APPENDIX III-2A

ATTACHMENTS

Atlas 14 Point Precipitation Frequency Estimates (NOAA)
Hydraulic Design Manual (TxDOT)
Infrastructure Design Manual (Houston Public Works)
Part 630 Hydrology National Engineering Handbook (NRCS)
Policy, Criteria, and Procedure Manual (HCFCD)
Urban Hydrology for Small Watersheds TR-55 (NRCS)

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Precipitation frequency estimates

Hydrometeorological Design Studies Center is updating precipitation frequency (PF) estimates for various areas of the U.S. as Volumes of NOAA Atlas 14. Estimates in a variety of formats with supplementary information and documentation are available from the PF Data Server (PFDS). Publications for states not covered by Atlas 14 are also available.

learn more >

Probable maximum precipitation

National Weather Service (NWS) has provided probable maximum precipitation (PMP) guidance and studies since the late 1940s at the request of various federal agencies and with funding provided by those agencies. Probable maximum precipitation activities were discontinued in 1999 due to lack of funding, but copies of NWS PMP documents can be found on this site.

learn more >

Miscellaneous information

Also available on this site:

- NWS publications of interest for PF and PMP studies (NOAA Atlas 14, NOAA Atlas 2, Technical Reports, Technical Papers, Hydrometeorological Reports)

learn more >

- Probability analysis for selected historical storm events

learn more >

- Record point precipitation for the USA and the world

learn more >

NOAA Atlas 14, Volume 11, Version 2
Location name: Houston, Texas, USA*
Latitude: 29.8515°, Longitude: -95.5604°
Elevation: 104.43 ft**
* source: ESRI Maps
** source: USGS

POINT PRECIPITATION FREQUENCY ESTIMATES

Sanja Perica, Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Orlan Wilhite

NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.496 (0.376-0.656)	0.581 (0.444-0.759)	0.718 (0.547-0.943)	0.832 (0.625-1.11)	0.990 (0.719-1.36)	1.11 (0.786-1.57)	1.23 (0.851-1.79)	1.37 (0.918-2.03)	1.55 (1.00-2.38)	1.69 (1.07-2.67)
10-min	0.786 (0.595-1.04)	0.921 (0.703-1.20)	1.14 (0.869-1.50)	1.33 (0.995-1.77)	1.58 (1.15-2.17)	1.78 (1.26-2.51)	1.97 (1.36-2.86)	2.17 (1.46-3.23)	2.43 (1.58-3.74)	2.62 (1.66-4.14)
15-min	1.00 (0.759-1.32)	1.17 (0.893-1.53)	1.44 (1.10-1.89)	1.67 (1.25-2.22)	1.97 (1.43-2.71)	2.21 (1.56-3.12)	2.45 (1.69-3.55)	2.71 (1.82-4.03)	3.06 (1.99-4.71)	3.33 (2.11-5.26)
30-min	1.44 (1.09-1.90)	1.67 (1.27-2.19)	2.05 (1.56-2.69)	2.36 (1.77-3.14)	2.78 (2.01-3.80)	3.10 (2.18-4.36)	3.43 (2.36-4.97)	3.80 (2.55-5.66)	4.33 (2.82-6.68)	4.77 (3.02-7.54)
60-min	1.89 (1.43-2.50)	2.21 (1.69-2.89)	2.73 (2.08-3.59)	3.17 (2.38-4.22)	3.77 (2.73-5.15)	4.22 (2.97-5.93)	4.70 (3.24-6.81)	5.26 (3.54-7.85)	6.11 (3.97-9.43)	6.82 (4.32-10.8)
2-hr	2.28 (1.73-3.00)	2.77 (2.10-3.55)	3.51 (2.68-4.58)	4.17 (3.15-5.54)	5.13 (3.74-7.00)	5.90 (4.18-8.28)	6.76 (4.68-9.76)	7.80 (5.26-11.6)	9.40 (6.13-14.5)	10.8 (6.85-17.0)
3-hr	2.48 (1.89-3.26)	3.10 (2.33-3.92)	4.00 (3.06-5.19)	4.84 (3.66-6.41)	6.08 (4.45-8.29)	7.12 (5.07-9.99)	8.31 (5.76-12.0)	9.74 (6.58-14.4)	12.0 (7.82-18.4)	13.9 (8.86-21.9)
6-hr	2.85 (2.18-3.73)	3.69 (2.76-4.58)	4.88 (3.73-6.28)	6.02 (4.57-7.93)	7.77 (5.72-10.6)	9.28 (6.65-13.0)	11.1 (7.70-15.9)	13.2 (8.92-19.4)	16.4 (10.8-25.1)	19.3 (12.3-30.1)
12-hr	3.26 (2.51-4.24)	4.32 (3.21-5.28)	5.78 (4.43-7.40)	7.22 (5.50-9.47)	9.46 (7.01-12.9)	11.4 (8.25-16.0)	13.8 (9.62-19.7)	16.5 (11.2-24.1)	20.6 (13.6-31.4)	24.2 (15.5-37.7)
24-hr	3.71 (2.86-4.81)	5.00 (3.72-6.04)	6.75 (5.20-8.60)	8.51 (6.51-11.1)	11.3 (8.42-15.3)	13.8 (9.99-19.2)	16.7 (11.7-23.7)	19.9 (13.6-29.0)	24.7 (16.2-37.3)	28.6 (18.4-44.5)
2-day	4.22 (3.26-5.43)	5.78 (4.28-6.90)	7.87 (6.08-9.97)	10.0 (7.68-13.0)	13.4 (10.1-18.3)	16.6 (12.1-23.2)	20.1 (14.1-28.5)	23.6 (16.1-34.2)	28.4 (18.8-42.7)	32.1 (20.8-49.7)
3-day	4.60 (3.57-5.91)	6.30 (4.69-7.51)	8.58 (6.65-10.8)	10.9 (8.39-14.1)	14.5 (11.0-19.8)	18.0 (13.2-25.1)	21.7 (15.3-30.7)	25.3 (17.3-36.6)	30.1 (19.9-45.0)	33.6 (21.8-51.9)
4-day	4.93 (3.83-6.32)	6.68 (5.01-8.00)	9.07 (7.05-11.5)	11.5 (8.84-14.8)	15.2 (11.5-20.7)	18.6 (13.7-26.0)	22.4 (15.8-31.6)	26.0 (17.9-37.6)	30.8 (20.4-46.1)	34.4 (22.3-53.0)
7-day	5.69 (4.44-7.28)	7.50 (5.70-9.07)	10.0 (7.83-12.7)	12.5 (9.67-16.1)	16.3 (12.4-22.0)	19.7 (14.5-27.3)	23.4 (16.6-33.0)	27.1 (18.6-39.0)	31.9 (21.2-47.6)	35.6 (23.1-54.6)
10-day	6.34 (4.96-8.10)	8.19 (6.28-9.96)	10.8 (8.48-13.7)	13.4 (10.4-17.2)	17.2 (13.0-23.1)	20.6 (15.2-28.4)	24.2 (17.2-34.0)	27.9 (19.2-40.0)	32.7 (21.8-48.7)	36.4 (23.7-55.8)
20-day	8.39 (6.59-10.7)	10.3 (8.05-12.7)	13.2 (10.4-16.7)	15.9 (12.4-20.4)	19.8 (15.0-26.4)	23.1 (17.1-31.6)	26.6 (19.0-37.2)	30.1 (20.9-43.2)	34.8 (23.3-51.7)	38.4 (25.1-58.6)
30-day	10.1 (7.97-12.8)	12.1 (9.56-15.1)	15.3 (12.1-19.2)	18.0 (14.1-23.1)	22.0 (16.7-29.1)	25.3 (18.6-34.4)	28.6 (20.5-39.9)	32.0 (22.3-45.8)	36.5 (24.6-54.2)	40.0 (26.2-60.9)
45-day	12.6 (9.98-16.0)	14.8 (11.8-18.6)	18.4 (14.6-23.1)	21.4 (16.7-27.3)	25.5 (19.3-33.6)	28.7 (21.1-38.8)	31.8 (22.8-44.3)	35.0 (24.5-50.0)	39.2 (26.4-58.0)	42.4 (27.8-64.3)
60-day	14.9 (11.8-18.8)	17.3 (13.9-21.7)	21.3 (17.0-26.7)	24.5 (19.2-31.1)	28.7 (21.7-37.6)	31.8 (23.5-42.9)	34.8 (25.0-48.4)	37.8 (26.5-54.0)	41.7 (28.2-61.6)	44.5 (29.3-67.5)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).
Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.
Please refer to NOAA Atlas 14 document for more information.

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PF graphical

NOAA Atlas 14, Volume 11, Version 2
Location name: Houston, Texas, USA*
Latitude: 29.8515°, Longitude: -95.5604°
Elevation: 104.43 ft**
* source: ESRI Maps
** source: USGS

POINT PRECIPITATION FREQUENCY ESTIMATES

Sanja Perica, Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Orlan Wilhite

NOAA, National Weather Service, Silver Spring, Maryland

PF tabular | PF graphical | Maps & aerials

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	**5.95** (4.51-7.87)	**6.97** (5.33-9.11)	**8.62** (6.56-11.3)	**9.98** (7.50-13.3)	**11.9** (8.63-16.3)	**13.3** (9.43-18.8)	**14.8** (10.2-21.5)	**16.4** (11.0-24.4)	**18.5** (12.0-28.6)	**20.2** (12.8-32.0)
10-min	**4.72** (3.57-6.23)	**5.53** (4.22-7.22)	**6.85** (5.21-9.00)	**7.95** (5.97-10.6)	**9.47** (6.90-13.0)	**10.7** (7.55-15.1)	**11.8** (8.17-17.2)	**13.0** (8.75-19.4)	**14.6** (9.47-22.4)	**15.7** (9.96-24.9)
15-min	**4.01** (3.04-5.30)	**4.67** (3.57-6.12)	**5.76** (4.39-7.57)	**6.66** (5.00-8.87)	**7.90** (5.74-10.8)	**8.84** (6.25-12.5)	**9.80** (6.76-14.2)	**10.8** (7.28-16.1)	**12.2** (7.94-18.8)	**13.3** (8.43-21.0)
30-min	**2.88** (2.18-3.80)	**3.34** (2.55-4.37)	**4.09** (3.12-5.38)	**4.71** (3.53-6.28)	**5.56** (4.03-7.60)	**6.19** (4.37-8.71)	**6.85** (4.72-9.93)	**7.59** (5.11-11.3)	**8.66** (5.63-13.4)	**9.54** (6.04-15.1)
60-min	**1.89** (1.43-2.50)	**2.21** (1.69-2.89)	**2.73** (2.08-3.59)	**3.17** (2.38-4.22)	**3.77** (2.73-5.15)	**4.22** (2.97-5.93)	**4.70** (3.24-6.81)	**5.26** (3.54-7.85)	**6.11** (3.97-9.43)	**6.82** (4.32-10.8)
2-hr	**1.14** (0.866-1.50)	**1.38** (1.05-1.77)	**1.76** (1.34-2.29)	**2.09** (1.57-2.77)	**2.57** (1.87-3.50)	**2.95** (2.09-4.14)	**3.38** (2.34-4.88)	**3.90** (2.63-5.79)	**4.70** (3.06-7.23)	**5.39** (3.42-8.48)
3-hr	**0.827** (0.630-1.09)	**1.03** (0.777-1.31)	**1.33** (1.02-1.73)	**1.61** (1.22-2.13)	**2.03** (1.48-2.76)	**2.37** (1.69-3.33)	**2.77** (1.92-3.99)	**3.25** (2.19-4.80)	**3.99** (2.61-6.13)	**4.64** (2.95-7.28)
6-hr	**0.477** (0.365-0.623)	**0.617** (0.461-0.765)	**0.815** (0.623-1.05)	**1.01** (0.762-1.33)	**1.30** (0.955-1.77)	**1.55** (1.11-2.17)	**1.85** (1.29-2.65)	**2.20** (1.49-3.24)	**2.74** (1.80-4.20)	**3.22** (2.05-5.03)
12-hr	**0.271** (0.208-0.352)	**0.358** (0.267-0.438)	**0.479** (0.368-0.614)	**0.599** (0.456-0.786)	**0.785** (0.582-1.07)	**0.949** (0.685-1.33)	**1.14** (0.799-1.63)	**1.37** (0.929-2.00)	**1.71** (1.13-2.61)	**2.01** (1.29-3.13)
24-hr	**0.155** (0.119-0.200)	**0.208** (0.155-0.252)	**0.281** (0.217-0.358)	**0.355** (0.271-0.463)	**0.469** (0.351-0.639)	**0.573** (0.416-0.802)	**0.694** (0.487-0.987)	**0.828** (0.565-1.21)	**1.03** (0.677-1.56)	**1.19** (0.768-1.85)
2-day	**0.088** (0.068-0.113)	**0.120** (0.089-0.144)	**0.164** (0.127-0.208)	**0.208** (0.160-0.271)	**0.279** (0.211-0.381)	**0.345** (0.253-0.483)	**0.418** (0.295-0.593)	**0.492** (0.336-0.713)	**0.592** (0.391-0.889)	**0.669** (0.432-1.03)
3-day	**0.064** (0.050-0.082)	**0.087** (0.065-0.104)	**0.119** (0.092-0.151)	**0.151** (0.116-0.196)	**0.202** (0.153-0.276)	**0.249** (0.184-0.349)	**0.301** (0.213-0.426)	**0.351** (0.241-0.508)	**0.418** (0.276-0.626)	**0.467** (0.303-0.721)
4-day	**0.051** (0.040-0.066)	**0.070** (0.052-0.083)	**0.095** (0.073-0.119)	**0.119** (0.092-0.155)	**0.158** (0.120-0.215)	**0.194** (0.143-0.271)	**0.233** (0.165-0.329)	**0.271** (0.186-0.391)	**0.321** (0.213-0.480)	**0.358** (0.232-0.552)
7-day	**0.034** (0.026-0.043)	**0.045** (0.034-0.054)	**0.060** (0.047-0.075)	**0.074** (0.058-0.096)	**0.097** (0.074-0.131)	**0.117** (0.087-0.163)	**0.139** (0.099-0.196)	**0.161** (0.111-0.232)	**0.190** (0.126-0.283)	**0.212** (0.138-0.325)
10-day	**0.026** (0.021-0.034)	**0.034** (0.026-0.042)	**0.045** (0.035-0.057)	**0.056** (0.043-0.072)	**0.072** (0.054-0.096)	**0.086** (0.063-0.118)	**0.101** (0.072-0.142)	**0.116** (0.080-0.167)	**0.136** (0.091-0.203)	**0.152** (0.099-0.232)
20-day	**0.017** (0.014-0.022)	**0.022** (0.017-0.027)	**0.028** (0.022-0.035)	**0.033** (0.026-0.042)	**0.041** (0.031-0.055)	**0.048** (0.036-0.066)	**0.055** (0.040-0.078)	**0.063** (0.044-0.090)	**0.073** (0.049-0.108)	**0.080** (0.052-0.122)
30-day	**0.014** (0.011-0.018)	**0.017** (0.013-0.021)	**0.021** (0.017-0.027)	**0.025** (0.020-0.032)	**0.031** (0.023-0.040)	**0.035** (0.026-0.048)	**0.040** (0.028-0.055)	**0.044** (0.031-0.064)	**0.051** (0.034-0.075)	**0.055** (0.036-0.084)
45-day	**0.012** (0.009-0.015)	**0.014** (0.011-0.017)	**0.017** (0.014-0.021)	**0.020** (0.015-0.025)	**0.024** (0.018-0.031)	**0.027** (0.020-0.036)	**0.029** (0.021-0.041)	**0.032** (0.023-0.046)	**0.036** (0.024-0.054)	**0.039** (0.026-0.060)
60-day	**0.010** (0.008-0.013)	**0.012** (0.010-0.015)	**0.015** (0.012-0.019)	**0.017** (0.013-0.022)	**0.020** (0.015-0.026)	**0.022** (0.016-0.030)	**0.024** (0.017-0.034)	**0.026** (0.018-0.037)	**0.029** (0.020-0.043)	**0.031** (0.020-0.047)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

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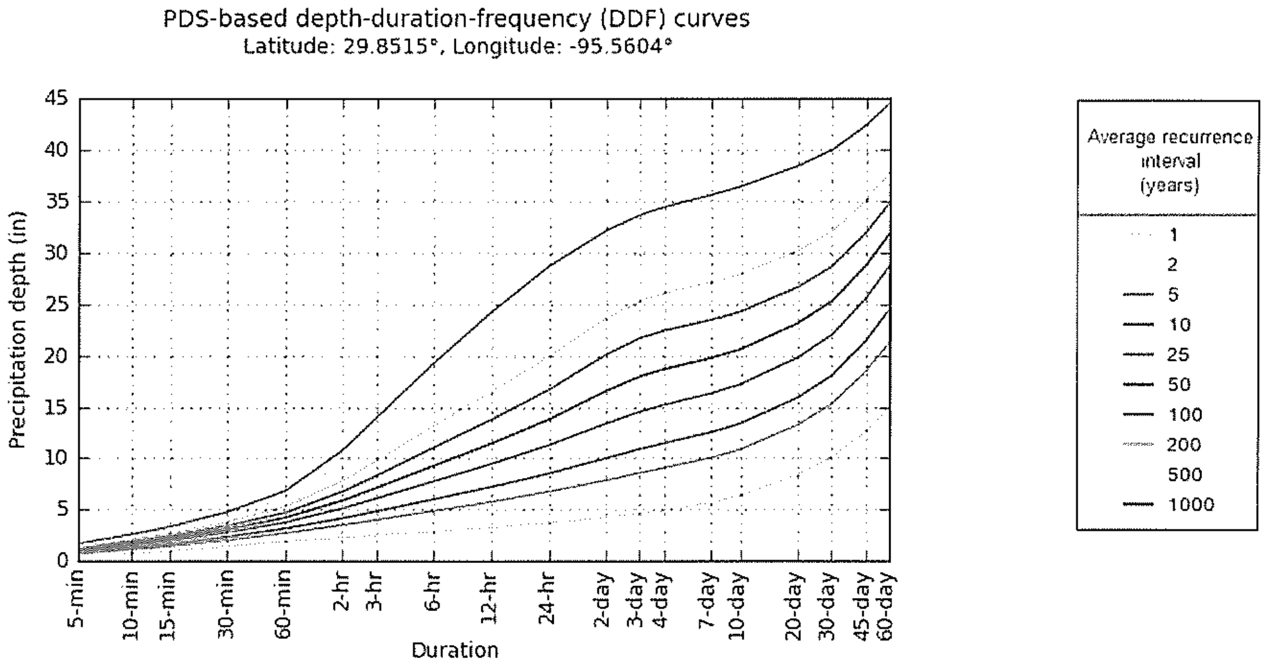
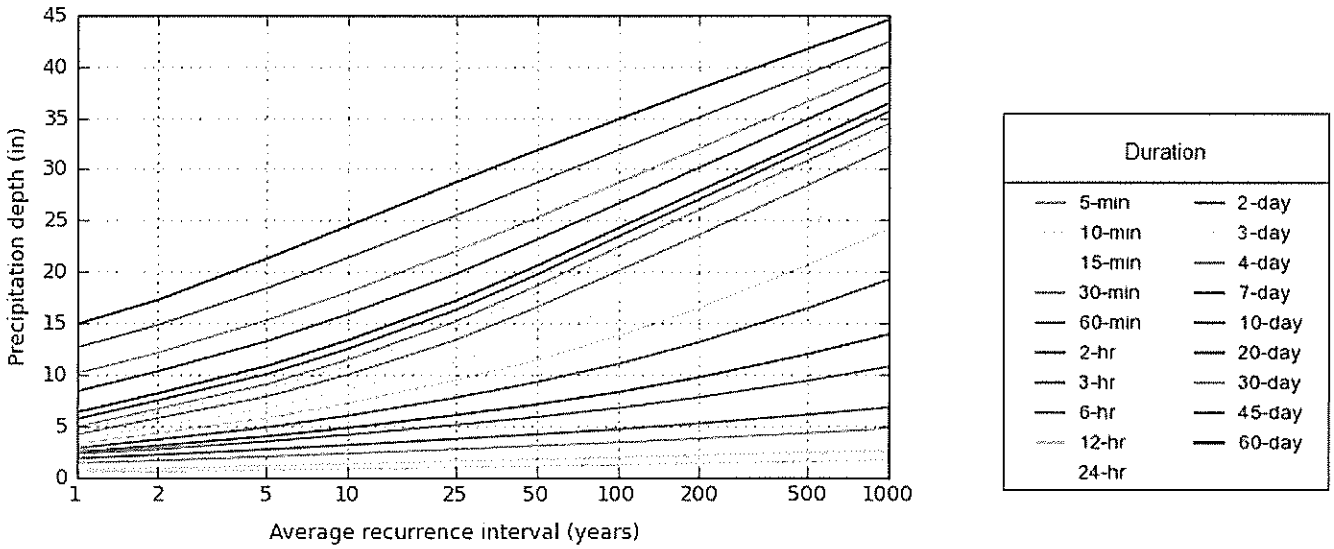
PF graphical





NOAA Atlas 14, Volume 11, Version 2 Created (GMT): Fri Mar 27 14:26:14 2020

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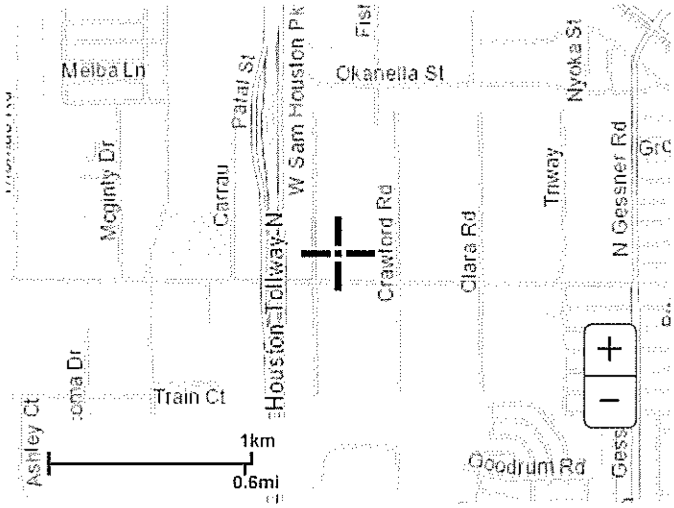
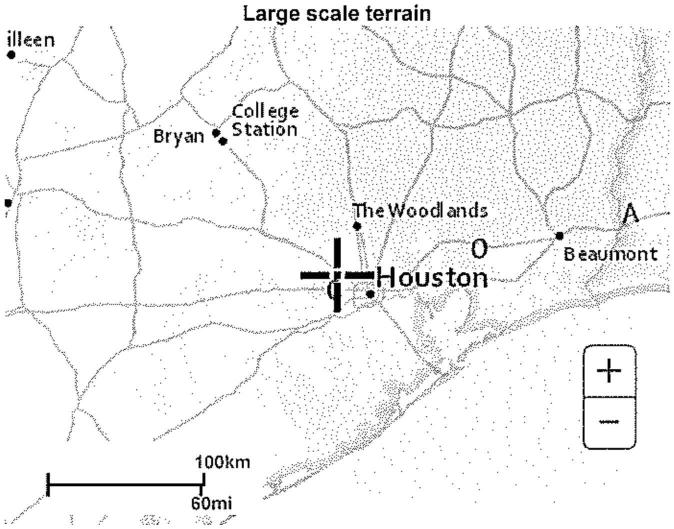
Maps & aerials

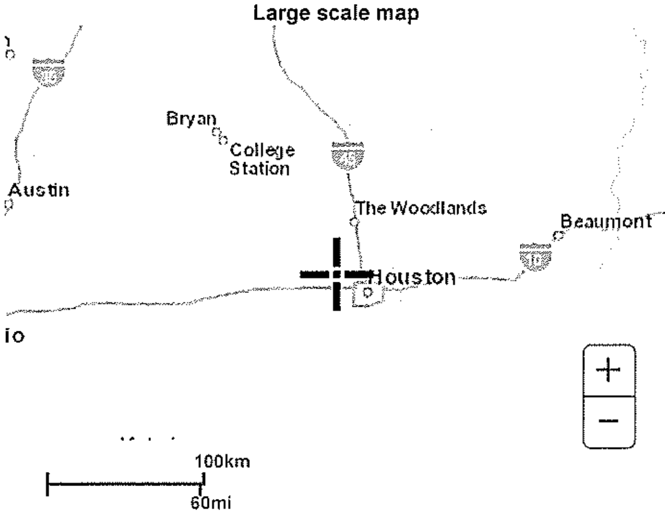
Small scale terrain



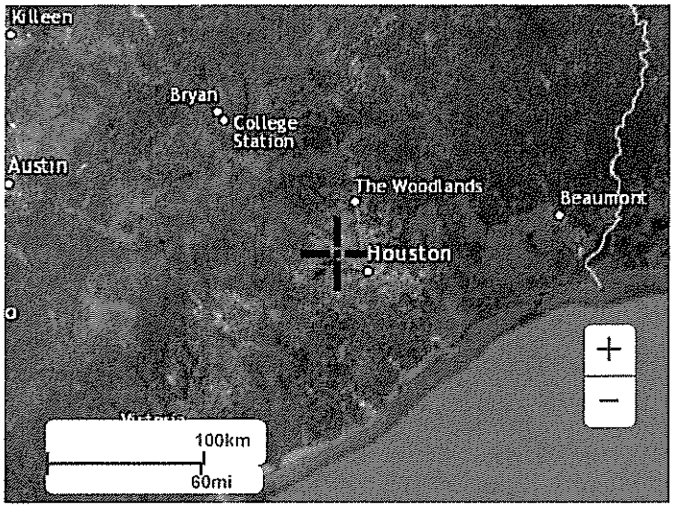
Large scale terrain



Large scale map



Large scale aerial



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National Oceanic and Atmospheric Administration
National Weather Service
National Water Center
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Questions?: HDSC.Questions@noaa.gov

Hydraulic Design Manual

Texas Department of Transportation

Revised September 2019

Manual Notice 2019-1

From: Camille Thomason, P.E.

Manual: *Hydraulic Design Manual*

Effective Date: September 12, 2019

Purpose

To implement new research and best practices.

Contents

The following updates were made to the *Hydraulic Design Manual*:

Chapter 4 – Hydrology

- Section 2 – Added brief discussion on significant digits.
- Section 9 – Updated Statistical Analysis of Stream Gage Data with new release of USGS Bulletin 17C.
- Section 10 – Updated mean annual precipitation map for use in Regression equations.
- Section 11 – Minor edits to time of concentration (Tc) guidance.
- Section 12 &13 – Updated to NOAA Atlas 14 rainfall data.
- Section 13 – Update on Rainfall Temporal Distribution based on NRCS guidance.
- Section 13 – Added additional Peak Rate Factor (PRF) guidance.

Chapter 15 – Coastal Hydraulic Design

- Added a new chapter providing guidance for designing or evaluating coastal hydraulic transportation infrastructure projects.

Supersedes

The revised manual supersedes prior versions of the *Hydraulic Design Manual.*

Contact

Please direct any questions about this manual to Ab Maamar-Tayeb, P.E., CFM at (512) 416-2328 or Abderrahmane.MaamarTayeb@txdot.gov.

Procedure for using the Rational Method

The rational formula estimates the peak rate of runoff at a specific location in a watershed as a function of the drainage area, runoff coefficient, and mean rainfall intensity for a duration equal to the time of concentration. The rational formula is:

$$Q = \frac{CIA}{Z}$$

Equation 4-20.

Where:

Q = maximum rate of runoff (cfs or m^3/sec.)

C = runoff coefficient

I = average rainfall intensity (in./hr. or mm/hr.)

A = drainage area (ac or ha)

Z = conversion factor, 1 for English, 360 for metric

Rainfall Intensity

The rainfall intensity (I) is the average rainfall rate in in./hr. for a specific rainfall duration and a selected frequency. The duration is assumed to be equal to the time of concentration. For drainage areas in Texas, you may compute the rainfall intensity using Equation 4-21, which is known as a rainfall intensity-duration-frequency (IDF) relationship (power-law model).

$$I = \frac{b}{(t_c + d)^e}$$

Equation 4-21.

Where:

I = design rainfall intensity (in./hr.)

t_c = time of concentration (min) as discussed in Section 11

e, b, d = coefficients based on rainfall IDF data.

In September 2018, the National Oceanic and Atmospheric Administration (NOAA) released updated precipitation frequency estimates for Texas. These estimates are available through NOAA's Precipitation Frequency Data Server (PFDS) website and the report documenting the approach is also available at the same website - NOAA Atlas 14, Volume 11: Precipitation-Frequency Atlas of the United States. This new rainfall data is considered best available data and should be used for all projects. Tabular IDF data are available from the PFDS, but linear interpolation or curve generation is needed to obtain intensity values between tabular durations. Ongoing TxDOT research will produce future e, b, d coefficients to better automate intensity calculations. However, barring significant project implementation concerns, Atlas 14 IDF data should be used. Exceptions must be approved by the DHE or DES HYD and noted on the plans or drainage report.

Currently, the coefficients in Equation 4-21 can be found in the EBDLKUP-2015v2.1.xlsx spreadsheet lookup tool (developed by Cleveland et al. 2015) for specific frequencies listed by county (See video/tutorial on the use of the EBDLKUP-2015v2.1.xlsx spreadsheet tool). This spreadsheet is based on prior rainfall frequency-duration data contained in the Atlas of Depth-Duration Frequency (DDF) of Precipitation of Annual Maxima for Texas (TxDOT 5-1301-01-1).

If a project is approved to use the older values from the EBDLKUP-2015v2.1.xlsx spreadsheet lookup tool or from existing functionality in design software like GEOPAK, they should still evaluate the new NOAA rainfall changes for their project area and, if there are increases for the design frequency, estimate an appropriate level of freeboard for use. The freeboard amount and a description of how it was generated should be noted in both the plans and the drainage report. Software that facilitates Rational Method calculations often has IDF curves from rainfall data embedded into the software. Location-specific IDF from the new NOAA rainfall data can be imported for each project into the software.

TxDOT is currently working with Texas Transportation Institute (TTI) staff, as part of research project 0-6980, to update the IDF curve relationships for the state of Texas based on the 2018 NOAA rainfall data. This work will include an update of the EBDLKUP-2015v2.1.xlsx file linked above and planned for inclusion in the next HDM update.

The general shape of a rainfall IDF curve is shown in Figure 4-9. As rainfall duration approaches zero, the rainfall intensity tends towards infinity. Because the rainfall intensity/duration relationship is assessed by assuming that the duration is equal to the time of concentration, small areas with exceedingly short times of concentration could result in design rainfall intensities that are unrealistically high. To minimize this likelihood, use a minimum time of concentration of 10 minutes. As the duration tends to infinity, the design rainfall tends towards zero. Usually, the area limitation of 200 acres for Rational Method calculations should result in rainfall intensities that are not unrealistically low. However, if the estimated time of concentration is

Table 4-10: Runoff Coefficients for Urban Watersheds

Type of drainage area	Runoff coefficient
Business:	
Downtown areas	0.70-0.95
Neighborhood areas	0.30-0.70
Residential:	
Single-family areas	0.30-0.50
Multi-units, detached	0.40-0.60
Multi-units, attached	0.60-0.75
Suburban	0.35-0.40
Apartment dwelling areas	0.30-0.70
Industrial:	
Light areas	0.30-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.30-0.40
Railroad yards	0.30-0.40
Unimproved areas:	
Sand or sandy loam soil, 0-3%	0.15-0.20
Sand or sandy loam soil, 3-5%	0.20-0.25
Black or loessial soil, 0-3%	0.18-0.25
Black or loessial soil, 3-5%	0.25-0.30
Black or loessial soil, > 5%	0.70-0.80
Deep sand area	0.05-0.15
Steep grassed slopes	0.70
Lawns:	
Sandy soil, flat 2%	0.05-0.10
Sandy soil, average 2-7%	0.10-0.15
Sandy soil, steep 7%	0.15-0.20
Heavy soil, flat 2%	0.13-0.17
Heavy soil, average 2-7%	0.18-0.22

Table 4-10: Runoff Coefficients for Urban Watersheds

Type of drainage area	Runoff coefficient
Heavy soil, steep 7%	0.25-0.35
Streets:	
Asphaltic	0.85-0.95
Concrete	0.90-0.95
Brick	0.70-0.85
Drives and walks	0.75-0.95
Roofs	0.75-0.95

Rural and Mixed-Use Watershed

Table 4-11 shows an alternate, systematic approach for developing the runoff coefficient. This table applies to rural watersheds only, addressing the watershed as a series of aspects. For each of four aspects, the designer makes a systematic assignment of a runoff coefficient "component." Using Equation 4-22, the four assigned components are added to form an overall runoff coefficient for the specific watershed segment.

The runoff coefficient for rural watersheds is given by:

$$C = C_r + C_i + C_v + C_s$$

Equation 4-22.

Where:

C = runoff coefficient for rural watershed

C_r = component of coefficient accounting for watershed relief

C_i = component of coefficient accounting for soil infiltration

C_v = component of coefficient accounting for vegetal cover

C_s = component of coefficient accounting for surface type

The designer selects the most appropriate values for C_r, C_i, C_v, and C_s from Table 4-11.

CITY OF HOUSTON
HOUSTON PUBLIC WORKS

INFRASTRUCTURE DESIGN MANUAL

CAROL ELLINGER HADDOCK, P.E.,
DIRECTOR

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CITY ENGINEER

JULY 2019

HOUSTON PUBLIC WORKS

CITY OF HOUSTON
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July 1, 2019

The 2019 edition of the City of Houston Infrastructure Design Manual will be effective July 1, 2019. The manual has been updated and revised to reflect changes to the City of Houston's (City) graphic requirements, storm water design requirements, and the storm water quality design requirements.

Please keep in mind that the purpose of this manual is to establish the basic criteria from which engineers can design infrastructure in a manner acceptable to the Department and is not intended to address all design conditions or specialized situations.

For Houston Public Works capital improvement projects managed by the Capital Projects service line, Phase II final designs that have not been submitted for a required review prior to July 1, 2019, will be required to comply with all standards in the 2019 Infrastructure Design Manual. The only exception will be the new graphic requirements outlined in Chapter 3. See the attached Executive Summary for additional information.

Projects in the public/private sector that submit plans for initial review after July 1, 2019 will be required to comply with all standards in the 2019 Infrastructure Design Manual.

For more detailed information concerning the updates to the Infrastructure Design Manual, standard drawings and the City's Construction Specifications see the attached Executive Summary.

Respectfully,

Carol Haddock

Carol Ellinger Haddock, P.E.
Director, Houston Public Works

Joseph T. Myers

Joseph T. Myers, P.E., CFM
City Engineer

Attachment: Executive Summary

cc: Eric Dargan, Chief Operating Officer
Jeffrey S. Weatherford, P.E., PTOE, Deputy Director
Christon K. Butler, MCD, Deputy Director
Brian P. Alcott, P.E., CCM, Managing Engineer

9.2.01(B)(3)(a)(1) continued

Land Use Type	Runoff Coefficient (C)
Residential Districts	
Lots more than 1/2 acre	0.35
Lots 1/4 - 1/2 acre	0.45
Lots less than 1/4 acre	0.55
Townhomes	0.60
Multi-Family areas	
Less than 20 Service Units/Acre	0.65
20 Service Units/Acre or Greater	0.80
Business Districts	0.80
Industrial Districts	
Light Areas	0.65
Heavy Areas	0.75
Railroad Yard Areas	0.30
Parks/Open Areas	0.18
Pavement/ROW	0.90

(2) Alternatively, the runoff coefficient C in the Rational Method formula can be calculated from the equation:

$$C = 0.6Ia + 0.2$$

Where: C = watershed coefficient
Ia = impervious area/total area

(3) If the alternate form is to be submitted, the calculation of C shall be provided as part of the drainage calculations.

b. Determination of Time of Concentration.
Time of concentration can be calculated from the following formula:

$$TC = 10A^{0.1761}+15$$

Where: TC = time of concentration (minutes)
A = subarea (acres)

c. Sample Calculation Forms.

(1) Figure 9.2, City of Houston Storm Sewer Calculation Form, is a sample calculation form for storm sewer systems.

(2) Figure 9.3, City of Houston Roadside Ditch Worksheet, is a sample calculation form for roadside ditch systems.

4. Hydrograph Development.

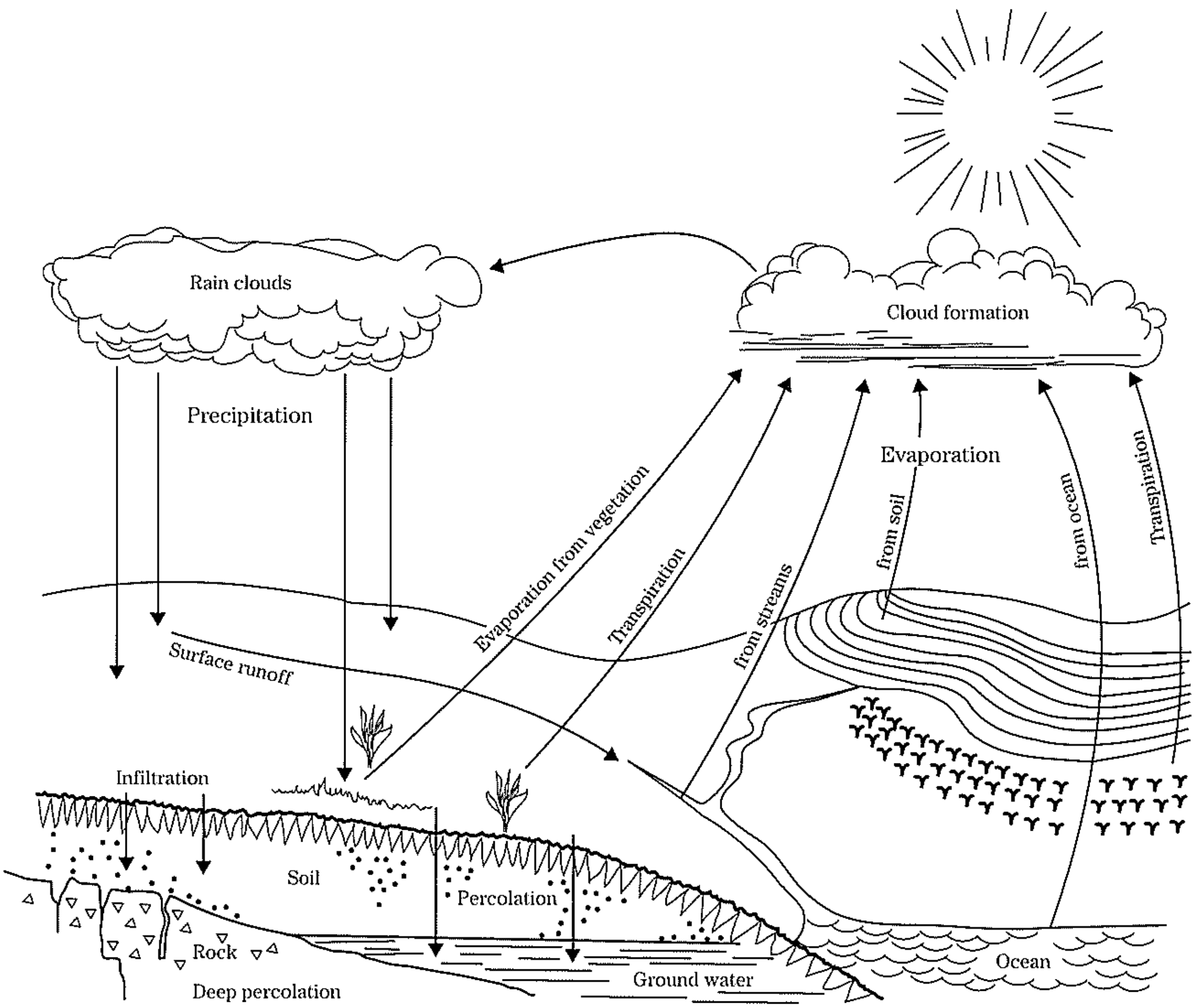
Where necessary to calculate runoff hydrographs, the peak flow of the hydrograph should match the Rational Method peak flow as calculated above. The hydrograph should be calculated using the entire drainage area, the FIS rainfall distribution, Green & Ampt loss rates, and the Clark Unit Hydrograph (T_C&R) methodology.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 630 Hydrology
National Engineering Handbook

Chapter 15 Time of Concentration



where:

V = average velocity, ft/s

r = hydraulic radius, ft

$= \frac{a}{P_w}$

a = cross-sectional flow area, ft^2

P_w = wetted perimeter, ft

s = slope of the hydraulic grade line (channel slope), ft/ft

n = Manning's n value for open channel flow

Manning's n values for open channel flow can be obtained from standard hydraulics textbooks, such as Chow (1959), and Linsley, Kohler, and Paulhus (1982). Publications dealing specifically with Manning's n values are Barnes (1967); Arcement and Schneider (1989); Phillips and Ingersoll (1998); and Cowen (1956). For guidance on calculating Manning's n values, see NEH630.14, Stage Discharge Relations.

Applications and limitations—The velocity method of computing time of concentration is hydraulically sound and provides the opportunity to incorporate changes in individual flow segments if needed. The velocity method is the best method for calculating time of concentration for an urbanizing watershed or if hydraulic changes to the watercourse are being considered.

Often, the average velocity and valley length of a reach are used to compute travel time through the reach using equation 15–1. If the stream is quite sinuous, the channel length and valley length may be significantly different and it is up to the modeler to determine which is the appropriate length to use for the depth of flow of the event under consideration.

The role of channel and valley storage is important in the development and translation of a flood wave and the estimation of lag. Both the hydraulics and storage may change from storm to storm and the velocity distribution may vary considerably both horizontally and vertically. As a result, actual lag for a watershed may have a large variation. In practice, calculations are typically based on the 2-year frequency discharge event since it is normally assumed that the time of concentration computed using these characteristics is representative of travel time conditions for a wide range of storm events. Welle and Woodward's simplification of Manning's kinematic equation was developed assuming the 2-year, 24-hour precipitation value.

630.1503 Other considerations

(a) Field observations

At the time field surveys to obtain channel data are made, there is a need to observe the channel system and note items that may affect channel efficiency. Observations such as the type of soil materials in the banks and bottoms of the channel; an estimate of Manning's roughness coefficients; the apparent stability or lack of stability of channel; indications of debris flows as evidenced by deposition of coarse sediments adjacent to channels, size of deposited materials, etc., may be significant.

(b) Multiple subarea watersheds

For multiple subarea watersheds, the time of concentration must be computed for each subarea individually, and consideration must be given to the travel time through downstream subareas from upstream subareas. Travel time and attenuation of hydrographs in valley reaches and reservoirs are accounted for using channel and reservoir routing procedures addressed in NEH630.17.

(c) Surface flow

Both of the standard methods for estimating time of concentration, as well as most other methods, assume that flow reaching the channel as surface flow or quick return flow adds directly to the peak of the subarea hydrograph. Locally derived procedures might be developed from data where a major portion of the contributing flow is other than surface flow. This is normally determined by making a site visit to the watershed.

(d) Travel time through bodies of water

The potential for detention is the factor that most strongly influences travel time through a body of water. It is best to divide the watershed such that any potential storage area is modeled as storage.

In many cases, the travel time for a water droplet through a body of water is assumed to be nearly instantaneous. An assumption is made that at the instant the droplet arrives at the upstream end of the lake, reservoir, or wetland the water level is raised a small amount and this same amount of water leaves the water body via the outlet. In such cases, time of concentration is computed using standard methods to the upstream end of the water body, and travel time through the water body is ignored.

In other cases, such as with a watershed having a relatively large body of water in the flow path, time of concentration is computed to the upstream end of the water body using standard methods, and velocity for the flow segment through the water body may be computed using the wave velocity equation coupled with equation 15–1 to convert the velocity to a travel time through the water body. The wave equation is:

$$V_w = \sqrt{gD_m} \qquad \text{(eq. 15–11)}$$

where
V_w = wave velocity, ft/s
g = 32.2 ft/s^2
D_m = mean depth of lake or reservoir, ft

Generally, V_w will be high; however, equation 15–11 only provides for estimating travel time through the water body and for the inflow hydrograph to reach the outlet. It does not account for the time required for the passage of the inflow hydrograph through reservoir storage and spillway outflow. The time required for the passage of the inflow hydrograph through the reservoir storage and spillway outflow can be determined using storage routing procedures described in NEH630.17.

Equation 15–11 can be used for wetlands with much open water, but where the vegetation or debris is relatively thick (less than about 25 percent open water), Manning's equation may be more appropriate.

(e) Variation in lag and time of concentration

Rao and Delleur (1974) concluded that lag time, and hence time of concentration, is not a unique watershed characteristic and varies from storm to storm. Reasons for the variation in lag time may include amount, duration and intensity of rainfall; vegetative growth stage and available temporary storage. However, without further examination and study of these characteristics, no obvious trend may be readily observed to explain the variation. Table 15–4 illustrates that lag is not a constant for a single watershed, but does vary from storm to storm. The lag times in table 15–4 were developed by Thomas, Monde, and Davis (2000) for three watersheds in Maryland using USGS stream gage data.

Table 15–4 Variation in lag time for selected events for selected streams on three watersheds in Maryland

Stream	USGS number	Area (mi^2)	Date	Storm duration (min)	Precipitation (in)	Lag (h)
Brien Run	1585400	1.97	8/21/1986	30	1.85	2.35
			8/22/1986	45	0.32	1.94
			9/8/1987	120	1.03	2.44
Jones Falls	1589440	26.2	8/10/1984	15	1.84	4.16
			2/12/1985	285	1.59	6.91
			12/24/1986	165	2.47	5.20
Deer Creek	1580000	94.4	9/8/1987	75	2.2	5.06
			9/18/1987	15	1.02	7.15
			5/6/1989	60	5.00	9.67

POLICY, CRITERIA, AND PROCEDURE MANUAL FOR APPROVAL AND ACCEPTANCE OF INFRASTRUCTURE

HARRIS COUNTY FLOOD CONTROL DISTRICT

Submitted by: Russell A. Poppe, P.E.
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Adopted by Harris County Commissioners Court

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Jack Cagle
Commissioner, Precinct 4

Adopted October 2004
Updated October 2018

3.7 Optional Project Routing Technique

Introduction 3.7.1

The Optional Project Routing Technique can be used for calculating detention volume and sizing the outflow structure for moderate project drainage areas (50 to 640 acres, see Section 6.9.2, Methods) as well as verifying the effects of the proposed development and detention basin downstream on the receiving channel. It also provides a limited degree of correlation with current watershed models.

If a model other than HEC-HMS is used, another model is used in conjunction with HEC-HMS, or a unit hydrograph method other than Clark's Unit Hydrograph is used, contact the HCFCD for verification of the model and technical approach to be used.

See A.2, Optional Project Routing Technique Example in Appendix A.

Applications 3.7.2

The Optional Project Routing Technique is used for analysis and design of detention basins for new land development or public agency projects:

- For drainage areas between 50 and 640 acres.
- To facilitate analysis and design using common computer programs and techniques.

Limitations 3.7.3

- Do not use this technique
  - To compare hydrograph timing with existing HCFCD HEC-HMS or HEC-RAS watershed models.
  - To define or modify effective FEMA regulatory flood plains or floodways.
- When comparing pre- and post- project peak flows, compare at the detention basin outfall in the outfall channel and at least three nodes downstream on the main stem.

Clark's Unit Hydrograph 3.7.4

If Clark's Unit Hydrograph approach is used in the HEC-HMS model, do not use the HCFCD hydrologic methodology to calculate TC and R. Instead,

- Estimate TC using a velocity based method, and
- Adjust R such that the peak discharge matches the Site Runoff Curve peak value and the runoff volume approximates the value in the effective model or the value calculated using direct runoff depths in Section 3.6.6, Section 3.6.7, Section 3.6.8, and Section 3.6.9.

4.3 Manning's Equation, Continued

Manning's "n" Values 4.3.5

Manning's "n" value represents the relative roughness of the channel, conduit, or overbank area. Values to use for design purposes are in the table below. Submit justification when a different "n" value is used.

Description	Manning's "n" Value
Channel	
Grass-Lined	0.040[1]
Riprap-Lined	0.040[1]
Articulated Concrete Block - Grassed	0.040[1]
Articulated Concrete Block - Bare	0.030
Concrete-Lined	0.015
Natural or Overgrown Channels	Usually 0.050 – 0.080
Overbanks	
Some flow	Usually 0.080 – 0.150
Ineffective flow areas	0.99[2]
Conduit[3]	
Concrete Pipe	0.013
Concrete Box	0.013
Corrugated Metal Pipe	0.024

[1] For design flows larger than 10,000 cfs, an "n" value of 0.035 may be used.

[2] Use the ineffective flow area option in HEC-RAS

[3] If the conduit is maintained by another jurisdiction, the "n" value specified by that jurisdiction can be used.

Adjustment to "n" for Trees in the Channel 4.3.6

Where trees are planted in a channel, adjust the "n" value to account for the additional head loss.

Contact the HCFCD for guidelines regarding "n" value adjustments to account for trees in the channel.

USDA

United States Department of Agriculture

Natural Resources Conservation Service

Conservation Engineering Division

Technical Release 55

June 1986

Urban Hydrology for Small Watersheds

TR-55

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click the bookmarks tab. It will navigate you to the contents,

chapters, rainfall maps, and printable forms.

Chapter 2 Estimating Runoff

SCS runoff curve number method

The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985). The SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \text{[eq. 2-1]}$$

where

Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in) and
I_a = initial abstraction (in)

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation:

$$I_a = 0.2S \qquad \text{[eq. 2-2]}$$

By removing I_a as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting equation 2-2 into equation 2-1 gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{[eq. 2-3]}$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \qquad \text{[eq. 2-4]}$$

Figure 2-1 and table 2-1 solve equations 2-3 and 2-4 for a range of CN's and rainfall.

Factors considered in determining runoff curve numbers

The major factors that determine CN are the hydrologic soil group (HSG), cover type, treatment, hydrologic condition, and antecedent runoff condition (ARC). Another factor considered is whether impervious areas outlet directly to the drainage system (connected) or whether the flow spreads over pervious areas before entering the drainage system (unconnected). Figure 2-2 is provided to aid in selecting the appropriate figure or table for determining curve numbers.

CN's in table 2-2 (*a* to *d*) represent average antecedent runoff condition for urban, cultivated agricultural, other agricultural, and arid and semiarid rangeland uses. Table 2-2 assumes impervious areas are directly connected. The following sections explain how to determine CN's and how to modify them for urban conditions.

Hydrologic soil groups

Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four HSG's (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting. Appendix A defines the four groups and provides a list of most of the soils in the United States and their group classification. The soils in the area of interest may be identified from a soil survey report, which can be obtained from local SCS offices or soil and water conservation district offices.

Most urban areas are only partially covered by impervious surfaces: the soil remains an important factor in runoff estimates. Urbanization has a greater effect on runoff in watersheds with soils having high infiltration rates (sands and gravels) than in watersheds predominantly of silts and clays, which generally have low infiltration rates.

Any disturbance of a soil profile can significantly change its infiltration characteristics. With urbanization, native soil profiles may be mixed or removed or fill material from other areas may be introduced. Therefore, a method based on soil texture is given in appendix A for determining the HSG classification for disturbed soils.

Table 2-2a Runoff curve numbers for urban areas [1]

Cover description: Cover type and hydrologic condition	Average percent impervious area [2]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

1 Average runoff condition, and $I_a = 0.2S$.
2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table 2-2b Runoff curve numbers for cultivated agricultural lands [1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

1 Average runoff condition, and I_a=0.2S
2 Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.
3 Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description: Cover type	Hydrologic condition	Curve numbers for hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.
2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.
3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.
4 Actual curve number is less than 30; use CN = 30 for runoff computations.
5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 2-2d Runoff curve numbers for arid and semiarid rangelands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition [2]	A [3]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

1 Average runoff condition, and I_a, = 0.2S. For range in humid regions, use table 2-2c.
2 Poor: <30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.
3 Curve numbers for group A have been developed only for desert shrub.

Chapter 3 Time of Concentration and Travel Time

Travel time (T_t) is the time it takes water to travel from one location to another in a watershed. T_t is a component of time of concentration (T_c), which is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed. T_c is computed by summing all the travel times for consecutive components of the drainage conveyance system.

T_c influences the shape and peak of the runoff hydrograph. Urbanization usually decreases T_c, thereby increasing the peak discharge. But T_c can be increased as a result of (a) ponding behind small or inadequate drainage systems, including storm drain inlets and road culverts, or (b) reduction of land slope through grading.

Factors affecting time of concentration and travel time

Surface roughness

One of the most significant effects of urban development on flow velocity is less retardance to flow. That is, undeveloped areas with very slow and shallow overland flow through vegetation become modified by urban development: the flow is then delivered to streets, gutters, and storm sewers that transport runoff downstream more rapidly. Travel time through the watershed is generally decreased.

Channel shape and flow patterns

In small non-urban watersheds, much of the travel time results from overland flow in upstream areas. Typically, urbanization reduces overland flow lengths by conveying storm runoff into a channel as soon as possible. Since channel designs have efficient hydraulic characteristics, runoff flow velocity increases and travel time decreases.

Slope

Slopes may be increased or decreased by urbanization, depending on the extent of site grading or the extent to which storm sewers and street ditches are used in the design of the water management system. Slope will tend to increase when channels are straightened and decrease when overland flow is directed through storm sewers, street gutters, and diversions.

Computation of travel time and time of concentration

Water moves through a watershed as sheet flow, shallow concentrated flow, open channel flow, or some combination of these. The type that occurs is a function of the conveyance system and is best determined by field inspection.

Travel time (T_t) is the ratio of flow length to flow velocity:

$$T_t = \frac{L}{3600V} \qquad \text{[eq. 3-1]}$$

where:

T_t = travel time (hr)
L = flow length (ft)
V = average velocity (ft/s)
3600 = conversion factor from seconds to hours.

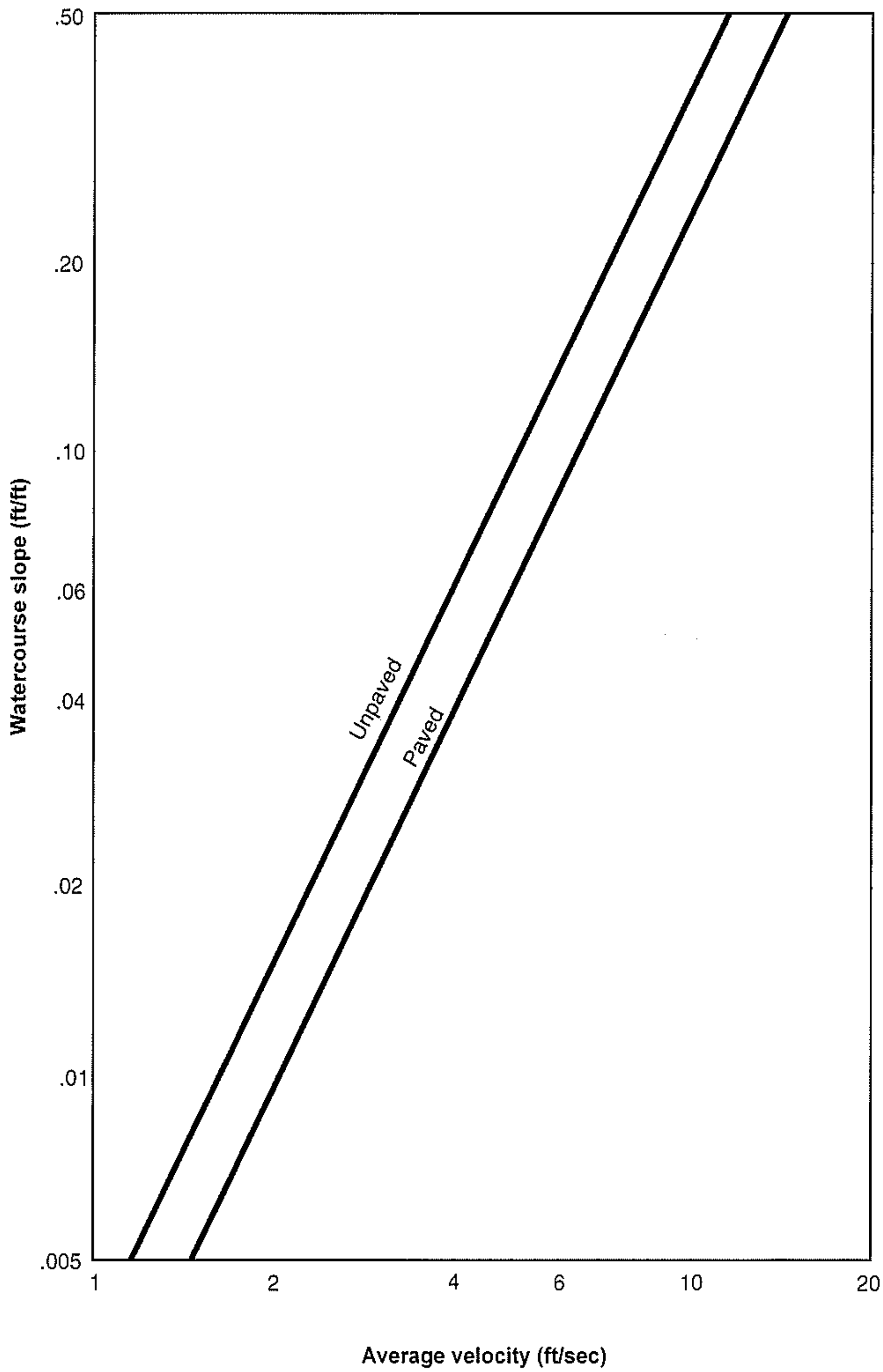
Time of concentration (T_c) is the sum of T_t values for the various consecutive flow segments:

$$T_c = T_{t_1} + T_{t_2} + \ldots T_{t_m} \qquad \text{[eq. 3-2]}$$

where:

T_c = time of concentration (hr)
m = number of flow segments

Figure 3-1 Average velocities for estimating travel time for shallow concentrated flow



Sheet flow

Sheet flow is flow over plane surfaces. It usually occurs in the headwater of streams. With sheet flow, the friction value (Manning's n) is an effective roughness coefficient that includes the effect of raindrop impact; drag over the plane surface; obstacles such as litter, crop ridges, and rocks; and erosion and transportation of sediment. These n values are for very shallow flow depths of about 0.1 foot or so. Table 3-1 gives Manning's n values for sheet flow for various surface conditions.

Table 3-1 Roughness coefficients (Manning's n) for sheet flow

Surface description	n [1]
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤20%	0.06
Residue cover >20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses [2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods:[3]	
Light underbrush	0.40
Dense underbrush	0.80

1 The n values are a composite of information compiled by Engman (1986).
2 Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.
3 When selecting n , consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

For sheet flow of less than 300 feet, use Manning's kinematic solution (Overtop and Meadows 1976) to compute T_t:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5}\, s^{0.4}} \qquad \text{[eq. 3-3]}$$

where:

T_t = travel time (hr),
n = Manning's roughness coefficient (table 3-1)
L = flow length (ft)
P_2 = 2-year, 24-hour rainfall (in)
s = slope of hydraulic grade line (land slope, ft/ft)

This simplified form of the Manning's kinematic solution is based on the following: (1) shallow steady uniform flow, (2) constant intensity of rainfall excess (that part of a rain available for runoff), (3) rainfall duration of 24 hours, and (4) minor effect of infiltration on travel time. Rainfall depth can be obtained from appendix B.

Shallow concentrated flow

After a maximum of 300 feet, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from figure 3-1, in which average velocity is a function of watercourse slope and type of channel. For slopes less than 0.005 ft/ft, use equations given in appendix F for figure 3-1. Tillage can affect the direction of shallow concentrated flow. Flow may not always be directly down the watershed slope if tillage runs across the slope.

After determining average velocity in figure 3-1, use equation 3-1 to estimate travel time for the shallow concentrated flow segment.

Open channels

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for bank-full elevation.

Appendix F — Equations for figures and exhibits

This appendix presents the equations used in procedure applications to generate figures and exhibits in TR-55.

Figure 2-1 (runoff equation):

$$Q = \frac{\left[P - .2\left(\frac{1000}{CN} - 10\right)\right]^2}{P + 0.8\left(\frac{1000}{CN} - 10\right)}$$

where
Q = runoff (in)
P = rainfall (in)
CN = runoff curve number

Figure 2-3 (composite CN with connected impervious area):

$$CN_c = CN_p + \left(\frac{P_{imp}}{100}\right)(98 - CN_p)$$

where
CN_c = composite runoff curve number
CN_p = pervious runoff curve number
P_{imp} = percent imperviousness.

Figure 2-4 (composite CN with unconnected impervious areas and total impervious area less than 30%):

$$CN_c = CN_p + \left(\frac{P_{imp}}{100}\right)(98 - CN_p)(1 - 0.5R)$$

where
R = ratio of unconnected impervious area to total impervious area.

Figure 3-1 (average velocities for estimating travel time for shallow concentrated flow):
Unpaved $V = 16.1345\,(s)^{0.5}$
Paved $V = 20.3282\,(s)^{0.5}$

where

V= average velocity (ft/s)
s = slope of hydraulic grade line (watercourse slope, ft/ft)

These two equations are based on the solution of Manning's equation (eq. 3-4) with different assumptions for n (Manning's roughness coefficient) and r (hydraulic radius, ft). For unpaved areas, n is 0.05 and r is 0.4; for paved areas, n is 0.025 and r is 0.2.

Exhibit 4 (unit peak discharges for SCS tvpe I, IA, II, and III distributions):

$$\log(q_u) = C_o + C_1 \log(T_c) + C_2\left[\log(T_c)\right]^2$$

where
q_u = unit peak discharge (csm/in)
T_c = time of concentration (hr) (minimum, 0.1; maximum, 10.0)
C_0, C_1, C_2 = coefficients from table F-1

Figure 6-1 (approximate detention basin routing through single- and multiple-stage structures for 24-hour rainfalls of the indicated type):

$$\frac{V_S}{V_r} = C_o + C_1\left(\frac{q_o}{q_i}\right) + C_2\left(\frac{q_o}{q_i}\right)^2 + C_3\left(\frac{q_o}{q_i}\right)^3$$

where
V_s/V_r = ratio of storage volume (V_s) to runoff volume (V_r)
q_o/q_i = ratio of peak outflow discharge (q_o) to peak inflow discharge (q_i)
C_0, C_1, C_2, C_3 = coefficients from table F-2