US Army Corps
of Engineers
Hydrologic Engineering Center

Investigation of Soil Conservation Service Urban Hydrology Techniques

May 1980

TP-77

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
May 1980

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Investigation of Soil Conservation Service Urban Hydrology Techniques

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Duke G. Altman, William H. Espey, Jr., Arlen D. Feldman

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
TP-77

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Presented at the American Geophysical Union U.S. – Canada Hydrology Symposium, Toronto, Canada, May 1980.

14. ABSTRACT

The application of the Soil Conservation Services (SCS) urban Hydrology techniques is made to four watersheds. The parameters of the methods are obtained from standard SCS guidance and from calibration of watershed model HEC-1 using the SCS method. A modified method of determining these parameters is also recommended to SCS runoff parameters are then used with design storms to illustrate the differences in frequency curves which may result.

15. SUBJECT TERMS
urban hydrology, curve numbers, flood frequency, design storm, calibration

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER**
U	U	U	UU	22	

Investigation of Soil Conservation Service Urban Hydrology Techniques

May 1980

US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

TP-77

Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution with the Corps of Engineers.

INVESTIGATION OF SOIL CONSERVATION SERVICE URBAN HYDROLOGY TECHNIQUES[a*]

By Duke G. Altman[1], William H. Espey, Jr.,[2] and Arlen D. Feldman[3]

INTRODUCTION

Today's engineer/hydrologist is often required to estimate flood discharges for various recurrence intervals in urban areas having little or no local rainfall and/or runoff data. Since rainfall frequency information is available for most of the country (e.g., National Weather Service-Technical Paper 40, 1961), methods that transform rainfall into runoff are often used to make these estimates. Some widely used methods can be grouped as: 1) rational method equations; 2) synthetic unit hydrograph methods; 3) regional flood frequency equations; and 4) kinematic wave methods. Quite often the synthetic unit hydrograph method is selected due to limitations of the other methods.

Two traditional synthetic unit hydrograph methods, the Snyder Method (Snyder, 1938) and the Clark Method (Clark, 1945), rely heavily on coefficients that are related to watershed physiography and/or runoff characteristics. These coefficients must be adequately determined to sufficiently define the time-varying flow ordinates of the unit hydrograph. To accurately define the effect of urbanization on these two coefficients, and ultimately the unit hydrograph shape, an analysis of regional or hydrologically similar urban watersheds is required; however, there is still a large number of areas where these studies have not been done due to a lack of need and/or data. Empirical unit hydrograph equations as reported in Espey et al., (1965), Espey et al., (1968), Hamm et al., (1973) and Espey, Altman and Graves (1977) offer other means of obtaining synthetic unit hydrographs based on the physiographic and urban characteristics of a watershed. These equations were developed from data on watersheds located throughout the United States.

The Soil Conservation Service (SCS) methods in urban hydrology are outlined in SCS-TR-55 (SCS, 1975) and have been developed in a generalized fashion to allow for relatively straight-forward determinations of storm runoff magnitudes, time-sequence and volume that appear applicable in many urban studies. For the more complex hydrologic investigations in urban areas, the National Engineering Handbook-Section 4 (SCS, 1971) and SCS-TR-20 (SCS, 1973) model can be utilized with SCS-TR-55 procedures to more precisely describe the runoff process.

---

[a] Original work funded by the U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, Calif. and included in the report "An Evaluation of the Effects of Urbanization on Flood Discharges" by Espey, Huston & Assoc., Inc. (1979).

[1] Sr. Staff Engr., Espey, Huston & Assoc., Inc. Austin, Tex.

[2] Pres., Espey, Huston & Assoc., Inc. Austin, Tex.

[3] Chief, Research Branch, HEC, U.S. Army Corps of Engineers, Davis, Calif.

[*] Paper presented at the American Geophysical Union U.S. - Canada Hydrology Symposium, Toronto, May 1980.

The SCS curve number method of determining rainfall loss rates is easy to use because it is based on soil and land use characteristics that are generally determinable from existing information. However, rainfall intensity is not considered in the method and only daily rainfall-runoff records from small agricultural watersheds were used in its development. The effect of urbanization on rainfall loss rates is dependent on the selection of appropriate curve numbers. Some problems may also be encountered in accurately determining an urban areas' curve number due to the compaction of soil by heavy equipment, inability to estimate variable vegetation conditions, introduction of fill material and mixing of surface and subsurface soils.

SCS relationships for hydrograph lag time in urban areas are based on limited data and analysis so additional study and evaluation is definitely needed. Use of a dimensionless unit hydrograph derived from numerous unit hydrographs for rural watersheds and then modified to reflect urban runoff relationships has a degree of uncertainty associated with it. However, familiarity with using the SCS method and the hydrologic processes involved will overcome much of this uncertainty.

In order for the professional community to gain confidence in the ability of SCS methods in predicting the effects of urbanization or flood discharges, these methods must be evaluated with data from a number of watersheds having a range of physiographic, urban and climatic conditions. The purpose of this study is to provide data and information to which additional evaluations can be added and allow for a better appreciation and understanding of the advantages and limitations of the SCS urban hydrologic techniques.

WATERSHEDS STUDIED

An urban and a matching undeveloped watershed were selected in each of two "regions" as study areas. The selected watersheds in each region have similar climatic and physiographic features. In this manner the hydrologic effects of urbanization are isolated to allow testing of the SCS procedures in evaluating such effects. The Waller and Wilbarger Creek watersheds were respectively chosen as the urban and undeveloped areas in the Austin, Texas region while the Turtle Creek and Spanky Branch watersheds respectively represent the urban and undeveloped areas in the Dallas, Texas region. Table 1 summarizes the physiographic and urban conditions of the four watersheds selected for analysis.

Since the Waller Creek watershed was undergoing urbanization during the period of record of rainfall and runoff gaging, it is studied for three distinctly different periods (degrees) of urbanization as shown in Table 1. The Turtle Creek watershed was fully urbanized prior to the regular analysis of storm event data by the U. S. Geological Survey (USGS) allowing only one urban condition to be studied.

CALCULATED VERSUS OPTIMIZED CURVE NUMBERS AND LAG TIMES

The first means of evaluating the SCS urban hydrologic techniques is accomplished by determining and comparing "calculated" versus "optimized" values of SCS runoff curve numbers (CNs) and hydrograph lag times (TLs) for the four watersheds.

TABLE 1

WATERSHED PHYSIOGRAPHIC FEATURES, LAG TIMES AND CURVE NUMBERS

Watershed (USGS Gage No)	Date(s)	A (sq mi)	CS (ft/ft)	WS (ft/ft)	L (ft)	Lca (ft)	I (%)	MHL (%)	TL (C) (hrs)	TL (A) (hrs)	TL (O) (hrs)	CN (C) (--)	CN (O) (--)
Austin, Texas Region:													
Waller Creek at 23rd Street (08157500)	1957-59	4.13(1)	0.009(1)	0.027(2)	27,600(3)	10,500(1)	24.5(1)	37(2)	1.74	--	--	84	92
	1962-65						31.3(1)	37(2)	1.62	--	0.60	84	79
	1964-75						40(2)	40(2)	1.50	0.90	0.36	84	81
Wilbarger Creek (08159150)	1964-75	4.61(1)	0.0074(1)	0.026(2)	20,000(2)	10,500(2)	--	--	1.98	1.74	1.50	83	85
Dallas, Texas Region:													
Turtle Creek (08056500)	1967-76	7.98(4)	0.0053(4)	0.019(2)	31,200(4)	14,700(2)	47(4)	15(5)	2.10	1.20	0.78	86	93
Spanky Branch (08057120)	1973-75	6.77(4)	0.0069(4)	0.026(2)	25,800(4)	12,500(2)	--	--	2.46	2.34	1.56	84	96

Abbreviations:

A = drainage area; CS = channel slope; WS = average watershed slope; L = main channel length; Lca = main channel length from mouth to opposite centroid of watershed; I = impervious cover; MHL = modified hydraulic length of main channel; TL (C) = watershed lag time calculated from Eq. 3-2 of SCS (1975); TL (A) = watershed lag time determined from an "alternate" method (see text); TL (O) = watershed lag time "optimized" from observed storm events utilizing HEC-1 (USCE, 1979); CN (C) = watershed curve number "calculated" from land use information, soil data, Table 2-2 of SCS (1975), and Table 9.1 of the SCS National Engineering Handbook; CN (O) = watershed curve number "optimized" from observed storm events utilizing HEC-1.

References:

(1) USGS records (Slade, 1979)
(2) Computed utilizing topographic maps, land use maps, aerial photographs, field surveys, etc.
(3) Espey (1965)
(4) Dempster (1974)
(5) Black (1979) pers. comm.

The general method used to calculate CNs for each of the four watersheds is outlined as follows:

1) Determine the areal portions covered by the different SCS hydrologic soil groups and land use/cover conditions utilizing detailed and/or general SCS soil maps, aerial photographs, land use maps and discussions with local SCS and city officials (see Tables 2 and 3). Calculate a CN representative of the entire watershed utilizing the procedures outlined in Sections 7, 8 and 9 of SCS (1971) and Table 2-2 of SCS (1975) (see Table 1).

Equation 3-2 of SCS (1975) was selected as one of two methods of calculating watershed lag times as the data was available to allow use of a consistent method in each watershed. This equation is provided below:

$$TL(C) = \frac{l^{0.8}(S+1)^{0.7}}{1,900\ Y^{0.5}}$$

where $TL(C)$ = calculated watershed lag time (hours)

l = hydraulic length of watershed (feet)

$S = \frac{1,000}{CN'} - 10$ (CN' is a retardance factor and is equivalent to the runoff curve number)

Y = average watershed slope (percent)

Values of TL(C) in Table 1 represent the "calculated" method utilizing this equation. Input data used in the equation are also presented in Table 1. The general method used to calculate respective watershed TLs is outlined below.

1) Evaluate Equation 3-2 of SCS (1975) utilizing the physiographic/urban conditions listed for each watershed in Table 1.

2) Adjusting the lag time for each urban watershed obtained in 1 (above) utilizing Figs. 3-4 and 3-5 of SCS (1975). Values for CN(C), percent of main channel modified (MHL), and percent of watershed impervious cover (I) used to evaluate the necessary lag time adjustment with Figs. 3-4 and 3-5 are found in Table 1.

The second method of calculating lag times was developed after a review of the results obtained from Equation 3-2 (SCS, 1975) appeared low for the urban watersheds when compared to results of other methods. Since the determination of calculated lag times directly affects other evaluations in the overall investigation of SCS techniques (such as subsequently provided in the peak discharge frequency curve analysis), an alternative method was also used. This alternative method is based on lag time relationships developed by Carter (1961), Eagleson (1962), Van Sickle (1962), Espey (1965), and Espey, Altman and Graves (1977). Each watershed was evaluated by techniques outlined in the listed references in addition to overland and channel travel time estimates and a representative lag time obtained from the results. The lag times developed from this alternative method are denoted as TL(A) values in Table 1.

TABLE 2

WATERSHED HYDROLOGIC SOIL GROUP AREAL COVERAGE

Watershed	SCS Hydrologic Soil Groups (% of Watershed)				
	A	B	C	D	Total
Austin, Texas Region					
Waller Creek	—	1	87	12	100
Wilbarger Creek	—	—	51	49	100
Dallas, Texas Region					
Turtle Creek	—	8	51	41	100
Spanky Branch	—	—	23	77	100

TABLE 3

WATERSHED LAND USE/COVER AREAL COVERAGE

Watershed	Land Use/Cover Classifications (% of Watershed)										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Austin, Texas Region											
Waller Creek											
1958	11.1	7.3	55.0	5.3	12.6	8.7					
1964	12.3	7.3	56.7	5.3	15.0	3.4					
1973	13.6	7.5	57.3	5.6	12.6	3.4					
Wilbarger Creek						50.3	25.6	7.3	15.5	1.3	
Dallas, Texas Region											
Turtle Creek	15.9	6.6	58.9	8.7	8.9	1.0					
Spanky Branch						33.1	55.1		10.6		1.2

NOTE: (1) = Commercial; (2) = Industrial; (3) = Single-family residential; (4) = Multi-family residential; (5) = Parks; (6) = Pasture/range/grassland; (7) = Row crops (straight row); (8) = Row crops (contoured); (9) = Row crops (contoured and terraced); (10) = Wooded; (11) = Roads

The HEC-1 computer program was used to optimize CN and TL values representative of each watershed and, in the case of the Waller Creek watershed, three different urban time periods. Storm rainfall and runoff data from USGS for several events were used in the optimization process for each watershed. The storms selected had relatively large peak discharges (in a single peak, if possible) and evenly distributed temporal and spatial rainfall throughout the watershed of a relatively constant intensity. Table 4 lists the dates of storms utilized along with other storm-specific information.

The methods used to obtain the optimized CN values representative of each watershed are given below.

1) The 5-day antecedent moisture conditions (AMC) previous to each storm was obtained from USGS daily rainfall files and is provided in Table 4.

2) An AMC-II CN was determined from Table 10.1 of SCS (1971) for each storm for which an optimization analysis was performed. These determinations are provided in Table 4.

3) The results from 2 (above) were then used to select a representative Condition II CN for each watershed and, in the case of Waller Creek, each time period. These Condition II CN values are denoted as CN(O)s in Table 1.

Due to difficulties such as finding storm events with spatial and temporal uniform rainfall over the watershed and the unsynchronized timing of observed hydrographs with their related hyetographs that can occur, it was determined that the results of the individual storm HEC-1 optimizations of lag times require a more selective review than the approach used in obtaining the optimized CN values. This process is generally described below and the results are presented in Tables 1 and 4.

1) The HEC-1 optimizations were reviewed closely to identify those storms having acceptable computed versus observed (recorded) runoff hydrographs. Hydrograph timing and peak discharge comparisons between the computed and observed hydrographs were considered to be the most important factors in measuring the suitability of each optimization.

2) An additional review was given the collective results of the several storm optimizations performed for a single watershed or a watershed urbanization time period in an effort to select the best representative lag time.

WATERSHED PEAK DISCHARGE FREQUENCY CURVES

To test the SCS hydrological techniques in determining peak discharge frequency curves, annual series and synthetic frequency curves were developed for a comparative analysis. Annual series frequency curves for each of the four

TABLE 4

WATERSHED STORM DATES, ANTECEDENT MOISTURE CONDITIONS, CURVE NUMBERS AND LAG TIMES USED/DETERMINED IN HEC-1 OPTIMIZATIONS

Watershed (USGS Gage No.)	Storm Dates	5-Day AMC/Rainfall (In)	Curve Numbers		Lag Times (Hrs)
			Storm	Condition II	
Austin, Texas Region:					
Waller Creek at	20-21 March 1957	I/0.50	87.4	95	0.16
23rd Street	26-28 April 1958	I/0.69	83.0	93	0.23
(08157500)	8 April 1959	I/0.05	80.2	91	0.17
	23 Sept 1959	I/0.11	77.4	90	0.19
				Avg = 92	Avg = 0.19
	3-4 June 1962	III/2.87	84.9	70	0.32
	27 Sept 1964 *	I/0.19	75.5	89	0.57
	16 May 1965 *	II/1.44	80.5	81	0.55
	18 May 1965 *	III/3.14	90.3	78	0.62
				Avg = 79	Avg = 0.52
	21-22 June 1971	I/0.03	78.7	91	0.18
	1-2 May 1972 *	III/2.33	83.4	67	0.35
	21-22 Oct 1972	II/1.47	81.9	82	0.22
	12-13 Oct 1973	III/5.94	93.3	84	1.20
				Avg = 81	Avg = 0.49
Wilbarger Creek	30-31 May 1964 *	I/0.2	76.3	89	1.14
(08159150)	15-16 June 1964 *	I/0.1	76.1	89	1.03
	16-17 June 1964 *	III/4.1	90.8	80	1.04
	18 May 1965 *	II/1.6	87.4	87	1.73
	15 Oct 1967 *	I/0.2	71.3	86	1.91
	17-18 Nov 1971	II/2.0	73.0	73	1.26
	21-22 Oct 1972 *	III/3.0	84.4	69	1.80
	11 Oct 1973 *	I/0.5	82.6	93	1.13
	13 Oct 1973 *	III/2.8	97.3	92	1.90
	23-24 Nov 1974 *	I/0	65.9	82	1.69
	9-10 June 1975 *	I/0.4	80.9	92	1.46
				Avg = 85	Avg = 1.46
Dallas, Texas Region:					
Turtle Creek	21 April 1967 *	I/0.9	88.7	96	0.73
(08056500)	3-4 Oct 1971 *	I/0	76.0	89	0.50
	18 Oct 1971 *	I/0.5	91.5	97	1.00
	19-20 Oct 1971 *	III/4.2	96.4	90	1.12
	11-12 May 1973 *	I/0.1	90.9	97	0.52
	17-19 April 1976 *	II/2.0	88.9	89	0.85
				Avg = 93	Avg = 0.79
Spanky Branch	30 Oct 1973 *	I/1.1	88.2	96	0.94
(08057120)	7-8 April 1975 *	II/1.5	92.1	92	1.21
	28 June 1975 *	I/0.1	95.9	99	2.46
				Avg = 96	Avg = 1.54

* - Storms used to obtain optimized lag times as shown in Table 1. Excluded storms had poor optimization results.

watersheds previously described in the Austin and Dallas, Texas regions were first developed utilizing USGS streamflow data and procedures of the U.S. Water Resources Council, Bulletin 17A (1976). These annual series frequency curves were developed utilizing the Pearson Type III distribution with log transformation of the peak discharge data and an expected probability adjustment applied to each curve. A generalized coefficient was weighted with the computed skew for each watershed data set as specified in Bulletin 17A. Figure 1 presents these frequency curves for the urban and undeveloped watersheds in the respective regions. The nonstationary (urbanizing) status of the urban watersheds was not considered in the construction of the annual series frequency curves.

Synthetic peak discharge frequency curves were generated utilizing the calculated and optimized CN and lag times values determined for each watershed as discussed previously, along with design storms of various frequencies. Synthetic peak discharges for the 2-, 10-, 25-, and 100-year frequencies were used to develop the curves as shown in Figs. 2, 3, 4, and 5. Specifically, NWS TP-40 rainfall amounts for the 2-, 10-, 25-, and 100-year frequencies were distributed according to an SCS Type II, 6-hour storm and input into the HEC-1 computer model to generate the peak discharges for each of the sets of calculated and optimized CN and lag time values.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Although it is impractical to make final conclusions concerning calculated versus optimized CNs and TLs based solely on the results of this study as shown in Table 1, the following points deserve mentioning.

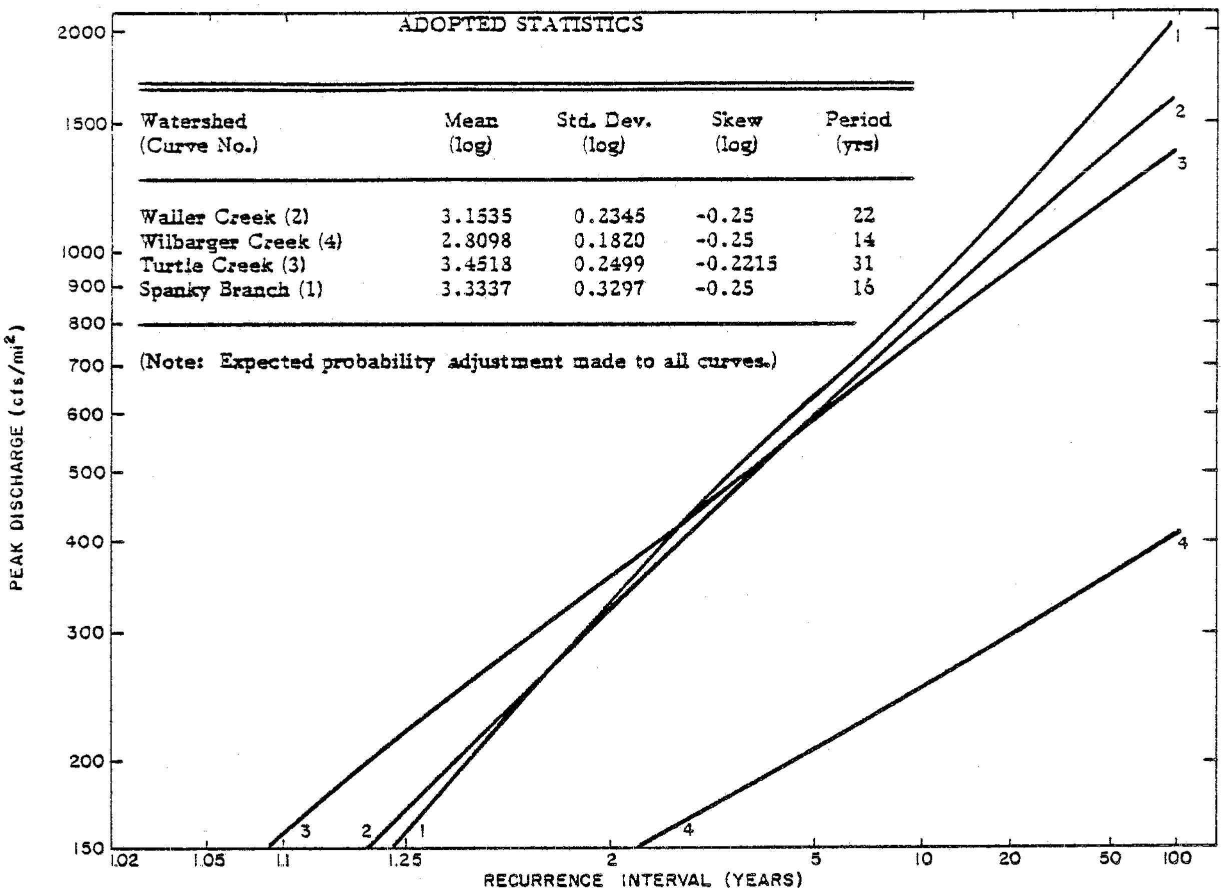
1) In four of the six watershed conditions studied, the CN(O) was greater than CN(C) especially in the Dallas, Texas watersheds. The exceptions were the Waller Creek watershed for the 1962-65 and 1971-73 study periods.

2) The undeveloped watersheds in the two regions had greater proportions of soils with a high runoff potential in comparison with their matching urban watersheds (see Table 2). This partially explains the small difference of CN(C) values for the undeveloped and urban areas.

3) There was considerable variability in CN(O) and TL(O) values especially the latter. This presented some problems in selecting representative values for each parameter.

4) TL(C) values, utilizing Equation 3-2 and Figs. 3-4 and 3-5 of SCS (1975), appear to be high in comparison with other methods of calculating lag times. Additional study is needed to evaluate the accuracy of this particular SCS method of computing lag time.

5) The alternate method lag times, TL(A)s, were closer to the TL(O)s than the TL(C)s for each watershed condition. The TL(C) values were the highest of the three methods in each instance.

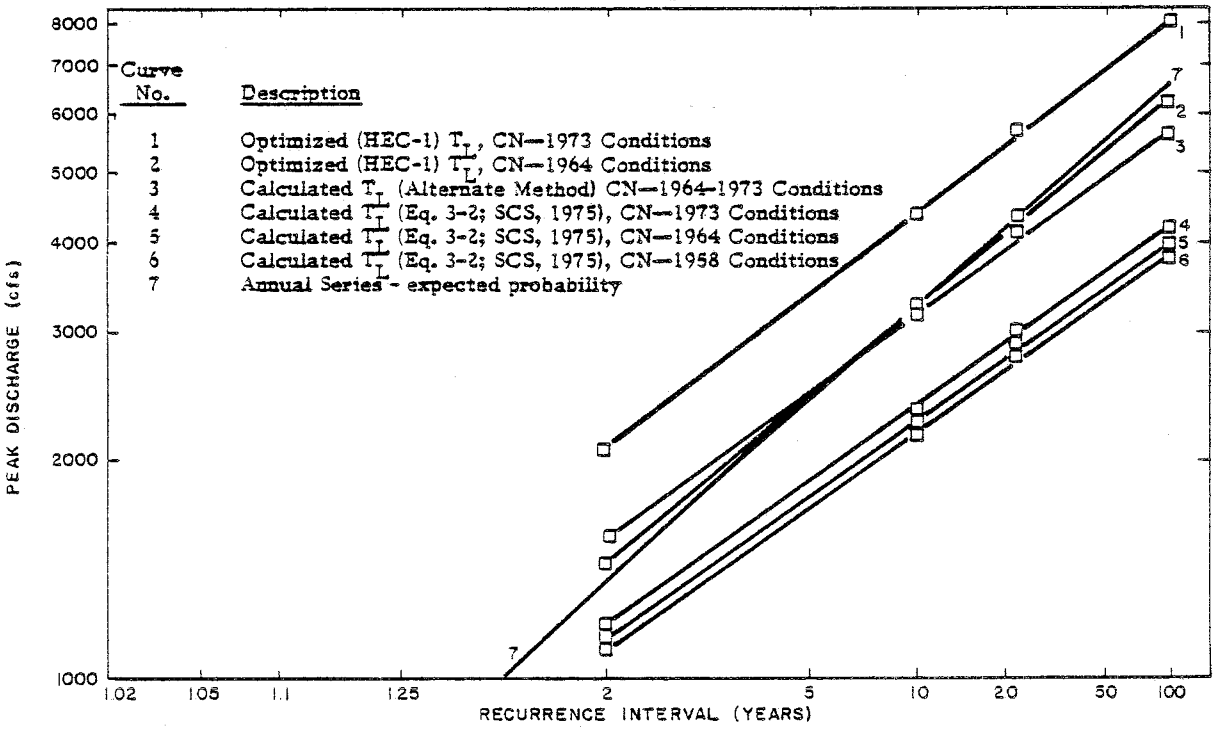


ADOPTED STATISTICS

Watershed (Curve No.)	Mean (log)	Std. Dev. (log)	Skew (log)	Period (yrs)
Waller Creek (2)	3.1535	0.2345	-0.25	22
Wilbarger Creek (4)	2.8098	0.1820	-0.25	14
Turtle Creek (3)	3.4518	0.2499	-0.2215	31
Spanky Branch (1)	3.3337	0.3297	-0.25	16

(Note: Expected probability adjustment made to all curves.)

Fig. 1 Annual Series Frequency Curves



Curve No.	Description
1	Optimized (HEC-1) T_L, CN—1973 Conditions
2	Optimized (HEC-1) T_L, CN—1964 Conditions
3	Calculated T_L (Alternate Method) CN—1964-1973 Conditions
4	Calculated T_L (Eq. 3-2; SCS, 1975), CN—1973 Conditions
5	Calculated T_L (Eq. 3-2; SCS, 1975), CN—1964 Conditions
6	Calculated T_L (Eq. 3-2; SCS, 1975), CN—1958 Conditions
7	Annual Series - expected probability

Fig. 2 Waller Creek Frequency Curves

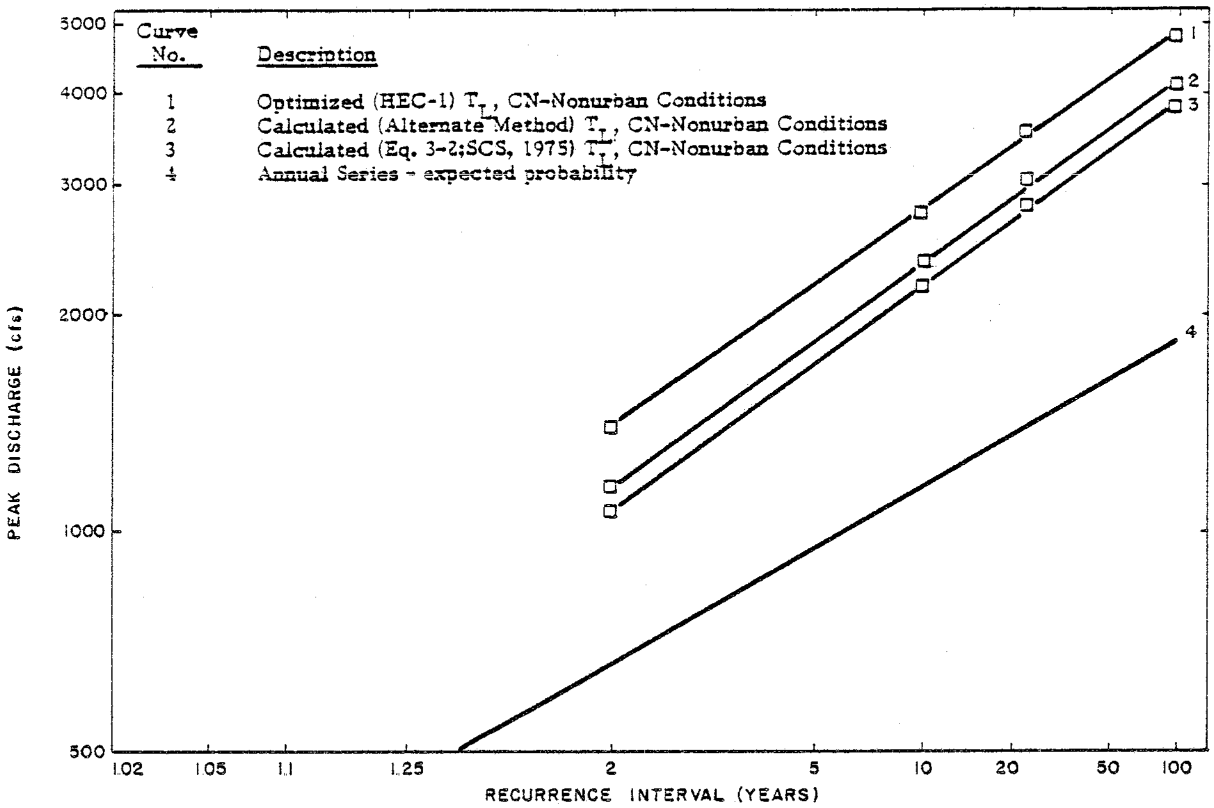


Fig. 3 Wilbarger Creek Frequency Curves

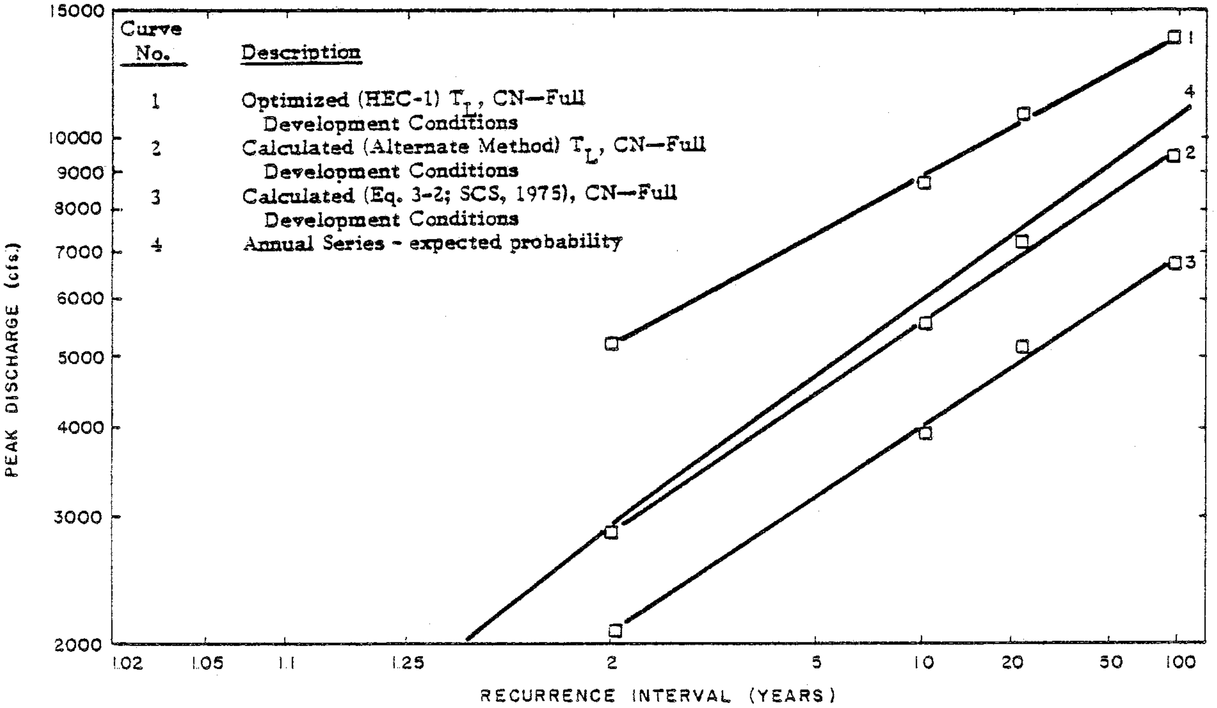


Fig. 4 Turtle Creek Frequency Curves

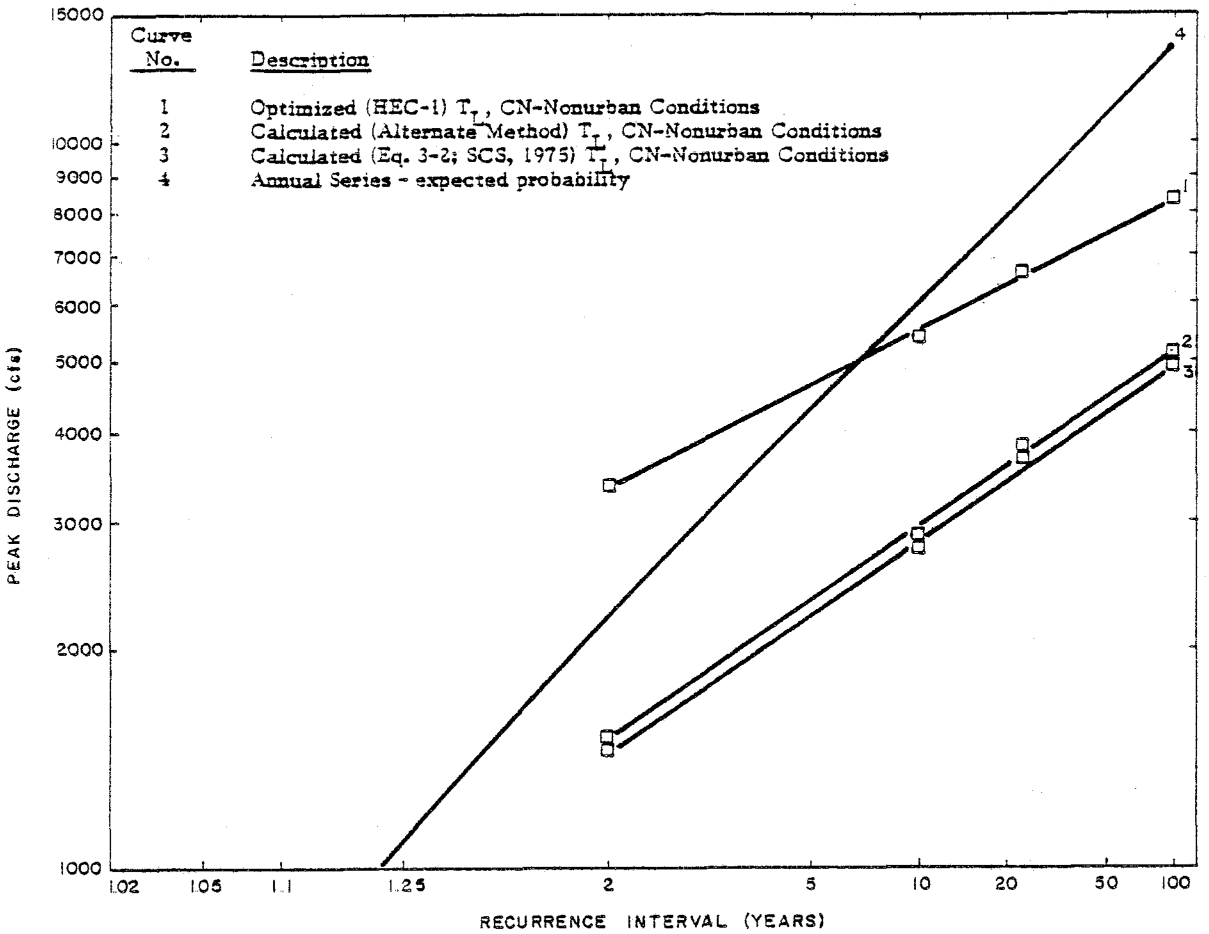


Fig. 5 Spanky Branch Frequency Curves

6) From Nos. 1, 4, and 5 (above) it appears that the SCS methods <u>may</u> provide relatively low peak discharge estimates in urban areas if using Equation 3-2 and Figs. 3-4 and 3-5 of SCS (1975).

The following general statements are made to aid in interpreting the results shown in Figs. 2 through 5 as related to the ability of the SCS procedures in predicting changes in flow frequency due to urbanization.

1) The annual series curves (Fig. 1) show opposite trends for the Austin and Dallas Regions when comparing peak discharges per square mile versus recurrence interval between the urban and undeveloped watersheds.

2) The frequency curves generated from CN(O) and TL(O) values are higher than those originating from CN(C) and TL(C) values.

3) The frequency curves generated from TL(A) estimates and CN(C) values closely approximate the annual series curve for the Waller Creek and Turtle Creek watersheds.

4) Frequency curves developed utilizing lag times calculated from Equation 3-2 and Figs. 3-4 and 3-5 in SCS (1975) are relatively low in all but the Wilbarger Creek watershed.

5) There is little difference shown between the Waller Creek and Wilbarger Creek synthetic frequency curves generated from CN(C) and TL(C) values. This is partially explained by the larger drainage area of Wilbarger Creek and its soils which have an overall higher runoff potential than those for the Waller Creek basin. This is not the case for the synthetic frequency curves generated from CN(O) and TL(O) or CN(C) and TL(A) values for the two watersheds.

6) The synthetic frequency curves representing the Turtle Creek and Spanky Branch watersheds indicate higher discharges for all frequencies for the urban versus undeveloped watersheds when comparing curves generated from the same method. The urban discharges are generally less than 50 percent and never more than 100 percent greater than those for non-urban areas utilizing this comparison.

In conclusion, the results of this analysis indicate that the generalized SCS techniques have potential in predicting effects of urbanization on flood discharges. However, additional research is needed to better define the capabilities and limitations of these techniques, especially concerning the estimation of lag time. Recommendations concerning future research should begin with a continuation of the analysis presented within this report. The scope and result of this study served to point out the need for additional work which is required to produce conclusive results. Comparisons of calculated versus optimized (from recorded storm data) watershed curve numbers and lag times can be accomplished utilizing relatively short periods of simultaneously recorded rainfall and runoff data. Various matching regional urban and nonurban watersheds having a multitude of physiographic and/or urban conditions should be incorporated into such a study.

REFERENCES

Black, W. H. (1979): Pers. Comm., U.S. Army Corps of Engineers, Fort Worth, Texas District.

Carter, R. W. (1961): Magnitude and Frequency of Floods in Suburban Areas, U.S. Geological Survey, Prof. Paper 424-B.

Clark, C. O. (1945): Storage and the Unit Hydrograph, Trans. ASCE Vol. 110.

Dempster, G. R. (1974): Effects of Urbanization of Floods in the Dallas, Texas Metropolitan Area, U.S. Geological Survey, Water Resources Investigations 60-73.

Eagleson, P. S. (1962): Unit Characteristics for Sewered Areas, Journal of the Hydraulics Division, ASCE, Vol. 88, No. HY2.

Espey, W. H., Jr., C. W. Morgan and F. D. Masch (1965): A Study of Some Effects of Urbanization on Storm Runoff from a Small Watershed, Tech. Report HYD 07-6501, CRWR-2, Center for Research in Water Resources, Department of Civil Engineering, University of Texas, Austin, Texas.

Espey, W. H., Jr., and D. E. Winslow (1968): The Effects of Urbanization on Unit Hydrographs for Small Watersheds, Tracor Document No. 68-975-U, including appendices.

Espey, W. H., Jr., D. G. Altman and C. B. Graves, Jr. (1977): Nomographs for Ten-Minite Unit Hydrographs for Small Urban Watersheds, ASCE Urban Water Resources Research Program, Tech. Memo. No. 32.

Hamm, D. W., C. W. Morgan and H. A. Reeder (1973): Statistical Analysis of Hydrograph Characteristics for Small Urban Watersheds, Tracor Doc. No. T73-AU-9559-U.

Hydrologic Engineering Center (1980): HEC-1 Flood Hydrograph Package, Computer Program Users Manual, U.S. Army Corps of Engineers, Davis, California.

National Weather Service (1961): Rainfall Frequency Atlas of the United States. Tech. Paper No. 40.

Slade, R. M. J. D. Gordon and R. N. Mitchell (1979): Hydrologic Data for Urban Studies in the Austin, Texas Metropolitan Area, 1977, U.S. Geological Survey, OFR/WRD 79-271.

Snyder, F. F. (1938): Synthetic Unit Hydrographs, Trans. Am. Geophysics Union, Vol. 19, Part 1.

Soil Conservation Service (1971): National Engineering Handbook, Section 4, Hydrology, U.S. Department of Agriculture, Washington, D.C.

______ (1973): Computer Program for Project Formulation Hydrology, Tech. Release No. 20, U.S. Department of Agriculture, Washington, D.C.

______ (1975): Urban Hydrology for Small Watersheds, Tech. Release No. 55, U.S. Department of Agriculture, Washington, D.C.

U.S. Water Resources Council, Hydrology Committee (1976): Guidelines for Determining Flood Flow Frequency, Bulletin 17A, Washington, D.C.

Van Sickle, D. (1962): The Effect of Urban Development on Storm Runoff, The Texas Engineer, Vol. 32, No. 12.

Technical Paper Series

TP-1	Use of Interrelated Records to Simulate Streamflow
TP-2	Optimization Techniques for Hydrologic Engineering
TP-3	Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4	Functional Evaluation of a Water Resources System
TP-5	Streamflow Synthesis for Ungaged Rivers
TP-6	Simulation of Daily Streamflow
TP-7	Pilot Study for Storage Requirements for Low Flow Augmentation
TP-8	Worth of Streamflow Data for Project Design - A Pilot Study
TP-9	Economic Evaluation of Reservoir System Accomplishments
TP-10	Hydrologic Simulation in Water-Yield Analysis
TP-11	Survey of Programs for Water Surface Profiles
TP-12	Hypothetical Flood Computation for a Stream System
TP-13	Maximum Utilization of Scarce Data in Hydrologic Design
TP-14	Techniques for Evaluating Long-Tem Reservoir Yields
TP-15	Hydrostatistics - Principles of Application
TP-16	A Hydrologic Water Resource System Modeling Techniques
TP-17	Hydrologic Engineering Techniques for Regional Water Resources Planning
TP-18	Estimating Monthly Streamflows Within a Region
TP-19	Suspended Sediment Discharge in Streams
TP-20	Computer Determination of Flow Through Bridges
TP-21	An Approach to Reservoir Temperature Analysis
TP-22	A Finite Difference Methods of Analyzing Liquid Flow in Variably Saturated Porous Media
TP-23	Uses of Simulation in River Basin Planning
TP-24	Hydroelectric Power Analysis in Reservoir Systems
TP-25	Status of Water Resource System Analysis
TP-26	System Relationships for Panama Canal Water Supply
TP-27	System Analysis of the Panama Canal Water Supply
TP-28	Digital Simulation of an Existing Water Resources System
TP-29	Computer Application in Continuing Education
TP-30	Drought Severity and Water Supply Dependability
TP-31	Development of System Operation Rules for an Existing System by Simulation
TP-32	Alternative Approaches to Water Resources System Simulation
TP-33	System Simulation of Integrated Use of Hydroelectric and Thermal Power Generation
TP-34	Optimizing flood Control Allocation for a Multipurpose Reservoir
TP-35	Computer Models for Rainfall-Runoff and River Hydraulic Analysis
TP-36	Evaluation of Drought Effects at Lake Atitlan
TP-37	Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes
TP-38	Water Quality Evaluation of Aquatic Systems
TP-39	A Method for Analyzing Effects of Dam Failures in Design Studies
TP-40	Storm Drainage and Urban Region Flood Control Planning
TP-41	HEC-5C, A Simulation Model for System Formulation and Evaluation
TP-42	Optimal Sizing of Urban Flood Control Systems
TP-43	Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-44	Sizing Flood Control Reservoir Systems by System Analysis
TP-45	Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-46	Spatial Data Analysis of Nonstructural Measures
TP-47	Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-48	Direct Runoff Hydrograph Parameters Versus Urbanization
TP-49	Experience of HEC in Disseminating Information on Hydrological Models
TP-50	Effects of Dam Removal: An Approach to Sedimentation
TP-51	Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-52	Potential Use of Digital Computer Ground Water Models
TP-53	Development of Generalized Free Surface Flow Models Using Finite Element Techniques
TP-54	Adjustment of Peak Discharge Rates for Urbanization
TP-55	The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-56	Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-57	Flood Damage Assessments Using Spatial Data Management Techniques
TP-58	A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-59	Testing of Several Runoff Models on an Urban Watershed
TP-60	Operational Simulation of a Reservoir System with Pumped Storage
TP-61	Technical Factors in Small Hydropower Planning
TP-62	Flood Hydrograph and Peak Flow Frequency Analysis
TP-63	HEC Contribution to Reservoir System Operation
TP-64	Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study
TP-65	Feasibility Analysis in Small Hydropower Planning
TP-66	Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-67	Hydrologic Land Use Classification Using LANDSAT
TP-68	Interactive Nonstructural Flood-Control Planning
TP-69	Critical Water Surface by Minimum Specific Energy Using the Parabolic Method

TP-70	Corps of Engineers Experience with Automatic Calibration of a Precipitation-Runoff Model
TP-71	Determination of Land Use from Satellite Imagery for Input to Hydrologic Models
TP-72	Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality
TP-73	Flood Mitigation Planning Using HEC-SAM
TP-74	Hydrographs by Single Linear Reservoir Model
TP-75	HEC Activities in Reservoir Analysis
TP-76	Institutional Support of Water Resource Models
TP-77	Investigation of Soil Conservation Service Urban Hydrology Techniques
TP-78	Potential for Increasing the Output of Existing Hydroelectric Plants
TP-79	Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U.S. Hydropower Reservoirs
TP-80	Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects
TP-81	Data Management Systems of Water Resources Planning
TP-82	The New HEC-1 Flood Hydrograph Package
TP-83	River and Reservoir Systems Water Quality Modeling Capability
TP-84	Generalized Real-Time Flood Control System Model
TP-85	Operation Policy Analysis: Sam Rayburn Reservoir
TP-86	Training the Practitioner: The Hydrologic Engineering Center Program
TP-87	Documentation Needs for Water Resources Models
TP-88	Reservoir System Regulation for Water Quality Control
TP-89	A Software System to Aid in Making Real-Time Water Control Decisions
TP-90	Calibration, Verification and Application of a Two-Dimensional Flow Model
TP-91	HEC Software Development and Support
TP-92	Hydrologic Engineering Center Planning Models
TP-93	Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program
TP-94	Dredged-Material Disposal Management Model
TP-95	Infiltration and Soil Moisture Redistribution in HEC-1
TP-96	The Hydrologic Engineering Center Experience in Nonstructural Planning
TP-97	Prediction of the Effects of a Flood Control Project on a Meandering Stream
TP-98	Evolution in Computer Programs Causes Evolution in Training Needs: The Hydrologic Engineering Center Experience
TP-99	Reservoir System Analysis for Water Quality
TP-100	Probable Maximum Flood Estimation - Eastern United States
TP-101	Use of Computer Program HEC-5 for Water Supply Analysis
TP-102	Role of Calibration in the Application of HEC-6
TP-103	Engineering and Economic Considerations in Formulating
TP-104	Modeling Water Resources Systems for Water Quality
TP-105	Use of a Two-Dimensional Flow Model to Quantify Aquatic Habitat
TP-106	Flood-Runoff Forecasting with HEC-1F
TP-107	Dredged-Material Disposal System Capacity Expansion
TP-108	Role of Small Computers in Two-Dimensional Flow Modeling
TP-109	One-Dimensional Model for Mud Flows
TP-110	Subdivision Froude Number
TP-111	HEC-5Q: System Water Quality Modeling
TP-112	New Developments in HEC Programs for Flood Control
TP-113	Modeling and Managing Water Resource Systems for Water Quality
TP-114	Accuracy of Computer Water Surface Profiles - Executive Summary
TP-115	Application of Spatial-Data Management Techniques in Corps Planning
TP-116	The HEC's Activities in Watershed Modeling
TP-117	HEC-1 and HEC-2 Applications on the Microcomputer
TP-118	Real-Time Snow Simulation Model for the Monongahela River Basin
TP-119	Multi-Purpose, Multi-Reservoir Simulation on a PC
TP-120	Technology Transfer of Corps' Hydrologic Models
TP-121	Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin
TP-122	The Estimation of Rainfall for Flood Forecasting Using Radar and Rain Gage Data
TP-123	Developing and Managing a Comprehensive Reservoir Analysis Model
TP-124	Review of U.S. Army corps of Engineering Involvement With Alluvial Fan Flooding Problems
TP-125	An Integrated Software Package for Flood Damage Analysis
TP-126	The Value and Depreciation of Existing Facilities: The Case of Reservoirs
TP-127	Floodplain-Management Plan Enumeration
TP-128	Two-Dimensional Floodplain Modeling
TP-129	Status and New Capabilities of Computer Program HEC-6: "Scour and Deposition in Rivers and Reservoirs"
TP-130	Estimating Sediment Delivery and Yield on Alluvial Fans
TP-131	Hydrologic Aspects of Flood Warning - Preparedness Programs
TP-132	Twenty-five Years of Developing, Distributing, and Supporting Hydrologic Engineering Computer Programs
TP-133	Predicting Deposition Patterns in Small Basins
TP-134	Annual Extreme Lake Elevations by Total Probability Theorem
TP-135	A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks
TP-136	Prescriptive Reservoir System Analysis Model - Missouri River System Application
TP-137	A Generalized Simulation Model for Reservoir System Analysis
TP-138	The HEC NexGen Software Development Project
TP-139	Issues for Applications Developers
TP-140	HEC-2 Water Surface Profiles Program
TP-141	HEC Models for Urban Hydrologic Analysis

TP-142	Systems Analysis Applications at the Hydrologic Engineering Center
TP-143	Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds
TP-144	Review of GIS Applications in Hydrologic Modeling
TP-145	Application of Rainfall-Runoff Simulation for Flood Forecasting
TP-146	Application of the HEC Prescriptive Reservoir Model in the Columbia River Systems
TP-147	HEC River Analysis System (HEC-RAS)
TP-148	HEC-6: Reservoir Sediment Control Applications
TP-149	The Hydrologic Modeling System (HEC-HMS): Design and Development Issues
TP-150	The HEC Hydrologic Modeling System
TP-151	Bridge Hydraulic Analysis with HEC-RAS
TP-152	Use of Land Surface Erosion Techniques with Stream Channel Sediment Models
TP-153	Risk-Based Analysis for Corps Flood Project Studies - A Status Report
TP-154	Modeling Water-Resource Systems for Water Quality Management
TP-155	Runoff simulation Using Radar Rainfall Data
TP-156	Status of HEC Next Generation Software Development
TP-157	Unsteady Flow Model for Forecasting Missouri and Mississippi Rivers
TP-158	Corps Water Management System (CWMS)
TP-159	Some History and Hydrology of the Panama Canal
TP-160	Application of Risk-Based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems
TP-161	Corps Water Management System - Capabilities and Implementation Status