or unpaved)		Unpaved			
8. Flow length, L	ft	600			
9. Watercourse slope, s	ft/ft	.045			
10. Average velocity, V (figure 3-1)	ft/s	3.4			
11. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	.05	+		= 0.05
Channel flow Segment ID		CD			
12. Cross sectional flow area, a	ft^2	3.0			
13. Wetted perimeter, p_w	ft	5.0			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft	0.6			
15. Channel slope, s	ft/ft	.045			
16. Manning's roughness coeff., n		.05			
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V	ft/s	4.7			
18. Flow length, L	ft	1200			
19. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	.07	+		= 0.07
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19)	hr				0.87



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Worksheet 5a: Basic watershed data

Project EXAMPLE 6.1C Location ______ By TSB Date 6-96

Circle one: Present Developed Sub-watersheds 1 & 2 Frequency (yr) 2,10 Checked ______ Date ______

Subarea name	Drainage area A_m (mi^2)	Time of concentration T_c (hr)	Travel time through subarea T_t (hr)	Downstream subarea names	Travel time summation to outlet ΣT_t (hr)	24-hr Rainfall P (in)	Runoff curve number CN	Runoff Q (in)	$A_m Q$ (mi^2-in)	Initial abstraction I_a (in)	I_a/P	
1	.015	0.74				3.5	68	0.90	.0135	.941	.27	2-yr
2	.024	0.87				3.5	61	0.57	.0137	1.279	.36	
1	.015	0.74				5.5	68	2.24	.034	.941	.17	10-yr
2	.024	0.87				5.5	61	1.68	.040	1.279	.23	

From worksheet 3 From worksheet 2 From table 5-1

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Worksheet 5b: Tabular hydrograph discharge summary

Project EXAMPLE 6.1 C   Location ______   By TSB   Date 6-96

Circle one: Present Developed   Sub-watersheds 1 & 2   Frequency (yr) 2, 10   Checked ______   Date ______

Subarea name	Basic watershed data used 1/ Sub-area T_c (hr)	ΣT_t to outlet (hr)	I_a/P	A_mQ (mi^2-in)	Select and enter hydrograph times in hours from exhibit 5-II 2/ 12.0	12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8	13.0	13.2	13.4
					Discharges at selected hydrograph times 3/ (cfs)											
1	.75		.30	.0135	0	0.1	0.4	1.2	2.4	3.6	4.4	4.7	4.4	3.3	2.4	1.9
2	.75		.30	.0137	0	0.1	0.4	1.2	2.4	3.6	4.5	4.8	4.5	3.4	2.5	1.9
2-yr	Composite		hydrograph		0	0.2	0.8	2.4	4.8	7.2	8.9	9.5	8.9	6.7	4.9	3.8
1	.75		.10	.034	1.6	2.3	3.9	6.6	10.0	12.9	14.4	13.9	12.5	8.6	5.8	4.2
2	.75		.30	.040	0	0.2	1.2	3.4	7.0	10.6	13.0	13.9	13.1	9.8	7.2	5.5
10-yr	Composite		hydrograph		1.6	2.5	5.1	10.0	17.0	23.5	27.4	27.8	25.6	18.4	13.0	9.7
Composite hydrograph at outlet																

1/ Worksheet 5a. Rounded as needed for use with exhibit 5.
2/ Enter rainfall distribution type used.
3/ Hydrograph discharge for selected times is A_mQ multiplied by tabular discharge from appropriate exhibit 5.

T_c, T_t Rounding

AREA 1		✓ $\boxed{1}$	2	3	AREA 2	✓ $\boxed{1}$	2	3
t_c	.74	.75	.5	.75	.87	.75	.75	1.0
t_t	0	0	0	0	0	0	0	0
SUM	.74	.75	.5	.75	.87	.75	.75	1.0

Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1C By TSB Date 6-96

Location ______ Checked ____ Date ____

Circle one: Present Developed Sub-watershed 1

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	Fig. 2-3	Fig. 2-4	Area ☐acres ☐mi² ☐%	Product of CN x area
B	Woods- good condition	55			2.0	110.0
B	Commercial / Industrial 78% Imp.	90			10.0	900.0

1/ Use only one CN source per line. Totals = 12.0 1010.0

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{1010}{12.0} = 84.16$; Use CN = $\boxed{84}$

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	2	10	
Rainfall, P (24-hour)	in	3.5	5.5	
Runoff, Q (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	in	1.94	3.73	

Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1 C By JSB Date 6-96

Location ______ Checked ____ Date ____

Circle one: Present **Developed** Sub-watershed 1

Circle one: T_c T_t through subarea

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)	Units	Segment ID: AB			
1. Surface description (table 3-1)		woods light			
2. Manning's roughness coeff., n (table 3-1)		.40			
3. Flow length, L (total L $\leq$ 300 ft)	ft	100			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.035			
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute T_t	hr	0.27	+		= 0.27

Shallow concentrated flow	Units	Segment ID: BC			
7. Surface description (paved or unpaved)		unpaved			
8. Flow length, L	ft	460			
9. Watercourse slope, s	ft/ft	.035			
10. Average velocity, V (figure 3-1)	ft/s	3.0			
11. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.04	+		= 0.04

Channel flow	Units	Segment ID: CP			
12. Cross sectional flow area, a	ft^2	3.0			
13. Wetted perimeter, p_w	ft	5.0			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft	0.6			
15. Channel slope, s	ft/ft	.04			
16. Manning's roughness coeff., n		.05			
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V	ft/s	4.7			
18. Flow length, L	ft	700			
19. $T_t = \frac{L}{3600\ V}$ Compute T_t	hr	0.04	+		= 0.04
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19)	hr				0.35

Worksheet 2: Runoff curve number and runoff

Project EXAMPLE 6.1C By TSB Date 6-96

Location ______ Checked ____ Date ____

Circle one: Present **Developed** Sub-watershed 2

1. Runoff curve number (CN)

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	CN 1/ Fig. 2-3	CN 1/ Fig. 2-4	Area ☐ acres ☐ mi^2 ☐ %	Product of CN x area
B	Woods - good condition	55			5.1	280.5
C	woods-good condition	70			6.0	420.0
B	Commercial/Industrial 78% Imp.	90			1.9	171.0
				Totals =	13.0	871.5

1/ Use only one CN source per line.

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{871.5}{13.0} = 67.04$; Use CN = $\boxed{67}$

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	2	10	
Rainfall, P (24-hour)	in	3.5	5.5	
Runoff, Q .... (Use P and CN with table 2-1, fig. 2-1, or eqs. 2-3 and 2-4.)	in	0.85	2.16	

Worksheet 3: Time of concentration (T_c) or travel time (T_t)

Project EXAMPLE 6.1 C By TSB Date 6-96

Location ______ Checked ______ Date ______

Circle one: Present **Developed** Sub-watershed 2

Circle one: T_c T_t through subarea

NOTES: Space for as many as two segments per flow type can be used for each worksheet.

Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)		Segment ID: AB			
1. Surface description (table 3-1)		Woods light			
2. Manning's roughness coeff., n (table 3-1)		.40			
3. Flow length, L (total L $\leq$ 300 ft)	ft	300			
4. Two-yr 24-hr rainfall, P_2	in	3.5			
5. Land slope, s	ft/ft	.025			
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ Compute T_t	hr	0.75	+		= 0.75

Shallow concentrated flow		Segment ID: BC			
7. Surface description (paved or unpaved)		Unpaved			
8. Flow length, L	ft	100′			
9. Watercourse slope, s	ft/ft	.045			
10. Average velocity, V (figure 3-1)	ft/s	3.4			
11. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.01	+		= 0.01

Channel flow		Segment ID: CD		DE	
12. Cross sectional flow area, a	ft^2	Pipe		3.0	
13. Wetted perimeter, p_w	ft	Flow		5.0	
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r	ft			0.6	
15. Channel slope, s	ft/ft			.04	
16. Manning's roughness coeff., n				.05	
17. $V = \frac{1.49\,r^{2/3}\,s^{1/2}}{n}$ Compute V	ft/s	Avg. 5.3		4.7	
18. Flow length, L	ft	500		1200	
19. $T_t = \frac{L}{3600\,V}$ Compute T_t	hr	0.03	+	0.07	= 0.10

20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) .... hr 0.86

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Worksheet 5a: Basic watershed data

Project EXAMPLE 6.1C Location ______ By TSB Date 6-96

Circle one: Present Developed Sub-watersheds 1&2 Frequency (yr) 2,10 Checked ______ Date ______

Subarea name	Drainage area A_m (mi^2)	Time of concentration T_c (hr)	Travel time through subarea T_t (hr)	Downstream subarea names	Travel time summation to outlet ΣT_t (hr)	24-hr Rainfall P (in)	Runoff curve number CN	Runoff Q (in)	A_mQ (mi^2-in)	Initial abstraction I_a (in)	I_a/P	
1	.019	0.35				3.5	84	1.94	.037	.381	0.11	2-yr
2	.020	0.86				3.5	67	0.85	.017	.985	0.28	
1	.019	0.35				5.5	84	3.73	.071	.381	.07	10-yr
2	.020	0.86				5.5	67	2.16	.043	.985	.18	

From worksheet 3 (Time of concentration, Travel time through subarea) — From worksheet 2 (Runoff curve number, Runoff) — From table 5-1 (Initial abstraction)

Worksheet 5b: Tabular hydrograph discharge summary

Project EXAMPLE 6.1C Location ______ By TSB Date 6-96

Circle one: Present **Developed** Sub-watersheds 1 & 2 Frequency (yr) 2, 10 Checked ______ Date ______

Subarea name	Basic watershed data used 1/ Sub-area T_c (hr)	ΣT_t to outlet (hr)	I_a/P	A_mQ (mi²-in)	Select and enter hydrograph times in hours from exhibit 5- II 2/ 12.0	12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8	13.0	13.2	13.4
					Discharges at selected hydrograph times 3/ (cfs)											
1	.40		.10	.037	5.2	10.0	17.3	21.9	21.2	15.9	11.0	8.0	6.0	3.8	2.8	2.3
2	.75		.30	.017	0	0.1	0.5	1.5	3.0	4.5	5.5	5.9	5.6	4.2	3.1	2.3
2-yr	Composite		hydrograph		5.2	10.1	17.8	23.4	24.2	20.4	16.5	13.9	11.6	8.0	5.9	4.6
1	.40		.10	.071	10.0	19.2	33.2	42.0	40.8	30.6	21.2	15.3	11.6	7.4	5.5	4.5
2	.75		.10	.043	2.0	2.9	4.9	8.3	12.6	16.3	18.2	17.6	15.9	10.8	7.4	5.3
10-yr	Composite		hydrograph		12.0	22.1	38.1	50.3	53.4	46.9	39.4	32.9	27.5	18.2	12.9	9.8
Composite hydrograph at outlet																

1/ Worksheet 5a. Rounded as needed for use with exhibit 5.
2/ Enter rainfall distribution type used.
3/ Hydrograph discharge for selected times is A_mQ multiplied by tabular discharge from appropriate exhibit 5.

t_c, t_t Rounding

	AREA1	1	2	3	AREA2	1	2	3
T_c	.35	.4	.3	.4	.86	.75	.75	1.0
T_t	0	0	0	0	0	0	0	0
SUM	.35	.4	.3	.4	.86	.75	.75	1.0

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EXAMPLE 6.1D

Using the Rational Method to analyze the full 25-acre watershed (**Example 6.1B**) yielded much higher peak discharges for the 2-year design storm then when using the Tabular Method in **Part C**. The analysis of Sub-watershed 1 using the Rational Method will provide a better opportunity to compare the two methods, since Sub-watershed 1 is less than the recommended maximum of 20 acres and the t_c is close to the recommended 20 minute upper limit.

Given:

Sub-watershed 1 as shown in **Figure 6.1-2** and described in **Part A**.

Find:

The peak discharge from Sub-watershed 1 using the Rational Method. Compare these results with those from **Part C**.

Solution:

The Rational Method is applied to Sub-watershed 1 as follows:

Sub-watershed 1:

Pre-developed weighted runoff coefficient C:

Land Use	**Area *A* (*ac.*)**	**Runoff Coefficient *C***	***C x A***
Agriculture	6.25	0.6	3.75
Woods	3.25	0.25	0.81
TOTAL	9.5		4.56

$$\text{Weighted runoff coefficient } C = \frac{4.56}{9.5} \text{ ' } 0.48$$

<u>Post-developed</u> weighted runoff coefficient C:

Land Use	Area *A* (*ac.*)	Runoff Coefficient *C*	*C x A*
Commercial/ Industrial	10.0	0.9	9.0
Woods	2.0	0.25	0.5
TOTAL	12.0		9.5

$$\text{Weighted runoff coefficient} = \frac{9.5}{12.0} \;' \; 0.79$$

TABLE 6.1 - 4
Hydrologic Summary - Sub-watershed 1, Example 6.1D
Rational Method Peak Discharge, Q = CIA

Condition	Area *A* (*ac.*)	Runoff Coefficient *C*	t_c* (*min.*)	*I*** (*in/hr*)	Q_2 (*cfs*)	Q_{10} (*cfs*)
Pre-developed	9.5	0.48	43.2	I_2 = 2.0; I_{10} = 2.8	9.1	12.8
Post-developed	12.0	0.79	21	I_2 = 3.3; I_{10} = 4.4	31.3	41.7

* t_c *based on SCS methods,* ***Part A***
** *Intensity from Richmond area I-D-F Curve,* ***Appendix 4D***

The results show a significant increase in both the pre- and post-developed 2-year storm peak discharges, and very similar pre- and post-developed 10-year storm peak discharges. This may be attributed to any one of several factors, however, there seems to be a consistent trend that the Rational Method over estimates the 2-year storm discharge when compared to the SCS methods.

Example 6.2

HYDRAULICS

EXAMPLE 6.2
ILLUSTRATIONS

#	FIGURES	PAGE

#	FIGURES	PAGE
6.2-1	Stage - Storage Table and Curve	6.2-5
6.2-2	Extended Detention Stage-Storage-Discharge Worksheet	6.2-7
6.2-3	TR-20 Input and Tabular Output - 1-yr. Extended Detention	6.2-8
6.2-4	Extended Detention and 10-year Flood Control (TRIAL 1) Stage-Storage-Discharge Worksheet	6.2-10
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6.2-6	Extended Detention and 10-year Flood Control (TRIAL 2) Stage-Storage-Discharge Worksheet	6.2-13
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#	TABLES	PAGE
6.2-1	Hydrologic Summary Example 6.1, SCS Methods	6.2-2

EXAMPLE 6.2

INTRODUCTION:

Example 6.2 will use the same hydrology for the 25-acre watershed that was presented in **Example 6.1** and illustrated in **Chapter 5**. A stormwater facility will be sized and designed to accept the runoff from the full 25-acre watershed. Note that it is usually most efficient to control stormwater quality and quantity within the subwatershed where the majority of the development occurs.

GIVEN:

The hydrology of the 25-acre watershed represented in **Example 6.1**, Part A, using the most representative flow path of the proposed development to determine the time of concentration. The summary of the hydrology (developed using the TR-20 computer program) is as follows:

Table 6.2-1
Hydrologic Summary*, *Example 6.1, SCS Methods

TR-20 COMPUTER RUN					
Condition	**DA**	**RCN**	t_c	Q_{10}	Q_{100}
PRE-DEV	25 *ac.*	64	0.87 *hr.*	25.5 *cfs**	52.7 *cfs*
POST-DEV	25 *ac.*	75	0.35 *hr.*	61.1 *cfs*	108.9 *cfs*

**** 10-year Allowable release rate***

The TR-20 hydrologic analysis input file and output summary are provided on the following pages.

FIND:

Design a stormwater management facility which provides 24 hour extended detention of the 1-year frequency design storm for channel erosion control, attenuation of the post-developed 10-year frequency design storm released at the pre-developed rate for flood control, and safe passage of the 100-year frequency design storm through a vegetated emergency spillway.

Note: There is no water quality enhancement required for this example. Also, extended detention of the runoff from the 1-year frequency storm is a calculation based on the *volume* of runoff rather than the *rate* of runoff. Therefore the hydrologic summary includes only the 10- and 100-year frequency storm peak rates of runoff.

SOLUTION:

Use the design procedures found in **Chapter 5-7** to design the basin and multi-stage riser structure. This is to include the design of the 1-year storm extended detention orifice in lieu of a 2-year control orifice. The design procedures for channel erosion extended detention are found in **Chapter 5-6.3**.

STEP 1 No water quality requirements for this facility.

STEP 2 Allowable release rates from the TR-20 computer run: $Q_{10\ allowable}$ = 25.5 cfs

STEP 3 The required storage volume for extended detention of the 1-year storm (V_{ce}):

1-year frequency design storm rainfall = 2.7" (**Appendix 4B**); 1-year frequency design storm runoff = 0.8" (**Appendix 4C**).
Runoff volume (25 ac.) (0.8") (1'/12") = V_{ce} = 1.66 ac.ft.

Note: The routing affect on the extended detention of the 1-year storm results in the actual use of approximately 60% of the design storage allocated in the basin (**Chapter 5-6.3**). Therefore, V_{ce} = (1.66 ac. ft.) (0.6) = 1.0 ac. ft. = 43,560 ft^3.

Required storage volume for 10-year flood control (V_{10}):

1. From TR-55: Storage Volume for Detention Basin **(Chapter 5-4.2)**:

$$Q_{o_{10}}/Q_{i_{10}} = 25.5 / 61.1 = 0.42$$

From **Figure 5-4**: $V_{s_{10}} / V_{r_{10}} = 0.31$

2. Runoff volume: $V_{r_{10}} = Q_{10} A_m 53.33$ = (2.85in.)(0.039 mi^2)(53.33) = 5.93 ac.ft.

3. Storage volume required: $V_{s_{10}} = \left(\frac{V_{s_{10}}}{V_{r_{10}}}\right) V_{r_{10}} = (0.31)\ 5.93\ ac.ft. = \underline{1.84\ ac.ft.}$

Note: Approximately 10% should be added to the required storage to account for the extended detention of the l-year storm within the 10-year design pool: (1.84 ac.ft.) (1.10) = 2.0 ac.ft.

STEP 4 The development of the stage-storage worksheet and curve, **Figure 6.2-1**, was presented in **Chapter 5-5.1**.

STEP 5 The extended detention orifice (1-year storm) is designed using the procedure outlined in **Chapter 5-6.3** as follows:

1. V_{ce} = 1.0 ac.ft.
2. Elevation for 1-year h_{max} = 89.0 (1.0 ac.ft.). h_{max} = 89 - 81 = 8.0 ft..
3. $$Q_{avg} = \frac{43{,}560\ ft^3}{(24\,hr.)(3{,}600\,\text{sec.}/hr.)} = 0.5\ cfs$$

   $Q_{max} = 2 \times Q_{avg}\ cfs = 2 \times 0.5 cfs = \underline{1.0\ cfs}$

4. The required orifice area, a, in ft^2 is:

$$a = \frac{Q}{C\sqrt{2gh_{max}}}$$

Equation 5-7
Rearranged Orifice equation

$$a = \frac{1.0}{0.6\sqrt{(2)(32.2)(8.0)}} = 0.073\ ft^2 = \pi r^2 = \pi d^2/4$$

$$d = \sqrt{\frac{4a}{\pi}} = \sqrt{\frac{4(0.073\ ft^2)}{\pi}} = .304 ft. = \underline{3.7\text{ in.}}$$

5. Route the 1-year storm to establish the 1-year design water surface elevation (wse) by completing steps 6 and 7.
6. The stage-discharge relationship is as follows:

$$Q = Ca\sqrt{2gh}$$

Equation 5-6
Orifice equation

$$Q = 0.6(.073)\sqrt{(2)(32.2)(h)} = \underline{0.33(h)^{1/2}}$$

where h = wse − 81.0 ft.

FIGURE 6.2-1
Stage-Storage Worksheet

PROJECT: Example 6.2 SHEET ____ OF ____

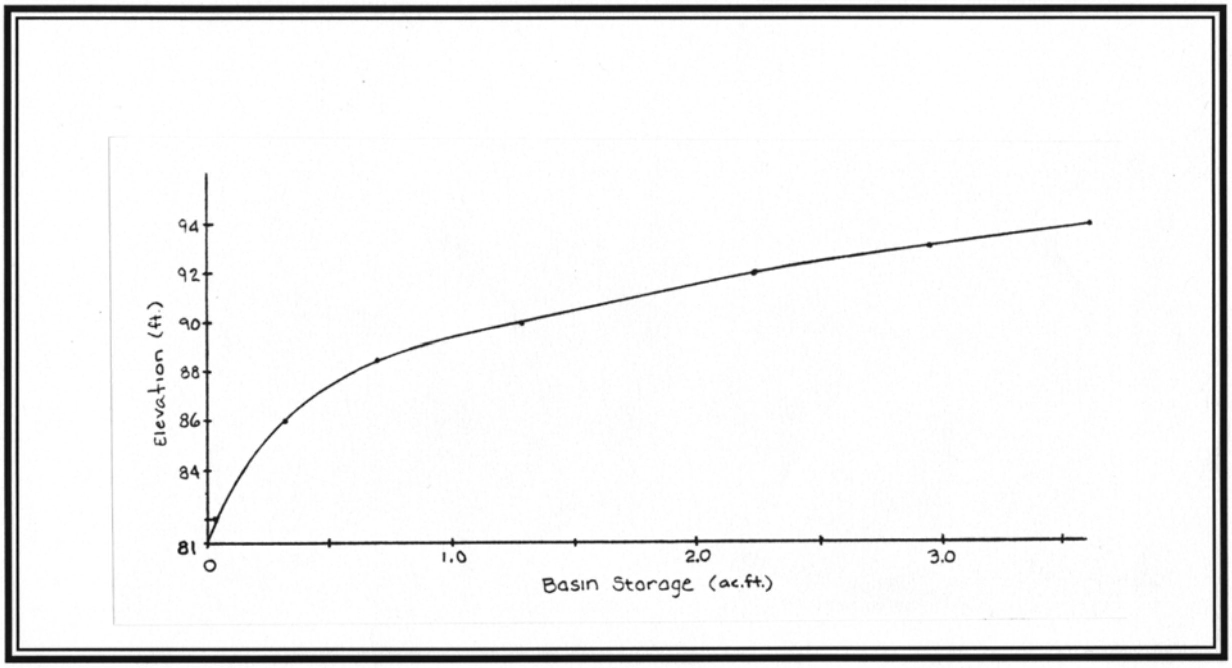
COUNTY: ________________ COMPUTED BY: ____________ DATE: ________

DESCRIPTION: 1-yr. extended detention, 10-yr. flood control, 100-yr. E.S.

ATTACH COPY OF TOPO: SCALE - 1" = ______ *ft.*

1	2	3	4	5	6	7	8
ELEV.	AREA (*in²*)	AREA (*ft²*)	AVG. AREA (*ft²*)	INTERVAL	VOL. (*ft³*)	TOTAL VOLUME (*ft³*)	(*ac.ft.*)
81	0	0				0	0
			900	1	900		
82	2.0	1800				900	0.02
			2520	2	5040		
84	3.6	3240				5940	0.14
			4207	2	8414		
86	5.7	5175				14354	0.33
			7614	2	15228		
88	11.2	10053				29582	0.68
			12991	2	25982		
90	17.7	15930				55564	1.28
			20700	2	41400		
92	28.3	25470				96964	2.23
			31102	1	31102		
93	40.8	36734				128066	2.94
			38105	1	38105		
94	43.9	39476				166171	3.81

FIGURE 6.2-1 contd.
Stage - Storage Curve



7. Complete a stage-storage-discharge table for the anticipated range of elevations using the stage-discharge relationship established in item 6 above. The completed extended detention portion of the stage-storage-discharge worksheet is presented in **Figure 6.2-2**.

In order to establish the 1-year extended detention water surface elevation, the designer may use the approximate value of 89.0 ft. established by the required storage volume calculation and the stage-storage curve, or an exact value may be determined by routing the 1-year storm through the basin. The TR-20 input file and tabular hydrograph output for the routing of the 1-year storm are provided, **Figure 6.2-3**. The routing results in a maximum extended detention water surface elevation of 88.69', a peak discharge of 0.97 cfs, and a brim drawdown time of 23.5 hrs. (39 hrs. - 15.5 hrs).

FIGURE 6.2-2
Extended Detention Stage-Storage-Discharge Worksheet

ELEV (MSL)	STORAGE (ac.ft.)	1-yr. ext.det. ~~WATER QUALITY~~ ORIFICE□ (1)	
		h	Q
81	0	0	0
82	0.02	1	0.3
84	0.14	3	0.6
86	0.33	5	0.7
88	0.68	7	0.9
89	0.95	8	1.0
90	1.28	9	1.1
91	1.75	10	1.1

$Q = 0.33(h)^{1/2}$ where h = w.s.e. ! 81.0ft.

STEP 6 / **STEP 7** 2-year storm control is not required since the channel erosion component of this design is covered by the extended detention of the 1-year storm.

FIGURE 6.2-3
TR-20 Input and Tabular Output - 1-yr. Extended Detention

```
******************80-80 LIST OF INPUT DATA FOR TR-20 HYDROLOGY******************

JOB TR-20                    FULLPRINT          SUMMARY
TITLE 001 STORMWATER HANDBOOK EXAMPLE PROBLEM 1: EX1ROUTA.DAT
TITLE     EXTENDED DETENTION 1 YR STORM
 3 STRUCT      01
 8                          81.0       0.0        0.0
 8                          82.0       0.3        0.02
 8                          84.0       0.6        0.14
 8                          86.0       0.7        0.33
 8                          88.0       0.9        0.68
 8                          89.0       1.0        0.95
 8                          90.0       1.1        1.28
 9 ENDTBL
 6 RUNOFF  1 001       1  .039       75.        0.35         1 1   1   1
 6 RESVOR  2     01 1  2  81.0                               1 1   1   1
   ENDATA
 7 INCREM  6             .25
 7 COMPUT  7 001      01 0.0         2.7        1.0          2 2  01  01
   ENDCMP  1
   ENDJOB  2
```

1-yr storm rainfall

```
*******************************END OF 80-80 LIST*******************************

EXECUTIVE CONTROL OPERATION INCREM     MAIN TIME INCREMENT =   .25 HOURS                              RECORD ID

EXECUTIVE CONTROL OPERATION COMPUT     FROM XSECTION   1  TO STRUCTURE  1                             RECORD ID
        STARTING TIME =    .00    RAIN DEPTH =  2.70    RAIN DURATION=  1.00    RAIN TABLE NO.= 2    ANT. MOIST. COND= 2
        ALTERNATE NO.= 1          STORM NO.= 1     MAIN TIME INCREMENT =   .25 HOURS

OPERATION RESVOR    STRUCTURE  1
          INPUT HYDROGRAPH= 1     OUTPUT HYDROGRAPH= 2
          SURFACE ELEVATION=   81.00

*** WARNING-NO PEAK FOUND, MAXIMUM DISCHARGE =         .97 CFS.

          PEAK TIME(HRS)              PEAK DISCHARGE(CFS)           PEAK ELEVATION(FEET)
            15.50                          .97                          88.69
```

TIME(HRS) FIRST HYDROGRAPH POINT = .00 HOURS TIME INCREMENT = .25 HOURS DRAINAGE AREA = .04 SQ.MI.

10.00	DISCHG	.00	.00	.00	.00	.00	.00	.02	.25	.61	.75
12.50	DISCHG	.86	.91	.92	.94	.95	.95	.96	.96	.97	.97
15.00	DISCHG	.97	.97	.97	.97	.97	.97	.97	.97	.97	.96
17.50	DISCHG	.96	.96	.96	.96	.96	.95	.95	.95	.95	.94
20.00	DISCHG	.94	.94	.93	.93	.93	.92	.92	.92	.91	.91
22.50	DISCHG	.91	.90	.90	.90	.89	.89	.88	.88	.87	.86
25.00	DISCHG	.85	.84	.83	.82	.81	.80	.79	.78	.77	.76
27.50	DISCHG	.75	.74	.74	.73	.72	.71	.70	.69	.69	.68
30.00	DISCHG	.67	.66	.66	.65	.64	.64	.63	.62	.62	.61
32.50	DISCHG	.60	.58	.55	.52	.50	.47	.45	.43	.40	.38
35.00	DISCHG	.37	.35	.33	.31	.28	.21	.15	.11	.08	.06
37.50	DISCHG	.04	.03	.02	.02	.01	.01	.01 39 hrs.			

RUNOFF VOLUME ABOVE BASEFLOW = .77 WATERSHED INCHES, 19.30 CFS-HRS, 1.60 ACRE-FEET; BASEFLOW = .00 CFS

<u>STEP 8</u> (Trial 1) The 10-year flood control opening is designed using the procedures outlined in **Chapter 5-7** as follows:

1. 1-year extended detention water surface elevation is 88.69ft.
2. Set 10-year control elevation at 88.8ft.
3. Approximate storage volume required for 10-year storm control is 2.0 ac.ft. from **<u>STEP 3</u>** above. From the stage storage curve h_{10max} = 91.5ft. ! 88.8ft. = 2.7ft.
4. The maximum allowable discharge, $Q_{10allowable}$ = 25.5 cfs.
5. A weir is chosen to control the 10-year release rate:

$$L = Q_{10allowable} / C_w h^{1.5}$$

Equation 5-9
Rearranged weir equation

$$L = 25.5 \text{ cfs} / (3.3)\ (2.7\text{ft.})^{1.5}$$

L = 1.74ft. For Trial 1, use a <u>1ft. - 8in. (1.7ft.) weir</u>

Note: Since the maximum head of 2.7 ft. is used, an average value of 3.3 for the weir coefficient (C_w) is used. See **Table 5-8**: Weir Flow Coefficients.

6. The stage discharge relationship is as follows:

$$Q_w = C_w\ L(h)^{1.5}$$

Equation 5-8
Weir flow equation

$$= 3.3\ (1.7\text{ft.})\ (h)^{1.5}$$

$Q_w = 5.6\ (h)^{1.5}$ where h = wse ! 88.8ft.

7. Complete a stage-storage-discharge table for the anticipated range of elevations using the stage-discharge relationship established in item 6 above. The completed extended detention and 10-year control (TRIAL 1) portion of the stage-storage-discharge worksheet is presented in **Figure 6.2-4**. Note the addition of the elevation 88.8ft. representing the crest of the 10-year weir.

<u>STEP 9</u> The TR-20 input file and output summary table for the routing of the 10-year storm through the basin (Trial 1) are provided (**Figure 6.2-5**). The routing results in a 10-year maximum water surface elevation of 91.77ft., and a peak discharge of <u>29.00 cfs. > 25.5 cfs</u>.

Try smaller weir and repeat from **<u>STEP 8</u>**, #6.

FIGURE 6.2-4
Extended Detention and 10-year Flood Control (TRIAL 1) Stage-Storage-Discharge Worksheet

ELEV (MSL)	STORAGE (ac.ft.)	1-yr. ext. det. ~~WATER QUALITY~~ ORIFICE□		TRIAL 1 10-YEAR CONTROL				TOTAL Q (cfs)
		(1)		WEIR (4)		ORIFICE (5)		
		h	Q	h	Q	h	Q	
81	0	0	0					0
82	.02	1	0.3					0.3
84	.14	3	0.6					0.6
86	.33	5	0.7					0.7
88	.68	7	0.9					0.9
88.8	.90	7.8	0.98	0	0			.98
89	.95	8	1.0	0.2	0.5			1.5
90	1.28	9	1.1	1.2	7.4			8.5
91	1.75	10	1.1	2.2	18.3			19.4
92	2.23	11	1.1	3.2	32.0			33.1

(1) $Q = 0.33(h)^{1.5}$ where h = w.s.e. ! 81.0ft.
(4) $Q_w = 5.6\ (h)^{1.5}$ where h = wse ! 88.8ft.

FIGURE 6.2-5

TR-20 Input and Output Summary - 1-yr. Extended Detention and 10-yr. Flood Control (TRIAL 1)

```
*******************80-80 LIST OF INPUT DATA FOR TR-20 HYDROLOGY*******************

JOB TR-20                    FULLPRINT          SUMMARY
TITLE 001 STORMWATER HANDBOOK EXAMPLE PROBLEM 1: EX1ROUTB.DAT
TITLE     EXTENDED DETENTION 1 YR STORM, 10 YR FLOOD CONTROL: TRIAL 1
 3 STRUCT      01
 8                        81.0        0.0         0.0
 8                        82.0        0.3         0.02
 8                        84.0        0.6         0.14
 8                        86.0        0.7         0.33
 8                        88.0        0.9         0.68
 8                        88.8        0.98        0.90
 8                        89.0        1.5         0.95
 8                        90.0        8.5         1.28
 8                        91.0        19.4        1.75
 8                        92.0        33.1        2.23
 9 ENDTBL
 6 RUNOFF 1 001       1  .039       75.         0.35         1 1   1   1
 6 RESVOR 2     01 1    2  81.0                               1 1   1   1
   ENDATA
 7 INCREM 6            .25
 7 COMPUT 7 001      01 0.0         2.7         1.0          2 2  01  01   1-yr storm
   ENDCMP 1
 7 COMPUT 7 001      01 0.0         5.5         1.0          2 2  01  02   10-yr storm
   ENDCMP 1
   ENDJOB 2

*********************************END OF 80-80 LIST*********************************
```

SUMMARY TABLE 1 - SELECTED RESULTS OF STANDARD AND EXECUTIVE CONTROL INSTRUCTIONS IN THE ORDER PERFORMED
(A STAR(*) AFTER THE PEAK DISCHARGE TIME AND RATE (CFS) VALUES INDICATES A FLAT TOP HYDROGRAPH
A QUESTION MARK(?) INDICATES A HYDROGRAPH WITH PEAK AS LAST POINT.)

SECTION/ STRUCTURE ID	STANDARD CONTROL OPERATION	DRAINAGE AREA (SQ MI)	RAIN TABLE #	ANTEC MOIST COND	MAIN TIME INCREM (HR)	PRECIPITATION BEGIN (HR)	PRECIPITATION AMOUNT (IN)	PRECIPITATION DURATION (HR)	RUNOFF AMOUNT (IN)	PEAK DISCHARGE ELEVATION (FT)	PEAK DISCHARGE TIME (HR)	PEAK DISCHARGE RATE (CFS)	PEAK DISCHARGE RATE (CSM)
ALTERNATE 1 STORM 1													
XSECTION 1	RUNOFF	.04	2	2	.25	.0	2.70	24.00	.76	---	12.17	14.68	376.4
STRUCTURE 1	RESVOR	.04	2	2	.25	.0	2.70	24.00	.77	88.68	15.50?	.97?	24.8
ALTERNATE 1 STORM 2													
XSECTION 1	RUNOFF	.04	2	2	.25	.0	5.50	24.00	2.83	---	12.10	61.12	1567.1
STRUCTURE 1	RESVOR	.04	2	2	.25	.0	5.50	24.00	2.87	91.77	12.49	29.99	769.0

STEP 8 6. (Trail 2) Try smaller weir : 1ft. - 4in. (1.33ft.). The stage-discharge relationship is as follows:

$$Q_w = C_w L h^{1.5}$$ **Equation 5-8** Weir equation

$$= (3.3)(1.33ft.)(h)^{1.5}$$

$$Q_w = 4.39 (h)^{1.5} \quad \text{where } h = wse - 88.8ft.$$

7. Complete a stage-storage-discharge table for the anticipated range of elevations using the stage-discharge relationship established in item 6 above. The completed extended detention and 10-year control (TRIAL 2) portion of the stage-storage-discharge worksheet is presented in **Figure 6.2-6**.

STEP 9 The TR-20 input file and output summary table for the routing of the 10-year storm through the basin (TRIAL 2) are provided (**Figure 6.2-7**). The routing results in a maximum water surface elevation of 92.03ft. and a peak discharge of 26.82 cfs. The peak discharge is slightly greater than the allowable, further reduction may be achieved through the design of the barrel.

FIGURE 6.2-6
Extended Detention and 10-year Flood Control (TRIAL 2) Stage-Storage-Discharge Worksheet

ELEV (MSL)	STORAGE (ac.ft.)	1-yr. ext. det. ~~WATER QUALITY~~ ORIFICE		TRIAL 2 10-YEAR CONTROL				TOTAL Q (cfs)
		(1)		WEIR (4)		ORIFICE (5)		
		h	Q	h	Q	h	Q	
81	0	0	0					0.0
82	.02	1	0.3					0.3
84	.14	3	0.6					0.6
86	.33	5	0.7					0.7
88	.68	7	0.9					0.9
88.8	.90	7.8	0.98	0	0			.98
89	.95	8	1.0	0.2	0.4			1.4
90	1.28	9	1.1	1.2	5.8			6.9
91	1.75	10	1.1	2.2	14.3			15.4
92	2.23	11	1.1	3.2	25.1			26.2
93	2.94	12	1.1	4.2	37.8			38.9

(1) $Q = 0.33(h)^{1.5}$ where h = wse ! 81.0ft.
(4) $Q_w = 4.39(h)^{1.5}$ where h = wse ! 88.8ft

FIGURE 6.2-7

TR-20 Input and Output Summary - 1-yr. Extended Detention and 10-yr. Flood Control (TRIAL 2)

```
*******************80-80 LIST OF INPUT DATA FOR TR-20 HYDROLOGY******************

JOB TR-20                    FULLPRINT          SUMMARY
TITLE 001 STORMWATER HANDBOOK EXAMPLE PROBLEM 1: EX1ROUTB.DAT
TITLE    EXTENDED DETENTION 1 YR STORM, 10 YR FLOOD CONTROL: TRIAL 2
 3 STRUCT      01
 8                       81.0       0.0        0.0
 8                       82.0       0.3        0.02
 8                       84.0       0.6        0.14
 8                       86.0       0.7        0.33
 8                       88.0       0.9        0.68
 8                       88.8       0.98       0.90
 8                       89.0       1.4        0.95
 8                       90.0       6.9        1.28
 8                       91.0      15.4        1.75
 8                       92.0      26.2        2.23
 8                       93.0      48.9        2.94
 9 ENDTBL
 6 RUNOFF 1 001       1  .039      75.        0.35       1 1  1  1
 6 RESVOR 2    01 1   2  81.0                            1 1  1  1
   ENDATA
 7 INCREM 6            .25
 7 COMPUT 7 001      01 0.0        2.7        1.0        2 2  01  01   1-yr storm
   ENDCMP 1
 7 COMPUT 7 001      01 0.0        5.5        1.0        2 2  01  02   10-yr storm
   ENDCMP 1
   ENDJOB 2

********************************END OF 80-80 LIST*********************************
```

SUMMARY TABLE 1 - SELECTED RESULTS OF STANDARD AND EXECUTIVE CONTROL INSTRUCTIONS IN THE ORDER PERFORMED
(A STAR(*) AFTER THE PEAK DISCHARGE TIME AND RATE (CFS) VALUES INDICATES A FLAT TOP HYDROGRAPH
A QUESTION MARK(?) INDICATES A HYDROGRAPH WITH PEAK AS LAST POINT.)

SECTION/ STRUCTURE ID		STANDARD CONTROL OPERATION	DRAINAGE AREA (SQ MI)	RAIN TABLE #	ANTEC MOIST COND	MAIN TIME INCREM (HR)	PRECIPITATION BEGIN (HR)	PRECIPITATION AMOUNT (IN)	PRECIPITATION DURATION (HR)	RUNOFF AMOUNT (IN)	PEAK DISCHARGE ELEVATION (FT)	PEAK DISCHARGE TIME (HR)	PEAK DISCHARGE RATE (CFS)	PEAK DISCHARGE RATE (CSM)
ALTERNATE 1 STORM 1														
XSECTION	1	RUNOFF	.04	2	2	.25	.0	2.70	24.00	.76	---	12.17	14.68	376.4
STRUCTURE	1	RESVOR	.04	2	2	.25	.0	2.70	24.00	.77	88.68	15.50?	.97?	24.8
ALTERNATE 1 STORM 2														
XSECTION	1	RUNOFF	.04	2	2	.25	.0	5.50	24.00	2.83	---	12.10	61.12	1567.1
STRUCTURE	1	RESVOR	.04	2	2	.25	.0	5.50	24.00	2.86	92.03	12.53	26.82	687.6

STEP 10 The barrel should be sized to control the flow before the riser structure transitions from riser weir flow control to riser orifice flow control. Therefore determine the geometry of the riser and the elevation at which the transition occurs. Also, if possible, a reduction in the 10-year discharge would be desirable. This is only possible if an emergency spillway is provided, since a barrel which controls the 10-year flow will be too small to efficiently pass the 100-year flow without a significant increase in storage volume.

a. Riser flow control: try a 4ft. × 4ft. (inside dimension) square box riser with 6" wall thickness. Set top of riser at elevation 92.2ft.

WEIR FLOW - Total weir length: 3ft. sides (2) = 6ft., 1.67ft. front; weir length = 7.67ft., elevation 92.2ft. (riser top weir); weir length = 1.33ft., elevation 88.8ft. (10-year weir)

$$Q_w = C_w L h^{1.5}$$

Equation 5-8
Weir equation

$$Q_w = 3.1\ (7.67\text{ft.})\ (h)^{1.5}$$
$$Q_w = 23.8\ (h)^{1.5} \quad \text{Where } h = \text{wse} - 92.2\text{ft.}$$

Note: The flow measured from elevation 92.2ft. represents the flow over the top of the riser (weir length 7.67ft.). The flow over the 10-year weir (elevation 88.8ft., length 1.33ft.) is added in the Stage-Storage-Discharge table (**Figure 6.2-8**) to provide a total riser weir flow (Refer to **Figure 6.2-10**). This value will then be compared to the riser orifice flow capacity calculated below. C_w values for low head conditions are averaged at 3.1. See **Table 5-8**: Weir Flow Coefficients

ORIFICE FLOW - Riser structure inside dimensions - 4ft. × 4ft., total riser orifice area = 16 ft^2 at elevation 88.8ft.

$$Q = Ca\sqrt{2gh}$$

Equation 5-6
Orifice Equation

$$Q = 0.6\,(16ft^2)\sqrt{(2)\,(32.2)\,(h)}$$

$Q = 77.03\ (h)^{1/2}$ where $h = \text{wse} - 88.8\text{ft.}$

Add the riser weir flow and orifice flow values to the stage-storage-discharge table, **Figure 6.2-8**.

This analysis shows that the riser does not transition from weir flow to orifice flow within the range of water surface elevations. Therefore, the barrel does not have to control the flow. However, we want to slightly restrict the 10-year discharge in order to reduce it to within 5% of the 10-year allowable release rate.

b. Barrel flow control: upstream invert: 80.75ft., downstream invert: 79.95ft., length = 80ft.; s = 1.0%

Start with elevation 92ft., determine the HW/D value to be: (92ft. ! 80.75ft.) / D = 11.25 / D. To provide the most economical pipe size, or as in this case, to restrict the flow at approximately 26 cfs in (during the 10-year storm) in order to achieve better 10-year control, set HW/D = 26 cfs and by trial and error, using Federal Highway Administration (FHA) culvert nomograph: **Figure 5-16** (Headwater Depths for Concrete Pipe Culverts with Inlet Control), entrance condition 1, determine that an 18 in. pipe comes closest to the desired flow: HW/D = 11.25 / 1.5 = 7.5 Since the upper limit of the nomograph is HW / D = 6, use 6, and read Q = 25 cfs. Try 18 in. RCP Barrel.

1. Inlet Control Using the above referenced FHA culvert chart **(Figure 5-16)** establish the stage - discharge relationship for an 18 in. concrete pipe barrel, (HW = wse ! 80.75), and add these values to the stage-storage-discharge table, **Figure 6.2-8**.

Where the upper limit of the nomograph HW/D values are exceeded, use the orifice equation to approximate the inlet control flow values:

$$Q = Ca\sqrt{2gh}$$

Equation 5-6
Orifice Equation

$$Q = 0.6\,(1.77ft^2)\sqrt{(2)\,(32.2)\,(h)}$$

$Q = 8.5\ (h)^{1/2}$ where h = wse ! 80.75ft.

2. Outlet Control Use **Equation 5-10** to establish the stage-discharge relationship for the 18" concrete barrel as follows:

$$Q = a\sqrt{\frac{2gh}{1+K_m+K_pL}}$$

Equation 5-10
Pipe flow control equation

Where:
a = 1.77 ft^2
h = wse - (79.95 + D/2) = wse - 80.7
Km = Ke + Kb (from **Figure 5-9**; square end pipe: Ke = 0.5
= 0.5 + 0.5 = 1.0
Kp = .0182 (from **Table 5.10**, 18" pipe, ‘n’ = .013
L = 80

$$Q = 1.77ft^2\sqrt{\frac{2(32.2)(h)}{1+1+(.0182)(80ft.)}}$$

$Q = 7.64\,(h)^{1/2}$ where h = wse − 80.75

Add the barrel inlet and outlet control flow values to the stage-storage-discharge table, **Figure 6.2-8**.

These flow values indicate the barrel is in outlet control for the entire range of expected water surface elevations. (The inlet control values are struck out to indicate that the outlet flow condition controls the discharge). The stage -storage-discharge table indicates that the barrel controls the discharge at elevation 93ft. and above.

The performance of the 10-year control and barrel hydraulics (Trial 2) can now be checked by routing the 10-year storm, or the designer may choose to size the emergency spillway first.

STEP 11 The emergency spillway is designed using the procedure outlined in **Chapter 5-8** as follows:

1. 10-year design water surface elevation is 92.03ft. Set the invert of the emergency spillway at 92.2ft.
2. Q_{100} = 109 cfs − [10-year weir release (27 cfs)] = 82 cfs
3. Since this is a relatively small facility with a low potential downstream hazard in the case of an embankment failure, the alternate design using **Figure 5-23**: Design Data for Earth Spillways, is used for the design. We want the maximum stage to be 93ft. which allows for approximately 0.8ft. (use 1.0ft.) of flow through spillway. From **Figure 5-23**: h_p = 1.0ft. for a design flow of 81 cfs, read b = 36ft., v_{max} = 4.0ft/s, and s_{min} = 3.0%.

Add these stage-discharge values to the stage-storage-discharge table, **Figure 6.2-8**.

STEP 12 The TR-20 input file and full output file for the routing of the 1-, 10-, and 100-year storms through the basin are provided.

STEP 13 Outlet protection is designed using the design procedure presented in **Chapter 5-7** (and STD & SPEC 3.18 in the VESCH) as follows:

1. Outlet discharges into a channel with a minimum tailwater condition ($T_w < 0.5$ barrel diameter).
2. Using **Figure 5-20**, Q_{10} = 25.8 cfs and d = 18in., read D_{50} = 0.8ft. and L_a = 22ft. Use Class AI riprap.
3. Riprap apron width is to conform to the existing channel geometry to the top of bank.
4. The depth of the riprap blanket is 2.25 x 0.9 (Class AI) = 2 ft.

STEP 14 Riser buoyancy calculation (**Chapter 5-7)** is as follows:

1. Determine buoyant force:
   height: 92.2ft. ! 80.75ft. = 11.45ft. × (4ft.× 4ft.) = 183 ft^3;
   base: 6ft. × 6ft. × 1ft. = 36 ft^3;
   total: 219 ft^3 × 62.4 lb/ft^3 = 13, 678 lb8

2. Downward/resisting force:
   volume of riser walls = (11.45ft. × 4ft. × 0.5ft. × 2) + (11.45ft. × 3ft. × 0.5ft. × 2) = 80.5 ft^3;
   volume of extended back wall = (1ft. × 4ft. × 0.5ft.) = 2 ft^3;
   volume of base = (6ft. × 6ft. × 1ft.) = 36 ft^3;
   volume of 10-year weir cutout = (3.4ft. × 1.33ft. × 0.5ft.) = !2.3 ft^3;
   volume of 18in. barrel and 10in. ext detention pipe cutouts = (2.41ft^2 + 0.78 ft^2) × 0.5ft. = !1.6 ft^3;
   total downward force = volume of concrete × unit weight (150lb/ft^3) : (80.5 ft^3 + 2 ft^3 + 36 ft^3 ! 2.3 ft^3 ! 1.6 ft^3) × (150lb/ft^3) = 17190 lb 9

3. Safety factor: 13, 678 lb8 x 1.25 = 17,0988 < 17190 lb 9 **Riser OK**

FIGURE 6.2-8
Stage-Storage-Discharge Table

ELEV (MSL)	STORAGE (ac.ft.)	1-yr. ext. det. ~~WATER QUALITY~~ ORIFICE (1)		TRIAL 2 10-YEAR CONTROL WEIR (4)		10-YEAR CONTROL ORIFICE (5)		RISER STRUCTURE WEIR (6)		RISER STRUCTURE ORIFICE (7)		BARREL INLET (8)		BARREL OUTLET (9)		EMERGENCY SPILLWAY (10)		TOTAL Q (cfs)
		h	Q	h	Q	h	Q	h	Q	h	Q	HW/D	Q	h	Q	h	Q	
81	0	0	0															0
82	.02	1	0.3															0.3
84	.14	3	0.6															0.6
86	.33	5	0.7															0.7
88	.68	7	0.9															0.9
88.8	.90	7.8	0.98	0	0				0/0	0	0							1.0
89	.95	8	1.0	0.2	0.4				~~0/0.4~~	0.2	~~34.4~~	5.5	~~24~~	8.3	~~22.0~~			1.4
90	1.28	9	1.1	1.2	5.8				~~0/5.8~~	1.2	~~84.4~~	6.2	~~26~~	9.3	~~23.3~~			6.9
91	1.75	10	1.1	2.2	14.3				~~0/14.3~~	2.2	~~114.3~~	6.8	~~27~~	10.3	~~24.5~~			15.4
92	2.23	11	~~1.1~~	3.2	~~25.1~~				~~0/25.1~~	3.2	~~139.8~~	7.5	~~28~~	11.3	25.7			25.7
92.2	2.40	11.2	~~1.1~~	3.4	~~27.5~~			0	~~0/27.5~~	3.4	~~142.0~~	7.6	~~29~~	11.5	25.9	0	0	25.9
93	2.94	12.0	~~1.1~~	4.2	~~37.8~~			0.8	~~17.0/54.8~~	4.2	~~157.9~~	8.1	~~30~~	12.3	26.8	0.8	54	80.8
94	3.81	13.0	~~1.2~~	5.2	~~52.0~~			1.8	~~27.5/109.5~~	5.2	~~175.7~~	8.8	~~31~~	13.3	27.8	1.8	214	241.8

(6) Q for elevations 88.8 to 92.2 ft. represents 10-yr. weir flow (4)
Q for elevations 92.2 to 94 ft represents 10-yr weir flow plus the top of riser weir flow: $Q = 23.8\,(h)^{1.5}$ where h = wse - 92.2 ft.

(7) $Q = 77.03\,(h)^{1/2}$ where h = wse - 88.8 ft
(8) $Q = 8.5\,(h)^{1/2}$ where h = wse - 80.75 ft
(9) $Q = 7.64\,(h)^{1/2}$ where h = wse - 80.75 ft
(10) Figure 5-23: Design Data for Earth Spillways.

FIGURE 6.2-9

TR-20 Input and Output Summary - 1-yr. Extended Detention, 10-yr. Flood Control, 100-yr. Emergency Spillway

```
******************80-80 LIST OF INPUT DATA FOR TR-20 HYDROLOGY******************

JOB TR-20                  FULLPRINT        SUMMARY
TITLE 001 STORMWATER HANDBOOK EXAMPLE PROBLEM 1: EX1ROUTC.DAT
TITLE     EXTENDED DETENTION 1 YR STORM, 10 YR FLOOD CONTROL, 100 YR SAFETY
 3 STRUCT      01
 8                      81.0      0.0       0.0
 8                      82.0      0.3       0.02
 8                      84.0      0.6       0.14
 8                      86.0      0.7       0.33
 8                      88.0      0.9       0.68
 8                      88.8      0.98      0.90
 8                      89.0      1.4       0.95
 8                      90.0      6.9       1.28
 8                      91.0     15.4       1.75
 8                      92.0     25.7       2.23
 8                      92.2     25.9       2.45
 8                      93.0     80.8       2.94
 8                      94.0    241.8       3.81
 9 ENDTBL
 6 RUNOFF 1 001      1  .039     75.        0.35        1 1  1  1
 6 RESVOR 2    01 1  2  81.0                            1 1  1  1
   ENDATA
 7 INCREM 6            .25
 7 COMPUT 7 001      01 0.0       2.7       1.0         2 2  01  01   1-yr storm
   ENDCMP 1
 7 COMPUT 7 001      01 0.0       5.5       1.0         2 2  01  02   10-yr storm
   ENDCMP 1
 7 COMPUT 7 001      01 0.0       8.0       1.0         2 2  01  03   100-yr storm
   ENDCMP 1
   ENDJOB 2
```

SUMMARY TABLE 1 - SELECTED RESULTS OF STANDARD AND EXECUTIVE CONTROL INSTRUCTIONS IN THE ORDER PERFORMED
(A STAR(*) AFTER THE PEAK DISCHARGE TIME AND RATE (CFS) VALUES INDICATES A FLAT TOP HYDROGRAPH
A QUESTION MARK(?) INDICATES A HYDROGRAPH WITH PEAK AS LAST POINT.)

SECTION/ STRUCTURE ID	STANDARD CONTROL OPERATION	DRAINAGE AREA (SQ MI)	RAIN TABLE #	ANTEC MOIST COND	MAIN TIME INCREM (HR)	PRECIPITATION BEGIN (HR)	AMOUNT (IN)	DURATION (HR)	RUNOFF AMOUNT (IN)	PEAK DISCHARGE ELEVATION (FT)	TIME (HR)	RATE (CFS)	RATE (CSM)
ALTERNATE 1 STORM 1													
XSECTION 1	RUNOFF	.04	2	2	.25	.0	2.70	24.00	.76	---	12.17	14.68	376.4
STRUCTURE 1	RESVOR	.04	2	2	.25	.0	2.70	24.00	.77	88.68	15.50?	.97?	24.8
ALTERNATE 1 STORM 2													
XSECTION 1	RUNOFF	.04	2	2	.25	.0	5.50	24.00	2.83	---	12.10	61.12	1567.1
STRUCTURE 1	RESVOR	.04	2	2	.25	.0	5.50	24.00	2.87	92.13	12.54	25.83	662.3
ALTERNATE 1 STORM 3													
XSECTION 1	RUNOFF	.04	2	2	.25	.0	8.00	24.00	4.99	---	12.09	108.87	2791.7
STRUCTURE 1	RESVOR	.04	2	2	.25	.0	8.00	24.00	5.10	93.06	12.30	90.54	2321.6

STEP 15 Anti-seep collars, rather than a drainage blanket, will be used on this facility since it is a dry facility. Anti-seep collars are designed using the procedure outlined in **Chapter 5-7** as follows:

1. Length of barrel within saturated zone:

$$L_s = Y\,(Z + 4)\ \hat{}\,1 + \ \hat{}\,\frac{S}{0.25 - S}$$

Equation 5-11
Barrel Length in Saturated Zone

where: Y = 92.13ft. ! 81.0ft. = 11.2ft.
Z = 3H : 1V; = 3
S = 1.0%

$$L_s = 11.2(\,3 + 4\,)\ \hat{}\,1 + \hat{}\,\frac{.01}{0.25 - .01}$$

L_s = 81ft.

<u>OR</u>

Extend a line at 4H:IV from the 10-year water surface elevation at the upstream face of the embankment downward until it intersects the barrel. The resulting point on the barrel measures approximately 81ft. From the low flow headwall.

2. (L_s) (0.15) = (81ft.) (0.15) = 12.1ft.
3. For an 18in. (1.5ft.) diameter barrel: 4ft. + 1.5ft. = 5.5ft.
4. Projection = 4ft.
5. Number of collars = 12.1 / 4 = 3 collars. Only two collars are desired: use a 6ft. projection 6ft. + 1.5ft. = 7.5ft. collars. 12.1 / 6 = 2. <u>Use 2 - 7.5ft. collars</u>

FIGURE 6.2-10
Riser Weir and Trash Rack - Perspective

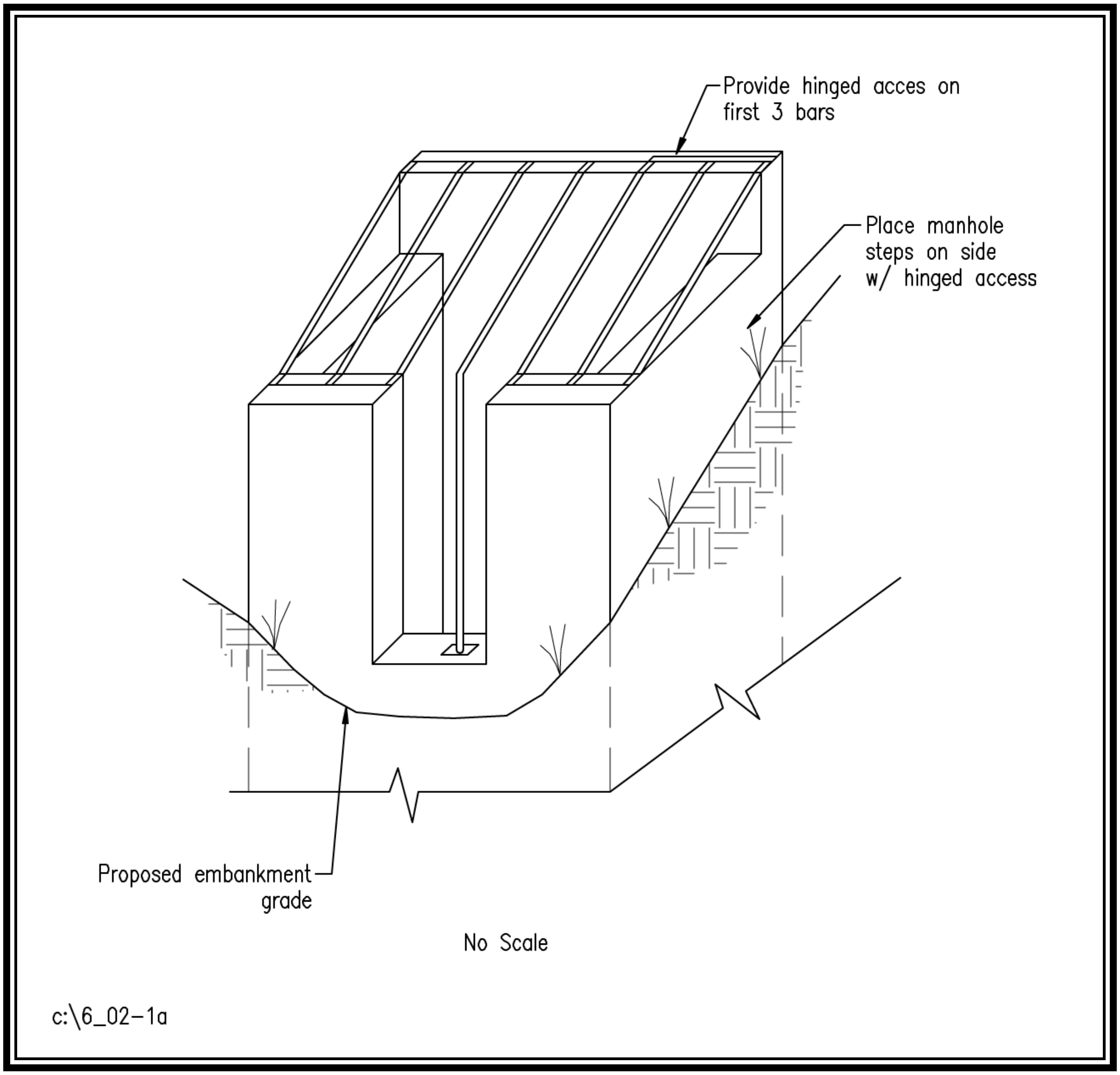


FIGURE 6.2-11
Riser Detail - Section

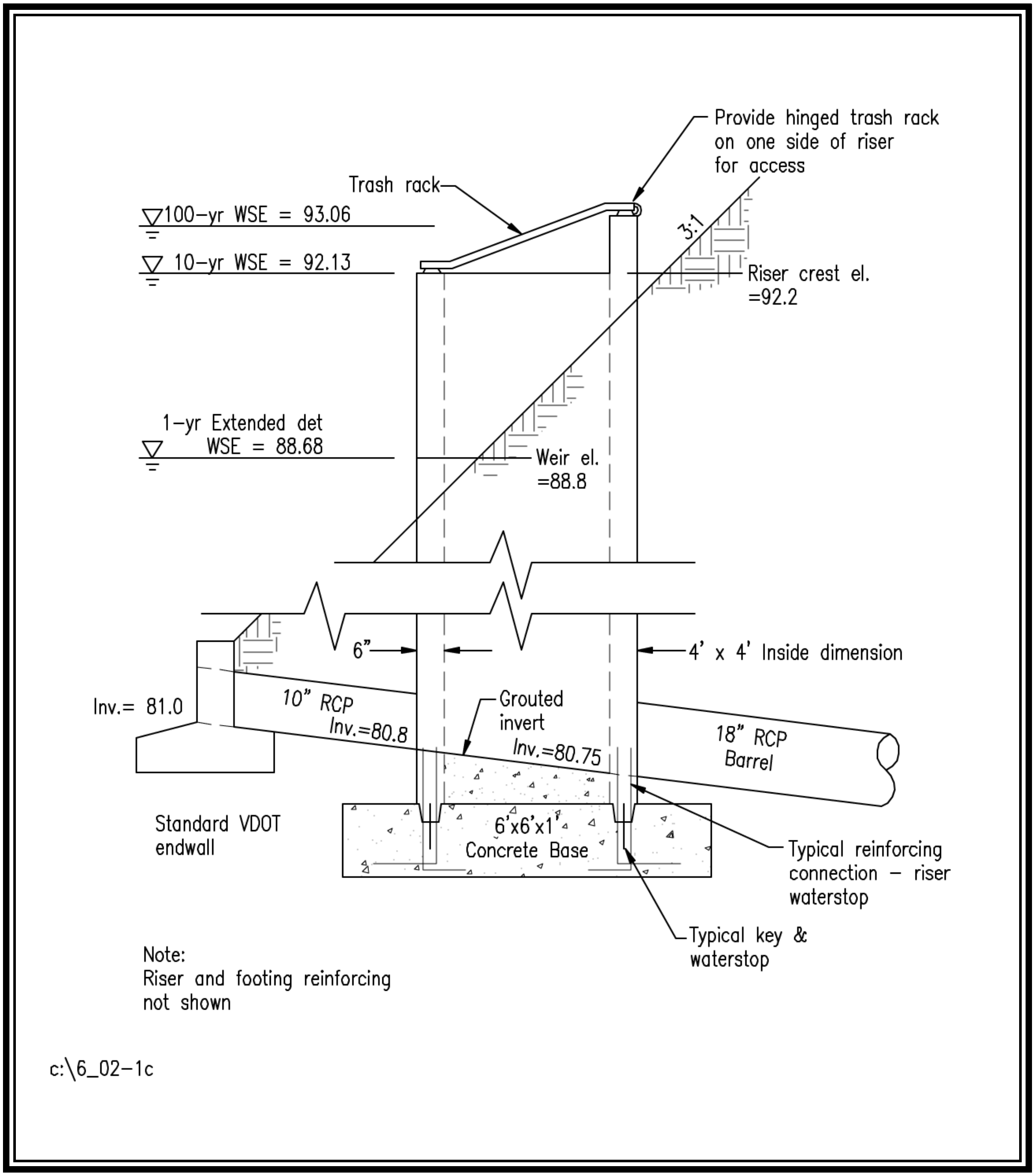
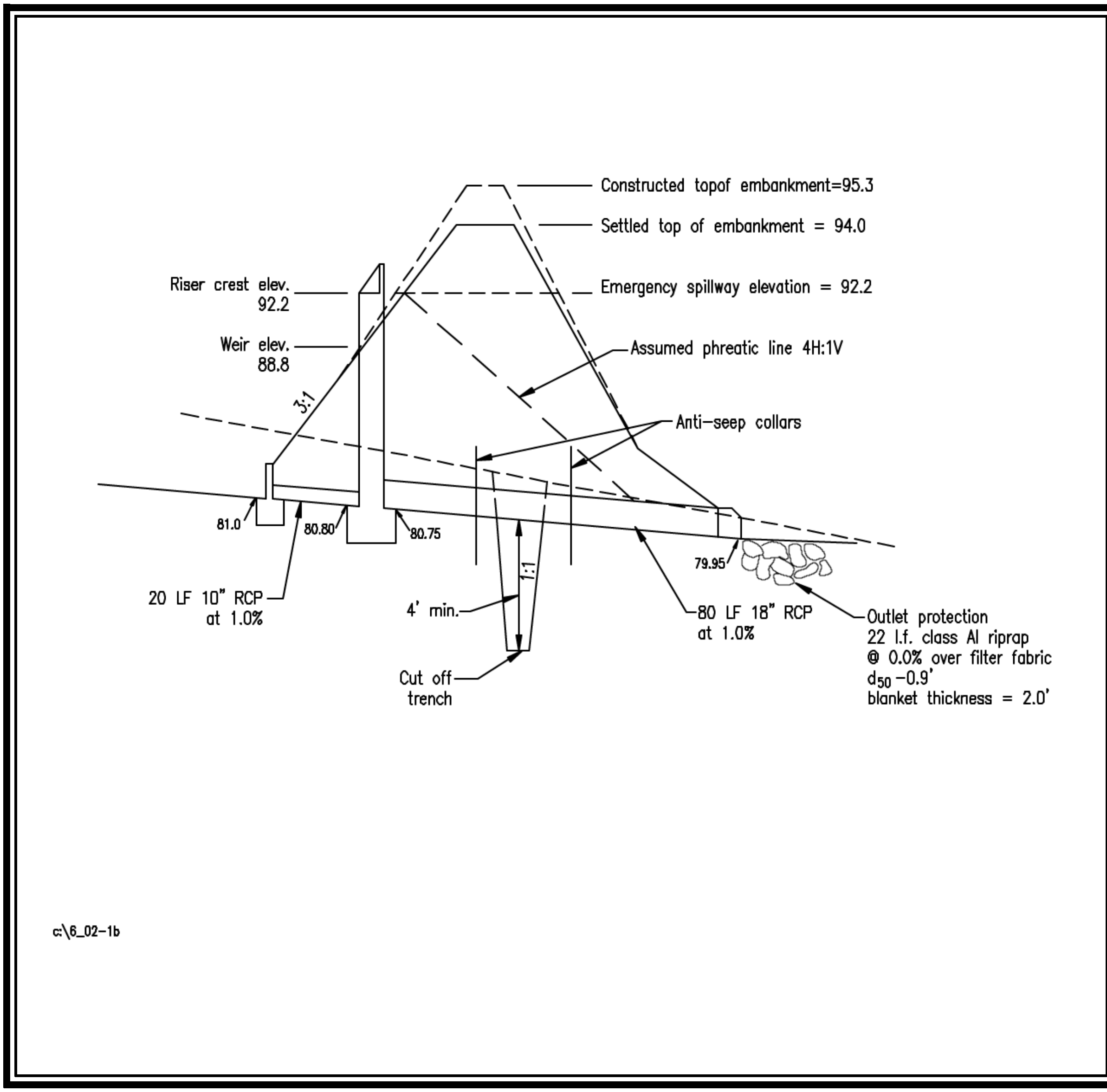


FIGURE 6.2-12
Principal Spillway - Profile



Example 6.3

BMP SELECTION

EXAMPLE 6.3

INTRODUCTION:

A 90.2 acre site is to be developed into an office park. Perimeter portions of the site are composed of steep slopes adjacent to two small tributaries which bound the site. Local zoning and Resource Protection Ordinances restrict the development to the upper, relatively flat center of the property. (This restriction is does not necessarily limit the development since the engineering costs of developing on the steep slopes, as well as minimizing the environmental impacts, would be prohibitive.) The site consists of soils with a moderately high runoff potential (Hydrologic Soil Group C) with no existing impervious cover.

The proposed buildings, parking lots, and other infrastructure are located on the site such that the developed condition is drained by three outfalls. These outfalls drain into the adjacent stream channels at the naturally occurring drainage paths from the site. The local stormwater management (SWM) program requires that all three components of stormwater management, water quality, stream channel erosion, and flooding, be investigated. This example will illustrate the application of these components, including a discussion of the *Performance-based* and *Technology-based* water quality criteria.

GIVEN:

The pre- and post-developed hydrology for the site is presented in **Table 6-3.1**. The drainage areas are measured to the proposed study points which have been located at the downstream limit of the potential BMP locations.

FIND:

Evaluate the BMP options and select the combination which best serve the proposed development.

SOLUTION:

The implementation of stormwater BMPs should be considered during the initial stages of the site design. An evaluation of the stormwater requirements prior to site design will allow the engineer to identify potential BMP locations and provide the most efficient alignment of the drainage infrastructure so as to enhance the use of natural drainage ways to convey stormwater runoff. (The internal drainage systems must satisfy the Erosion and Sediment Control, MS-19 criteria for channel adequacy.) Once the preliminary site design is completed, the engineer can calculate the water quality volume, pollutant loadings, peak rates of discharge, and channel capacities in order to finalize the BMP strategy for the site.

The most efficient method of evaluating the BMP requirements for a development site is one based on a hierarchy of potential impacts to the site design. This method would start with an evaluation of the flood component requirements since it is potentially the most land intensive component with regard to storage volume. In some cases the stream channel erosion component may require the largest storage volume. In either case, the analysis of the downstream conditions will determine the level of detention required to comply with either of these components. Water quality requirements, on the other hand, may be addressed with smaller BMPs or incorporated into the design of the detention structures required by the flooding or stream channel erosion components.

Table 6.3-1
Hydrologic Summary
TR-55 Graphical Peak Discharge Method

	Condition	**Area** (acres)	**% Imp Cover**	**RCN**	t_c (hrs.)	Q_2 (cfs)	Q_{10} (cfs)
SITE	Pre-dev	90.2		74			
	Post-dev	90.2	17	78			
DA - 1	Pre-dev	9.79		74	0.36	14	26
	Post-dev	16.16	36	83	0.34	37	59
DA - 2	Pre-dev	26.61		75	0.41	38	68
	Post-dev	26.39	35	83	0.40	56	89
DA - 3	Pre-dev	2.65		65	0.58	2.0	4.0
	Post-dev	2.65	19	71	0.58	3.0	5.0

Flooding

An analysis of the downstream receiving system must be performed in order to evaluate the flood way conveyance capacity of the of the two tributaries adjacent to the site as well as the downstream channel. The Virginia SWM Regulations (4VAC3-20-85) require that downstream properties be protected form damages from localized flooding due to increases in volume, velocity, and peak flow rate of stormwater runoff by detaining the 10-year post-developed peak rate of runoff and releasing it at the pre-developed rate. There is also a provision which allows an alternate criteria based upon geographic, land use, topographic, geologic factors or other downstream conveyance factors as appropriate. In this case, the local government has a Flodplain Management Ordinance in place which has restricted development within the flood way of the tributaries and the downstream channel. The analysis of the flood way reveals that there is sufficient capacity to convey the ultimate development condition runoff within the flood way, and that there is no existing development (or structures) within the flood way for the entire downstream reach to the confluence with the river.

Flood control (10-year storm) is not required in this case.

Stream Channel Erosion

The Virginia SWM Regulations (4VAC3-20-81) require that properties and receiving waterways downstream of any land development project be protected from erosion and damage due to increases in volume, velocity, and peak flow rate of stormwater runoff. A rigorous analysis of the downstream channel is required in order to verify the adequacy for conveying the post-developed runoff. The following items were completed for each channel in order to adequately verify the analysis:

1. **Channel geometry** - A minimum of three surveyed cross-sections were taken at a minimum spacing of 50' along the channel length downstream of the discharge point.

2. **Channel lining** - A sample of the channel lining was collected and analyzed to determine the composition relative to the permissible velocities found in Table 5-22 of the Virginia Erosion and Sediment Control Handbook.

3. **Channel slope** - Relative elevations were taken along the channel length at the channel cross sections in order to determine the average longitudinal slope of the channel.

4. **Channel Inspection** - The channel was physically inspected by walking the length to verify that there are no significant changes or obstructions such as undersized culverts or other "improved" restrictions which may restrict the flow and cause it to jump the banks or increase in velocity to an erosive level.

The channel analysis indicated that the post-developed condition runoff would cause an erosive condition in specific sections of the channel where the flow area narrows considerably. In addition, the physical inspection verified that several of these narrow areas as well as several bends are already experiencing some erosion under existing runoff conditions. Some of the options considered include:

1. **Channel improvements** - Channel improvements are is ruled out due to poor access conditions to the channel. Significant clearing would be required to not only gain access but also to maneuver construction equipment adjacent to the channels. Some possibilities do

exist for hand placed bioengineering stabilization of the eroded portions of the channel.

2. **Alternative site design** - Several alternate site configurations were evaluated in an effort to reduce the impervious cover, disconnect the impervious cover from the drainage system (disconnecting impervious cover include discharging roof down spouts into dry wells or into sheet flow conditions over pervious areas, placing grass or landscaped buffer strips between impervious surfaces and the improved drainage structures and conveyances), and create small pockets in which to detain runoff in an effort to increase the hydrologic flow time and decrease the peak rate of runoff from the site. While these efforts did result in some significant reductions in post-developed runoff, the resulting peak rate was still determined to be too high for the stream channels to convey in a non-erosive manner.

3. **Combination of channel improvements, site design, and detention** - The hydrologic analysis of the post-developed condition with the various alternative site designs and 24 hour extended detention of the runoff from the 1-year frequency storm yielded a peak rate of runoff significantly less than the runoff from the pre-developed condition 2-year storm. Further analysis indicated that the statistical occurrence frequency of the post-developed condition peak runoff equivalent to the pre-developed 2-year peak runoff occurs less than once in 5 years. This means that, according to the statistical analysis, it would take a five year frequency storm event to generate the pre-developed 2-year peak rate of runoff leaving the site.

Alternative 3 was selected in order to attempt to stabilize the natural channels adjacent to the site. Extended detention basins designed to detain the runoff from the 1-year 24 hour storm will be placed in drainage areas 1 (DA-1) and 2 (DA-2).

<u>Water Quality</u>

The designer must select either the *Performance-based* or *Technology-based* water quality criteria. The technology-based criteria considers the drainage area size and impervious cover draining to a BMP to establish the best available technology (BMP) for the drainage area or site being evaluated. The performance-based criteria uses the percent impervious cover of the site to calculate a total <u>site</u> pre- and post-developed pollutant load. The engineer then implements a BMP strategy which satisfies the <u>total</u> site pollutant reduction requirement.

Since the Performance-based water quality criteria allows for overall site compliance, it is not always necessary to place a water quality BMP in each drainage area on the site. DCR recommends, however, that the engineer evaluate the potential pollutant loading based on the amount of impervious cover and the concentration of that cover. In other words, if the impervious cover is concentrated, or located such that an improved drainage system is collecting the runoff, then the implementation of a water quality BMP(s) should be implemented for that area. This is the preferred solution, rather than placing a BMP in one drainage area, satisfying the performance-based total site pollutant removal requirement for the site, and then ignoring the other drainage areas and their associated impacts on downstream water quality. The key to the successful implementation of this recommendation is a menu of available, cost effective, and low maintenance BMPs. The menu of BMPs found in **Table 1** of the SWM Regulations, as well as the several new and innovative BMPs currently available, provide several low cost options. This is one of the strategies of Low Impact Development: relatively small and maintenance free BMPs to control small portions of the development area in landscaped settings in addition to development strategies which effectively reduce the impact of the impervious area on the runoff from the site. (Refer to the references found at the end of **Chapter 2** for more information on Low Impact Development.)

This example illustrates a development scenario in which the percent impervious cover determination for the performance-based criteria plays a significant role in the BMP strategy. The percent impervious cover for the *property* is low (15.73 acres of impervious cover on a 90.2 acre site: 17% impervious cover). The percent impervious cover for the *individual drainage areas* to the potential BMP locations, however, is much higher (a total of 45.2 acres at 35% impervious cover). As discussed in **Chapter 2**, one of the effects of using impervious cover as a regulatory water quality yardstick is to encourage the minimization of impervious cover and the preservation of green space and environmentally sensitive areas. In this example, the <u>total</u> impervious cover is limited to 17% of the <u>site</u>.

When using the performance-based criteria the derived benefit of such a low percent impervious cover is a minimal pollutant removal requirement. This minimal removal requirement illustrates the discussion above: a BMP placed in one of the drainage areas will most likely satisfy the removal requirement for the site, and the remaining drainage areas could be left uncontrolled for water quality. It stands to reason, however, that the highly concentrated impervious cover found within the other drainage areas will have a significant impact on the water quality of the adjacent streams. The use of the entire site to determine the percent impervious cover does not accurately reflect the changes to the land use. **Therefore, when using the performance-based criteria for large development parcels, DCR recommends that the percent impervious cover be calculated by using the drainage areas or an established *planning area*. In this example, a planning area may be established which consists of the portion of the site which is able to be developed.**

A planning area is defined as a designated portion of the parcel on which the land development project is located. Planning areas shall be established by delineation on a master plan. Once established, planning areas shall be applied consistently for all future projects.

The water quality requirements in terms of pollutant load removal are calculated using the **Performance-Based Water Quality Calculations: Worksheet 2** provided in **Appendix 5D**, and summarized below:

TRIAL 1: Entire site.

STEP 4: Equation 5-16

$\mathbf{L}_{\mathbf{pre(watershed)}}$ = [0.05 + (0.009 × 16%)] × 90.2 ac. × 2.28 = 39.9 pounds per year

STEP 5: Equation 5-21

$\mathbf{L}_{\mathbf{post}}$ = [0.05 + (0.009 × 17.4%)] × 90.2 ac. × 2.28 = 42.5 pounds per year

STEP 6:

RR = 42.5 ! 39.9 = 2.6 pounds per year

STEP 7:

EFF = (2.6 ÷ 42.5) × 100 = 6.1 %

If a BMP could serve the entire site, then a removal efficiency of 6.1% would be required. Since this can not be done, a minimum of 2.6 pounds of phosphorus must be removed from any one or combination of the drainage areas of the developed portion of the site.

TRIAL 2: Planning area consisting of the developable area of the site: 45.2 acres

STEP 4: Equation 5-16

$\mathbf{L}_{\mathbf{pre(watershed)}}$ = [0.05 + (0.009 × 16%)] × 45.2 ac. × 2.28 = 20.0 pounds per year

STEP 5: Equation 5-21

$\mathbf{L}_{\mathbf{post}}$ = [0.05 + (0.009 × 35.0%)] × 45.2 ac. × 2.28 = 37.6 pounds per year

STEP 6:

RR = 37.6 ! 20.0 = 17.6 pounds per year

STEP 7:

(1.) **EFF** = (17.6 ÷ 37.6) × 100 = 46.8 %

When considering the whole site (90.2 acres at 17% impervious cover), the pollutant removal requirement is 6% of the post-developed load (or 2.6 lbs of phosphorus) as calculated in Trial 1. When just the drainage areas to the BMP locations are considered (45.2 acres at 35% impervious cover), the pollutant removal requirement is 46.8% of the post-developed load (or 17.6 lbs of phosphorus).

Continuing with **TRIAL 2, STEP 7:**

(2.) Select BMP(s) from Table 5-15:

BMP 1: DA 1 - 16.16 ac.: Extended Detention (2×WQV) - 35% eff.
BMP 2: DA 2 - 26.39 ac.: Retention Basin III (4×WQV) - 65% eff.
BMP 3: DA 3 - 2.65 ac.: Bioretention Basin - 50% eff.

(3.) Determine pollutant load entering BMPs:

$\mathbf{L_{BMP1}}$ = [0.05 + (0.009 × 36%)] × 16.16 ac. × 2.28 = 13.8 pounds per year
$\mathbf{L_{BMP2}}$ = [0.05 + (0.009 × 35%)] × 26.39 ac. × 2.28 = 22.0 pounds per year
$\mathbf{L_{BMP3}}$ = [0.05 + (0.009 × 19%)] × 2.65 ac. × 2.28 = 1.3 pounds per year

(4.) Calculate the pollutant load removed by BMPs:

$\mathbf{L_{removed/BMP1}}$ = .35 × 13.8 = 4.83 pounds per year
$\mathbf{L_{removed/BMP2}}$ = .65 × 22.0 = 14.3 pounds per year
$\mathbf{L_{removed/BMP3}}$ = .50 × 1.3 = 0.65 pounds per year

(5.) Calculate the total pollutant load removed by the BMPs:

$\mathbf{L_{removed/total}}$ = 4.83 + 14.3 + 0.65 = 19.78 pounds per year

Several other combination of BMPs will satisfy the removal requirements of TRIAL 2 of this example. Since both drainage areas 1 and 2 require stream channel erosion protection, and an aesthetic retention pond was desirable as a focal point of the office setting, the combination presented above was selected. The dry storage above the permanent pool, as well as the storage above the water quality extended detention volume, are both to be designed to provide extended detention of the runoff from the 1-year 24 hour storm for stream channel erosion control.