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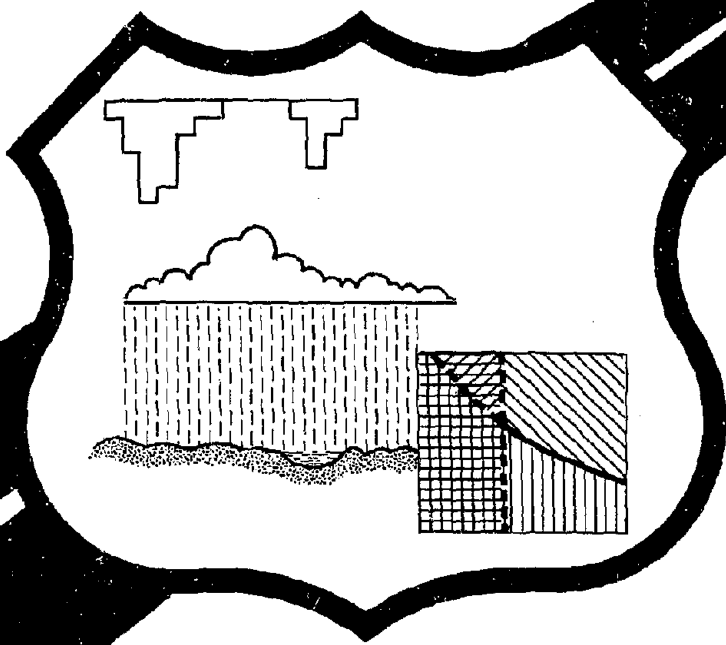
EXTENSION OF THE SOIL CONSERVATION SERVICE RAINFALL–RUNOFF METHODOLOGY FOR UNGAGED WATERSHEDS

July 1981

Final Report



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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Environmental Division
Washington, D.C. 20590

FOREWORD

This report describes the derivatimn of a simple procedure to obtain the proper corresponding hydraulic soil parameters of a watershed from the Soil Conservation Service curve number. These hydraulic soil parameters can then be used in the physically based infiltration equations for an accurate estimate of direct runoff of the watershed.

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for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

The estimation of direct runoff for ungaged watersheds is a common problem in engineering hydrology. The method of the Soil Conservation Services (SCS) is widely used due to its ease of application. Runoff estimates are based upon the soil types and land use practices occurring within a watershed. This report presents an extension of the SCS method employing modern physically based infiltration equations. Problems with the SCS equations are discussed and contrasted with the physically based equations. The requirement of equal amounts of total abstraction from constant rainfall events by both methods is taken as the criterion for establishing an equivalence between the SCS curve number (CN) and hydraulic soil parameters. A corresponding CN is found for each of nine major soil textural classes. Regression equations are used to generalize these results and form a table of correspondence. This table permits the estimation of direct runoff by physical infiltration equations for any ungaged watershed for which a CN may be determined by knowledge of soil types and land use. However because the CN tables of the SCS were established for actually observed storms which are not uniform the correspondence based on uniform storms is biased. The bias is removed by comparing the prediction of excess rainfall for pairs of storms of equal duration and total precipitation for the case of a uniform rainfall rate versus the case of a variable intensity pattern typical of extreme storms. On the basis of these comparisons a relationship, which eliminates the bias, is established between the CN based on soils and land use and the CN to be used to obtain the proper corresponding hydraulic soil parameters.

17. Key Words

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I. INTRODUCTION

When a hydrologist is faced with the task of estimating direct runoff for an ungaged watershed, very often the method employed is that of the Soil Conservation Service (SCS). The SCS method characterizes a watershed's potential for generating excess rainfall by identifying for it an appropriate curve number (CN). This single parameter is all that is needed to compute excess rainfall for an event of given depth and duration. Determination of the CN for a watershed is based upon a knowledge of its soil types and the land use practices within it. In addition, the influence of watershed wetness for a specific natural storm may be estimated by means of an index of antecedent moisture condition (AMC). AMC is a function of the five day antecedent rainfall depth and whether the storm occurs in the dormant or growing season.

The great value of the SCS method is that no runoff data are required for its use, only readily identifiable physical characteristics of the watershed. This is because the SCS used actual rainfall and runoff data to derive curve numbers for experimental watersheds with specific soil types and land covers. In a sense, the CN for a watershed has been precalibrated by the SCS based on runoff data for experimental watersheds with similar physical characteristics.

The object of the work to be described in this report is to exploit the calibration inherent in the SCS curve number by extending it to apply to the physical parameters appearing in infiltration equations. Achievement of this, in turn, permits the calculation of direct runoff for an ungaged watershed by means of modern, physically based infiltration equations instead of the equations of the SCS method, which are of questionable theoretical basis.

1. The SCS Method of Prediction of Direct Runoff

1.1 Review

The SCS method is meant as a means of estimating direct runoff. The SCS defines direct runoff as a combination of surface runoff and subsurface flow. Surface (or local) runoff is that produced when the rainfall rate exceeds the infiltration rate. Subsurface flow (also called interflow) occurs when infiltrated rainfall reappears on the surface due to the presence of an impermeable layer. Channel runoff is considered negligible and is therefore ignored. For a given rainfall event, cumulative direct runoff and cumulative excess precipitation are synonymous terms.

With the SCS method, the identification of a single parameter, CN, for a watershed permits the prediction of direct runoff. The equation for making this calculation is:

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \tag{1.1.1}$$

where P is the cumulative depth of rainfall, P_e is the cumulative depth of excess rainfall, and S is the maximum watershed storage, a transform of the watershed curve number by the relation:

$$S = \frac{1000}{CN} - 10 \tag{1.1.2}$$

S will have units of inches if calculated by Eq. (1.1.2). If it is desired to compute S in terms of millimeters, the constants 1000 and 10 appearing in Eq. (1.1.2) must be replaced by 25400 and 254 respectively. I_a is the intial abstraction, consisting of interception, depression storage and infiltration occurring prior to runoff. Based on observations of SCS experimental watersheds, the initial abstraction is commonly estimated (roughly) by the equation:

$$I_a = 0.2\ S \qquad (1.1.3)$$

Eq. (1.1.1) then simplifies to:

$$P_e = \frac{(P-0.2S)^2}{P+0.8S} \qquad (1.1.4)$$

The first step in the determination of CN for a watershed is the identification of the hydrologic soil groups occurring therein. The SCS defines four such groups:

"A. (Low runoff potential). Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission.

B. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

C. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

D. (High runoff potential). Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission." (From the SCS National Engineering Handbook, Section 4, Hydrology, page 7.2.)

State soil survey maps may be obtained to identify the *names* of the soils in a watershed. The SCS National Engineering Handbook, Section 4, Hydrology (NEH-4 for short) contains as its Table 7.1 a list of the names of over 4000 soils of the United States and Puerto Rico, each classified into a hydrologic soil group (A, B, C, or D). An example page of this list is presented here as Table 1.

Tables 2 and 3 display curve numbers for specific hydrologic soil-cover complexes. If more than one soil-cover complex is present in a watershed, a composite curve number may be determined by weighting each CN by its respective fraction of the total watershed area. Hydrologic condition refers to the relative quality of a land cover. For example, pasture which is heavily grazed would be judged to be in poor hydrologic condition; pasture in *good* hydrologic condition would be characterized by a deep, thick cover of grass with a high rainfall retention capacity.

Tables 2 and 3 indicate that the CN they present are for antecedent moisture condition of type II (AMC-II). The SCS defines three discrete levels of AMC:

AMC-I. Lowest runoff potential. The watershed soils are dry enough for satisfactory plowing or cultivation to take place. Although soils are dry, they have not reached the wilting point.

AMC-II. Average watershed wetness. Presumably, this is characterized by a soil moisture condition not unlike field capacity, where no water drainable by gravity is present, but the soil's capacity for holding water by capillarity is fully utilized.

AMC-III. Highest runoff potential. Antecedent rainfall has virtually saturated the watershed's soil.

Table 1. An example page of the SCS classification of soils into hydrologic groups A, B, C, and D. The table is presented in its entirety in the User's Manual for XSRAIN.

AABERG	C	AHL	C	ALMY	B	ANLAUF	C	AROOSTOOK	
AASTAD	B	AHLSTROM	C	ALOHA	C	ANNABELLA	B	AROSA	C
ABAC	D	AHMEEK	B	ALONSO	B	ANNANDALE	C	ARP	C
ABAJO	C	AHOLT	D	ALOVAR	C	ANNISTON	B	ARRINGTON	B
ABBOTT	D	AHTANUM	C	ALPENA	B	ANOKA	A	ARRITOLA	D
ABBOTTSTOWN	C	AHWAHNEE	C	ALPHA	C	ANONES	C	ARROLIME	C
ABCAL	D	AIBONITO	C	ALPON	B	ANSARI	D	ARRON	D
ABEGG	B	AIKEN	B/C	ALPOWA	B	ANSEL	B	ARROW	B
ABELA	B	AIKMAN	D	ALPS	C	ANSELMO	A	ARROWSMITH	B
ABELL	B	AILEY	B	ALSEA	B	ANSON	B	ARROYO SECO	B
ABERDEEN	D	AINAKEA	B	ALSPAUGH	C	ANTELOPE SPRINGS	C	ARTA	C
ABES	D	AIRMONT	C	ALSTAD	B	ANTERO	C	ARTOIS	C
ABILENE	C	AIROTSA	B	ALSTOWN	B	ANT FLAT	C	ARVADA	D
ABINGTON	B	AIRPORT	D	ALTAMONT	D	ANTHO	B	ARVANA	C
ABIQUA	C	AITS	B	ALTAVISTA	C	ANTHONY	B	ARVESON	D
ABO	B/C	AJO	C	ALTDORF	D	ANTIGO	B	ARVILLA	B
ABOR	D	AKAKA	A	ALTMAR	B	ANTILON	B	ARZELL	C
ABRA	C	AKASKA	B	ALTO	C	ANTIOCH	D	ASA	B
ABRAHAM	B	AKELA	C	ALTOGA	C	ANTLER	C	ASBURY	B
ABSAROKEE	C	ALADDIN	B	ALTON	B	ANTOINE	C	ASCALON	B
ABSCOTA	B	ALAE	A	ALTUS	B	ANTROBUS	B	ASCHOFF	B
ABSHER	D	ALAELOA	B	ALTVAN	B	ANTY	B	ASHBY	C
ABSTED	D	ALAGA	A	ALUM	B	ANVIK	B	ASHCROFT	B
ACACIO	C	ALAKAI	D	ALUSA	D	ANWAY	B	ASHDALE	B
ACADEMY	C	ALAMA	B	ALVIN	B	ANZA	B	ASHE	B
ACADIA	D	ALAMANCE	B	ALVIRA	C	ANZIANO	C	ASHKUM	C
ACANA	D	ALAMO	D	ALVISO	D	APACHE	D	ASHLAR	B
ACASCO	D	ALAMOSA	C	ALVOR	C	APAKUIE	A	ASHLEY	A
ACEITUNAS	B	ALAPAHA	D	AMADOR	D	APISHAPA	C	ASH SPRINGS	C
ACEL	D	ALAPAI	A	AMAGON	D	APISON	B	ASHTON	B
ACKER	B	ALBAN	B	AMALU	D	APOPKA	A	ASHUE	B
ACKMEN	B	ALBANO	D	AMANA	B	APPIAN	C	ASHUELOT	C
ACME	C	ALBANY	C	AMARGOSA	D	APPLEGATE	C	ASHWOOD	C
ACO	B	ALBATON	D	AMARILLO	B	APPLETON	C	ASKEW	[illegible]
ACOLITA	B	ALBEE	C	AMASA	B	APPLING	B	ASO	C
ACOMA	C	ALBEMARLE	B	AMBERSON		APRON	B	ASOTIN	C
ACOVE	C	ALBERTVILLE	C	AMBOY	C	APT	C	ASPEN	B
ACREE	C	ALBIA	C	AMBRAW	C	APTAKISIC	B	ASPERMONT	B
ACRELANE	C	ALBION	B	AMEDEE	A	ARABY		ASSINNIBOINE	B
ACTON	H	ALBRIGHTS	C	AMELIA	B	ARADA	C	ASSUMPTION	B
ACUFF	B	ALCALDE	C	AMENIA	B	ARANSAS	D	ASTATULA	A
ACWORTH	B	ALCESTER	B	AMERICUS	A	ARAPIEN	C	ASTOR	A/D
ACY	C	ALCOA	B	AMES	C	ARAVE	D	ASTORIA	B
ADA	B	ALCONA	B	AMESHA	B	ARAVETON	B	ATASCADERO	C
ADAIR	D	ALCOVA	B	AMHERST	C	ARBELA	C	ATASCOSA	D
ADAMS	A	ALDA	C	AMITY	C	ARBONE	B	ATCO	B
ADAMSON	B	ALDAX	D	AMMON	B	ARBOR	B	ATENCIO	B
ADAMSTOWN		ALDEN	D	AMOLE	C	ARBUCKLE	B	ATEPIC	D
ADAMSVILLE	C	ALDER	B	AMOR	B	ARCATA	B	ATHELWOLD	B
ADATON	D	ALDERDALE	C	AMOS	C	ARCH	B	ATHENA	B
ADAVEN	D	ALDERWOOD	C	AMSDEN	B	ARCHABAL	B	ATHENS	B
ADDIELOU	C	ALDINO	C	AMSTERDAM	B	ARCHER	C	ATHERLY	B
ADDISON	D	ALDWELL	C	ANTOFT	D	ARCHIN	C	ATHERTON	B/D
ADDY	C	ALEKNAGIK	B	AMY	D	ARCO	B	ATHMAR	C
ADE	A	ALEMEDA	C	ANACAPA	B	ARCOLA	C	ATHOL	B
ADEL	A	ALEX	B	ANAHUAC	D	ARD	C	ATKINSON	B
ADELAIDE	D	ALEXANDRIA	C	ANAMITE	D	ARDEN	B	ATLAS	D
ADELANTO	B	ALEXIS	B	ANAPRA	B	ARDENVOIR	B	ATLEE	C
ADELINO	B	ALFORD	B	ANASAZI	B	ARDILLA	C	ATMORE	B/D
ADELPHIA	C	ALGANSEE	B	ANATONE	D	AREDALE	B	ATOKA	C
ADENA	C	ALGERITA	B	ANAVERDE	B	ARENA	C	ATON	B
ADGER	D	ALGIERS	C/D	ANAWALT	D	ARENALES		ATRYPA	C
ADILIS	A	ALGOMA	B/D	ANCHO	B	ARENDTSVILLE	B	ATSION	C
ADIRONDACK		ALHAMBRA	B	ANCHORAGE	A	ARENOSA	A	ATTERBERRY	B
ADIV	B	ALICE	A	ANCHOR BAY	D	ARENZVILLE	B	ATTEWAN	A
ADJUNTAS	C	ALICEL	B	ANCHOR POINT	D	ARGONAUT	D	ATTICA	B
ADKINS	B	ALICIA	B	ANCLOTE	D	ARGUELLO	B	ATTLEBORO	
ADLER	C	ALIDA	B	ANCO	C	ARGYLE	B	ATWATER	B
ADOLPH	D	ALIKCHI	B	ANDERLY	C	ARIEL	C	ATWELL	C/D
ADRIAN	A/D	ALINE	A	ANDERS	C	ARIZO	A	ATWOOD	B
AENEAS	B	ALKO	D	ANDERSON	B	ARKABUTLA	C	AUBBEENAUBBEE	B
AETNA	B	ALLAGASH	B	ANDES	C	ARKPORT	B	AUBERRY	B
AFTON	D	ALLARD	B	ANDORINIA	C	ARLAND	B	AUBURN	C/D
AGAR	B	ALLEGHENY	B	ANDOVER	D	ARLE	B	AUBURNDALE	D
AGASSIZ	D	ALLEMANDS	D	ANDREEN	B	ARLING	D	AUDIAN	B
AGATE	D	ALLEN	B	ANDREESON	C	ARLINGTON	C	AU GRES	C
AGAWAM	B	ALLENDALE	C	ANDRES	B	ARLOVAL	C	AUGSBURG	B
AGENCY	C	ALLENS PARK	B	ANDREWS	C	ARMAGH	D	AUGUSTA	C
AGER	D	ALLENSVILLE	C	ANED	D	ARMIJO	D	AULD	D
AGNER	B	ALLENTINE	D	ANETH	A	ARMINGTON	D	AURA	D
AGNEW	B/C	ALLENWOOD	B	ANGELICA	D	ARMO	B	AURORA	C
AGNOS	B	ALLESSIO	B	ANGELINA	B/D	ARMOUR	B	AUSTIN	C
AGUA	B	ALLEY	C	ANGELO	C	ARMSTER	C	AUSTWELL	D
AGUADILLA	A	ALLIANCE	B	ANGIE	C	ARMSTRONG	D	AUXVASSE	D
AGUA DULCE	C	ALLIGATOR	D	ANGLE	A	ARMUCHEE	D	AUZQUI	B
AGUA FRIA	B	ALLIS	D	ANGLEN	B	ARNEGARD	B	AVA	C
AGUALT	B	ALLISON	C	ANGOLA	C	ARNHART	C	AVALANCHE	B
AGUEDA	B	ALLOUEZ	C	ANGOSTURA	B	ARNHEIM	C	AVALON	B
AGUILITA	B	ALLOWAY		ANHALT	D	ARNO	D	AVERY	B
AGUIRRE	D	ALMAC	B	ANIAK	D	ARNOLD	B	AVON	C
AGUSTIN	B	ALMENA	C	ANITA	D	ARNOT	C/D	AVONBURG	D
AHATONE	D	ALMONT	D	ANKENY	A	ARNY	A	AVONDALE	E

NOTES A BLANK HYDROLOGIC SOIL GROUP INDICATES THE SOIL GROUP HAS NOT BEEN DETERMINED
TWO SOIL GROUPS SUCH AS B/C INDICATES THE DRAINED/UNDRAINED SITUATION

Table 2. Runoff curve numbers for hydrologic soil-cover complexes (antecedent moisture condition II, and I_a = 0.2 S). From NEH-4, page 9.2.

Land use	Cover: Treatment or practice	Cover: Hydrologic condition	Hydrologic soil group: A	B	C	D
Fallow	Straight row	----	77	86	91	94
Row crops	"	Poor	72	81	88	91
	"	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	"	Good	65	75	82	86
	"and terraced	Poor	66	74	80	82
	" " "	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	"and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes 1/ or rotation meadow	Straight row	Poor	66	77	85	89
	" "	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	"	Good	55	69	78	83
	"and terraced	Poor	63	73	80	83
	"and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		----	59	74	82	86
Roads (dirt) 2/		----	72	82	87	89
(hard surface) 2/		---	74	84	90	92

1/ Close-drilled or broadcast.
2/ Including right-of-way.

Table 3. Runoff curve numbers for selected agricultural, suburban, and urban land use (antecedent moisture condition II, and $I_a = 0.2$ S). (1 acre = 0.4047 hectare). From SCS Technical Release No. 55, page 2-5.

LAND USE DESCRIPTION	HYDROLOGIC SOIL GROUP			
	A	B	C	D
Cultivated land[1/]: without conservation treatment	72	81	88	91
: with conservation treatment	62	71	78	81
Pasture or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or Forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover[2/]	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.				
good condition: grass cover on 75% or more of the area	39	61	74	80
fair condition: grass cover on 50% to 75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious).	81	88	91	93
Residential:[3/]				
Average lot size — Average % Impervious[4/]				
1/8 acre or less — 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
Paved parking lots, roofs, driveways, etc.[5/]	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers[5/]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

1/ For a more detailed description of agricultural land use curve numbers refer to National Engineering Handbook, Section 4, Hydrology, Chapter 9, Aug. 1972.

2/ Good cover is protected from grazing and litter and brush cover soil.

3/ Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

4/ The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

5/ In some warmer climates of the country a curve number of 95 may be used.

Determination of AMC for a watershed is done by summing the depths of rainfall for the five days previous to the date of interest. This sum is then compared to the seasonal criteria presented in Table 4. If the watershed wetness is found to be in a class other than AMC-II, the CN is revised by consulting Table 5.

1.2 Problems with the SCS Method

The foregoing discussion illustrates the relative convenience and ease of application of the SCS method for estimating direct runoff. However, this simplicity is not achieved without paying a price. Most inaccuracies inherent in the method stem from the fundamental equality from which Eq. (1.1.1) was developed, presented here as Eq. (1.2.1).

$$\frac{P - P_e}{S} = \frac{P_e}{P} \qquad (1.2.1)$$

The symbols have the same meanings as they had in Section 1.1. The justification for writing this equality is that, for a storm without initial abstraction and of long duration, late in the storm the ratios of abstracted precipitation to total watershed storage $\frac{P - P_e}{S}$ and cumulative excess rainfall to total rainfall $\frac{P_e}{P}$ both tend to one. However, there is no physical reason to believe that these ratios are equal to one another at any other time, so total acceptance of Eq. (1.2.1) requires a certain leap of faith. Introducing the initial abstraction concept to Eq. (1.2.1) yields:

$$\frac{P - I_a - P_e}{S} = \frac{P_e}{P - I_a} \qquad (1.2.2)$$

If Eq. (1.2.2) is solved for P_e, the result is Eq. (1.1.1):

$$P = \frac{(P - I_a)^2}{P - I_a + S}$$

Table 4. Seasonal rainfall limits for AMC. (1 inch = 25.4 mm). (After NEH-4, page 4.12).

AMC group	Total 5-day antecedent rainfall	
	Dormant season	Growing season
	Inches	Inches
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	Over 2.1

Table 5. Curve numbers (CN) and constants for the case $I_a = 0.2$ S. S values in inches, 1 inch = 25.4 mm. (After NEH-4, page 10.7.)

1	2	3	4	5	1	2	3	4	5
CN for condition II	CN for conditions I	III	S values*	Curve* starts where P =	CN for condition II	CN for conditions I	III	S values*	Curve* starts where P =
			(inches)	(inches)				(inches)	(inches)
100	100	100	0	0	60	40	78	6.67	1.33
99	97	100	.101	.02	59	39	77	6.95	1.39
98	94	99	.204	.04	58	38	76	7.24	1.45
97	91	99	.309	.06	57	37	75	7.54	1.51
96	89	99	.417	.08	56	36	75	7.86	1.57
95	87	98	.526	.11	55	35	74	8.18	1.64
94	85	98	.638	.13	54	34	73	8.52	1.70
93	83	98	.753	.15	53	33	72	8.87	1.77
92	81	97	.870	.17	52	32	71	9.23	1.85
91	80	97	.989	.20	51	31	70	9.61	1.92
90	78	96	1.11	.22	50	31	70	10.0	2.00
89	76	96	1.24	.25	49	30	69	10.4	2.08
88	75	95	1.36	.27	48	29	68	10.8	2.16
87	73	95	1.49	.30	47	28	67	11.3	2.26
86	72	94	1.63	.33	46	27	66	11.7	2.34
85	70	94	1.76	.35	45	26	65	12.2	2.44
84	68	93	1.90	.38	44	25	64	12.7	2.54
83	67	93	2.05	.41	43	25	63	13.2	2.64
82	66	92	2.20	.44	42	24	62	13.8	2.76
81	64	92	2.34	.47	41	23	61	14.4	2.88
80	63	91	2.50	.50	40	22	60	15.0	3.00
79	62	91	2.66	.53	39	21	59	15.6	3.12
78	60	90	2.82	.56	38	21	58	16.3	3.26
77	59	89	2.99	.60	37	20	57	17.0	3.40
76	58	89	3.16	.63	36	19	56	17.8	3.56
75	57	88	3.33	.67	35	18	55	18.6	3.72
74	55	88	3.51	.70	34	18	54	19.4	3.88
73	54	87	3.70	.74	33	17	53	20.3	4.06
72	53	86	3.89	.78	32	16	52	21.2	4.24
71	52	86	4.08	.82	31	16	51	22.2	4.44
70	51	85	4.28	.86	30	15	50	23.3	4.66
69	50	84	4.49	.90					
68	48	84	4.70	.94	25	12	43	30.0	6.00
67	47	83	4.92	.98	20	9	37	40.0	8.00
66	46	82	5.15	1.03	15	6	30	56.7	11.34
65	45	82	5.38	1.08	10	4	22	90.0	18.00
64	44	81	5.62	1.12	5	2	13	190.0	38.00
63	43	80	5.87	1.17	0	0	0	infinity	infinity
62	42	79	6.13	1.23					
61	41	78	6.39	1.28					

*For CN in column 1.

Another shortcoming of the SCS method lies with the estimation of the initial abstraction using Eq. (1.1.3), namely:

$$I_a = 0.2\ S$$

This equation was developed by the SCS by plotting data for experimental watersheds and fitting a straight line through the points. Figure 1 illustrates how this was done. Note that the points are plotted on a logarithmic scale for both abscissa and ordinate (log-log plot) and still the scatter of points is very large. The experimental data are not well fitted by a straight line. This is another example of the price paid for simplification.

It is instructive to consider the infiltration behavior implied by the use of the SCS method. A derivation of such an equation is presented here. Consider the constant rainfall intensity event depicted in Figure 2. The cumulative infiltration, W, may be expressed as:

$$W = P - P_e + W_e - I_a \tag{1.2.3}$$

where W_e is the cumulative infiltration at time t_e, the end of the initial abstraction. Eq. (1.2.3) applies for any time after the initial abstraction has been satisfied. Eq. (1.1.1) may be manipulated in the following manner to yield an expression for $P - P_e$, namely:

$$P - P_e = P - \frac{(P-I_a)^2}{P-I_a+S}$$

Reduction of the right hand side of this equation to a common denominator leads to the result:

$$P - P_e = \frac{P(S+I_a)-I_a^2}{P-I_a+S} \tag{1.2.4}$$

Substitution of Eq. (1.2.4) into Eq. (1.2.3) yields after reduction:

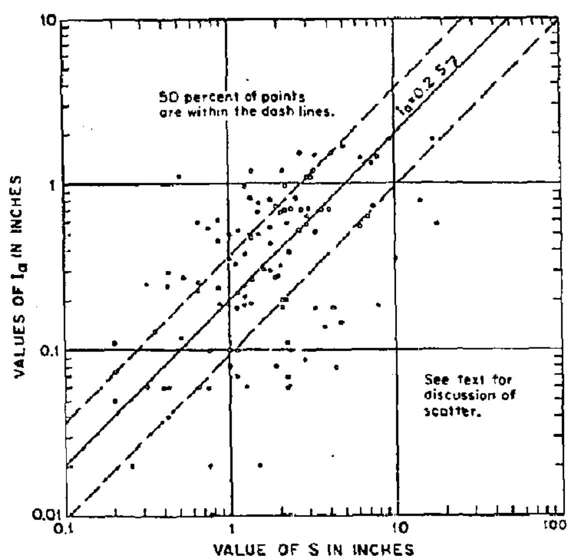

Figure 1. Relationship of I_a and S. Plotted points are derived from experimental watershed data. From Soil Conservation Service National Engineering Handbook Section 4, Hydrology, pg. 10.23. (1 inch = 25.4 mm)

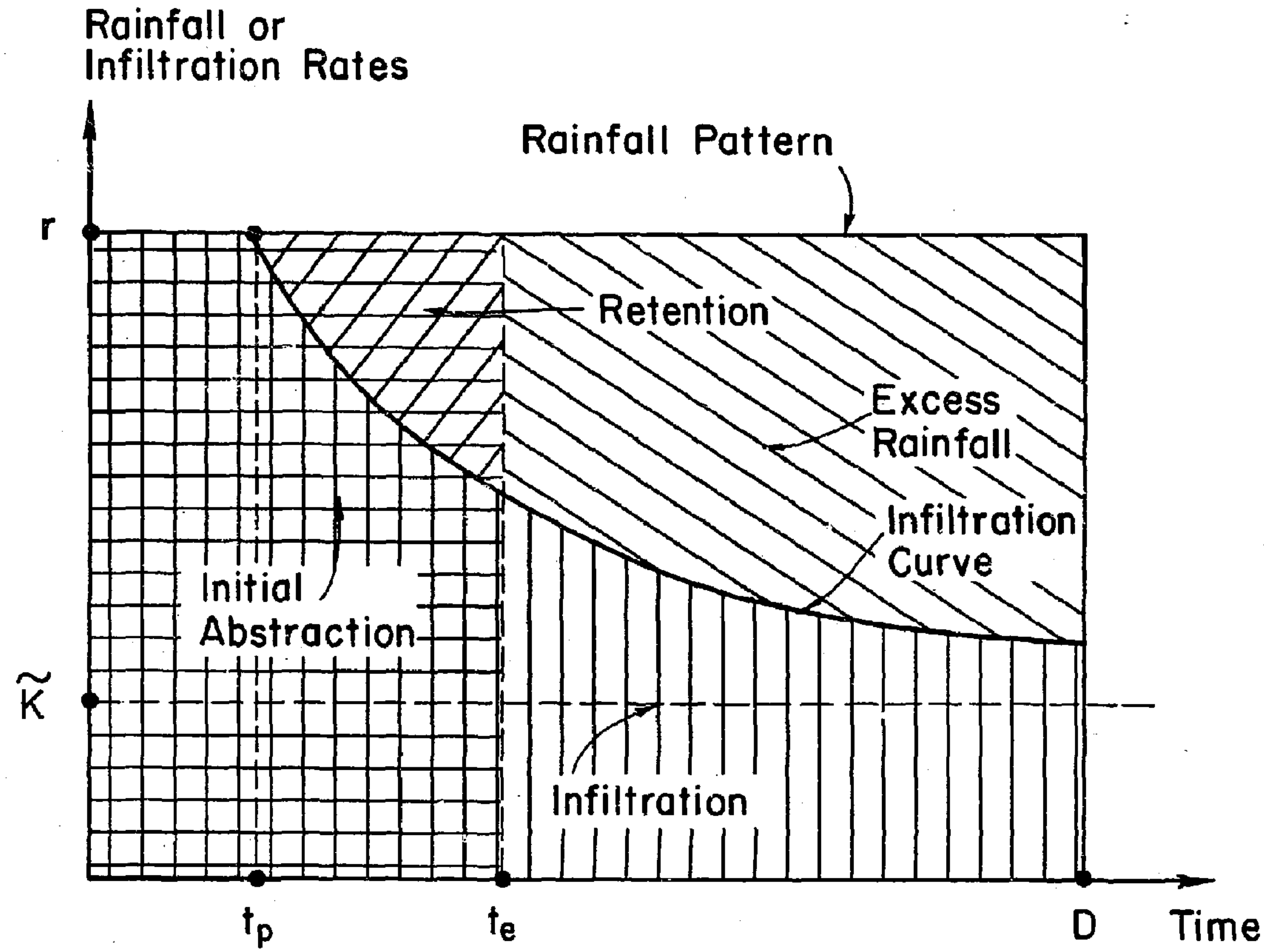

Figure 2. Disposition of rainfall into infiltration, retention and excess rainfall.

$$W = \frac{P(S+I_a)-I_a^2}{P-I_a+S} + W_e - I_a$$

$$W = \frac{PS+PI_a-I_a^2-PI_a+I_a^2-SI_a}{P-I_a+S} + W_e$$

$$W = \frac{S(P-I_a)}{P-I_a+S} + W_e \qquad (1.2.5)$$

If one takes the derivative with respect to time of Equation 1.2.5, the result is the infiltration rate for times greater than t_e, that is, after the initial abstraction has been satisfied. One can write:

$$I = \frac{dW}{dt} = \frac{d}{dt}\left[\frac{S(P-I_a)}{P-I_a+S}\right]$$

since W_e is a constant whose time derivative is zero. Applying the rules of calculus for differentiation of a fraction, one obtains:

$$\frac{dW}{dt} = \frac{d}{dt}\left(\frac{u}{v}\right) = \frac{v\frac{du}{dt}-u\frac{dv}{dt}}{v^2} = \frac{r[(P-I_a+S)S-S(P-I_a)]}{(P-I_a+S)^2}$$

Reduction of this expression yields:

$$I = \frac{dW}{dt} = \frac{S^2 r}{(P-I_a+S)^2} \qquad (1.2.6)$$

In Eq. (1.2.6), r is the rainfall intensity (or rate).

Eq. (1.2.6) is the equation put forward by Aron, Miller and Lakatos (1977) as a "new" infiltration equation. However, as it was brought out by Smith and Eggert (1978) in their discussion of this equation, there is nothing new about it at all. It appears in Smith (1976) as Eq. (6). Moreover, it is the implicit infiltration function when computing the variation of excess rainfall by Eq. (1.1.1), as is done in Example 10.7 of NEH-4.

Examination of Eq. (1.2.6) shows that the SCS infiltration rate has current cumulative rainfall depth in the denominator. This is as it should be, tending to reduce the infiltration rate as the storm progresses. However, the glaring flaw in Eq. (1.2.6) is the presence of the rainfall intensity, r, in the numerator. This suggests that the infiltration rate is directly proportional to, and will fluctuate with, the rainfall intensity. This is in direct disagreement with field experience, laboratory evidence and physical infiltration theory, all of which show that, for a ponded surface condition, infiltration rate is controlled by a monotonically decreasing infiltration capacity curve, independent of rainfall intensity. The SCS infiltration rate only yields a monotonic curve for a constant r.

As an example, consider the simplified rainfall pattern tabulated below for times beyond the end of the initial abstraction, (1 inch = 25.4 mm):

r (in/hr)	1.0	1.0	1.0	1.0	3.0	3.0	3.0	3.0	0.8	0.8	0.8	0.8
$t-t_e$ (hr)	0.25	0.50	0.75	1.0	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
$P-I_a$ (in)	0.25	0.50	0.75	1.0	1.75	2.50	3.25	4.00	4.20	4.40	4.60	4.80

Calculating the infiltration rate by Eq. (1.2.6) one obtains, for a watershed of CN = 83.3, S = 2.0 in:

r	Post-I_a Infiltration Rate (I, in/hr)											
1.0	0.79	0.64	0.53	0.44								
3.0				1.33	0.85	0.59	0.44	0.33				
0.8								0.09	0.08	0.08	0.07	0.07

The dependence of Eq. (1.2.6) gives a clearly discontinuous, and therefore unrealistic, infiltration rate. The results are displayed in Figure 3.

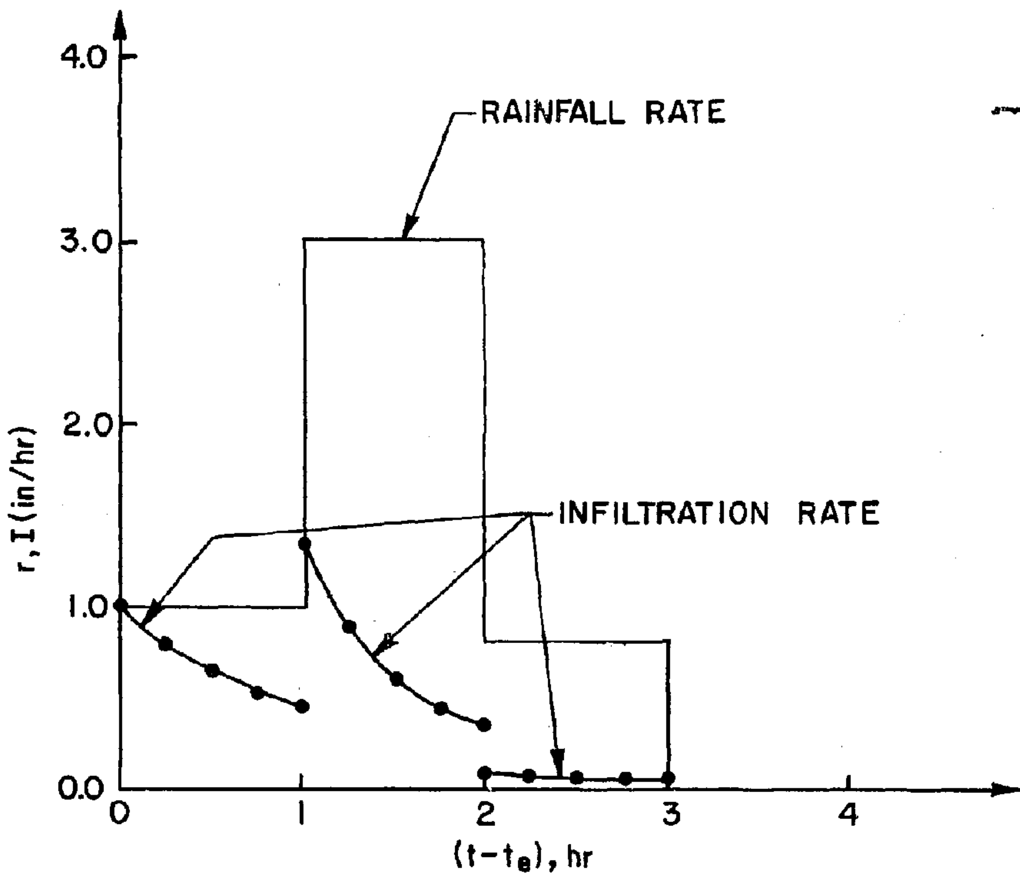

Figure 3. Example of discontinuous infiltration rate, computed with Eq. (1.2.6). (1 inch = 25.4 mm)

If the SCS infiltration rate behaves in a nonphysical manner, the implication naturally follows that the excess rainfall rate is also unrealistic. This is borne out by taking the derivative with respect to time of Eq. (1.1.1):

$$\frac{dP_e}{dt} = r_e = \frac{d}{dt}\left[\frac{(P-I_a)^2}{P-I_a+S}\right]$$

Again, applying the rules for differentiation of a fraction, we have:

$$r_e = \frac{dP_e}{dt} = \frac{d}{dt}\left(\frac{u}{v}\right) = \frac{v\frac{du}{dt}-u\frac{dv}{dt}}{v^2} = \frac{(P-I_a+S)(P-I_a)2r-(P-I_a)^2 r}{(P-I_a+S)^2}$$

Reducing:

$$r_e = \frac{(P-I_a)(P+2S-I_a)r}{(P-I_a+S)^2} \tag{1.2.7}$$

Eq. (1.2.7) suggests that, once ponding has been achieved, there will be excess rainfall as long as there is any rainfall at all, no matter how small the value of r. The implication is that a ponded condition is maintained throughout the rainfall event. In reality, this may not be the case at all.

In light of what Eqs. (1.2.6) and (1.2.7) tell us, it would appear that the SCS method has the potential for yielding misleading excess rainfall patterns. This can be important if the excess rainfall pattern is to be used, in conjunction with the SCS dimensionless unit hydrograph, to generate a design hydrograph for an ungaged watershed. One may even draw the conclusion that the SCS method is best applied only to storms of uniform rainfall intensity.

2. Estimation of Excess Rainfall by Infiltration Approach

2.1 Physical Infiltration Equations

Physical infiltration equations are those which portray the passage of water from surface to subsurface as a function of the hydraulic characteristics of the soil and the rainfall intensity. This is what distinguishes them from empirical infiltration equations whose variables do not explicitly represent any physical processes, but are instead calibrated according to observation data. An example of an empirical infiltration equation is that of Horton (Viessman et al., 1977, p. 71), which enjoys popular usage. The first infiltration equation derived with physical soil parameters as variables was that of Green and Ampt (1911), although a piston-type displacement by water and immediate ponding were assumed. Mein and Larson (1973) extended the Green and Ampt approach to compute the quantity infiltrated previous to the onset of runoff, thereafter applying the Green and Ampt equation. This approach, however, assumes a constant rainfall rate and also a piston displacement by water. Most recently, Morel-Seytoux (1978) derived equations which can accommodate variable rainfall intensities and include the refinement of accounting for the viscous flow of air without the assumption of piston displacement by water.

The infiltration approach employed in this study lies somewhere between that of Mein and Larson and the equations of Morel-Seytoux which account for the viscous flow of air.

Figure 4 illustrates the general paradigm by which physical infiltration equations abstract rainfall from a given event. There is an initial period in which all incident rainfall infiltrates. This period ends when the soil at the surface becomes saturated and ponding occurs. Following ponding, the infiltration capacity of the soil

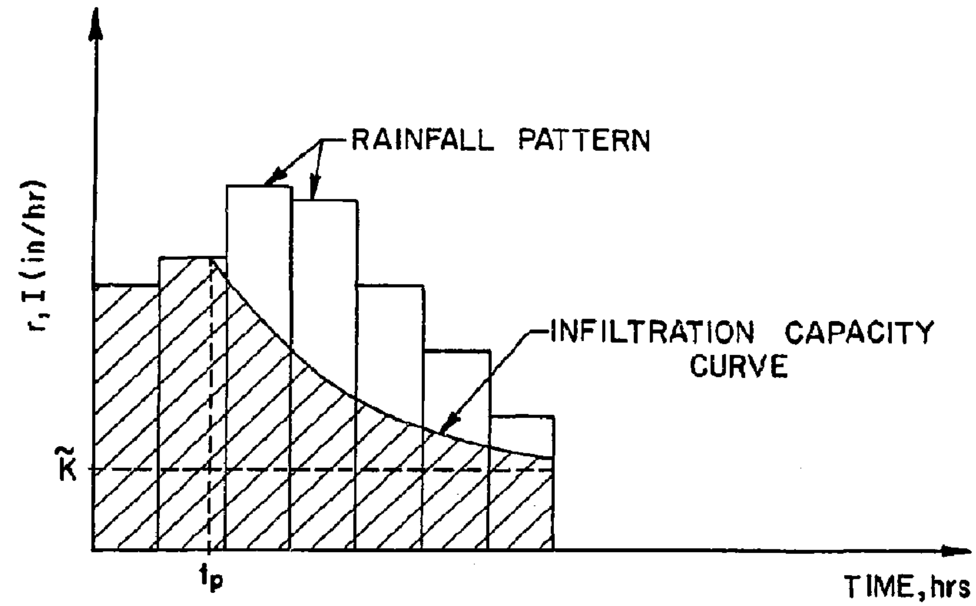

Figure 4. Abstraction of infiltration from a rainfall event by use of physically based equations. (1 inch = 25.4 mm)

follows a monotonically decreasing curve. This curve is asymptotic to $\tilde{K}$, the hydraulic conductivity of the soil under conditions of natural saturation (that is, when the water content, $\tilde{\theta}$, is somewhat less than the porosity, ϕ, due to inevitably trapped air).

In practice, then, it takes two equations to describe the infiltration process: the first is used to compute ponding time, and the second defines the monotonically decreasing infiltration capacity curve for times thereafter.

For the case of assumed constant rainfall, the Mein and Larson ponding time formula is:

$$t_p = \frac{H_f(\tilde{\theta}-\theta_i)}{r(\frac{r}{\tilde{K}} - 1)} \tag{2.1.1}$$

where $\tilde{\theta}$ is the water content at natural saturation, θ_i is the initial water content, r is the rainfall rate, $\tilde{K}$ is the hydraulic conductivity of the soil at natural saturation, H_f is the effective capillary drive (or wetting front suction), and t_p is the ponding time.

For convenience, one may define the composite terms:

$$S_f = (\tilde{\theta}-\theta_i)\ H_f,$$

where S_f is referred to as the *storage suction factor* and:

$$r^* = \frac{r}{\tilde{K}}$$

which is simply the rainfall rate normalized with respect to the hydraulic conductivity. Substituting these into the equation for ponding time, one arrives at the formula:

$$t_p = \frac{S_f}{r(r^*-1)} \tag{2.1.2}$$

For post-ponding infiltration for the case of constant rainfall, Morel-Seytoux has derived a generalized form of Philip's equation:

$$W = W_p + S(\theta_i)\left(\frac{r^*}{r^*-1}\right) \left[\sqrt{t-t_p + \frac{t_p}{2}\left(\frac{r^*}{r^*-1}\right)^3} - \sqrt{\frac{t_p}{2}\left(\frac{r^*}{r^*-1}\right)^3}\,\right] + \tilde{K}(t-t_p) \tag{2.1.3}$$

where t is any time between t_p and t_D, the time of duration of the rainfall; W_p is equal to rt_p, the quantity infiltrated up to ponding time; $S(\theta_i)$ is equal to $\sqrt{2\tilde{K}S_f}$, the Green and Ampt sorptivity; and W is the cumulative depth of infiltration at time t.

The derivation of Eq. (2.1.3) stems from the well known fact (Morel-Seytoux, 1979) that for short times infiltration capacity varies inversely with the square root of time, and also from the requirement that at ponding time the rainfall rate and the infiltration rate are the same.

The analogous equations for the variable rainfall case are somewhat more complicated, yet only involve the same unknowns as those encountered in the constant rainfall case. The equation for finding ponding time takes the form:

$$t_p = t_{j-1} + \frac{1}{r_j}\left[\frac{S_f}{r_j^*-1} - \sum_{v=1}^{j-1} r_v\,(t_v - t_{v-1})\right] . \tag{2.1.4}$$

where j is the index of the time step of consideration and v is the index over which all rainfall occurring previous to t_j is summed. The meaning of the symbols is illustrated on Figure 5. Eq. (2.1.3) must be applied iteratively until the computed t_p falls within time step j. Post-ponding infiltration is computed by the expression:

$$W = W_p + S(W_p,\theta_i)\,\{\sqrt{t-t_p + B} - \sqrt{B}\} + \tilde{K}(t-t_p) \tag{2.1.5}$$

where:

$$S(W_p,\theta_i) = \sqrt{\frac{2\tilde{K}(S_f+W_p)^2}{S_f}}$$

is the rainfall sorptivity,

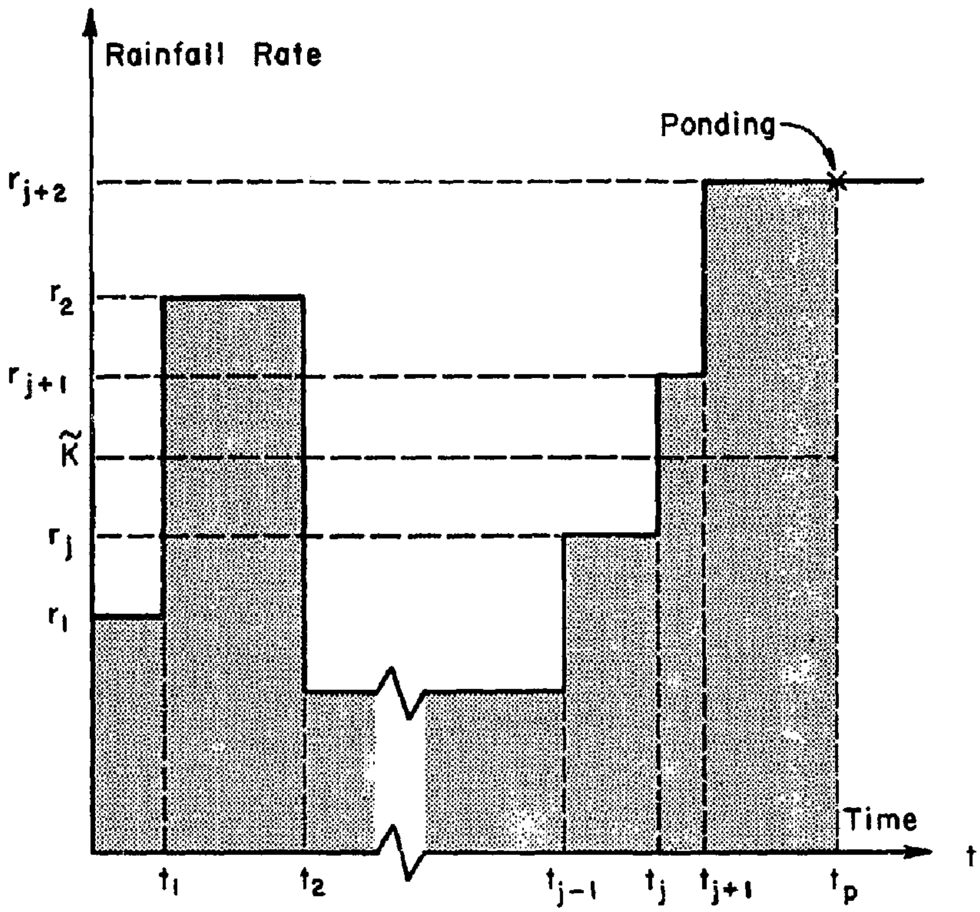

Figure 5. Illustration of terms appearing in Eq. (2.1.4).

$$B = \frac{1}{2} \frac{(S_f+W_p)^2}{\tilde{K}\, S_f(\frac{r_p}{\tilde{K}} - 1)^2}$$

and r_p is the rainfall intensity which produced ponding. The parameter B results from the requirement that at ponding time, the rainfall rate (r_p) is equal to the infiltration rate.

Eq. (2.1.5) is the expression for the cumulative depth of infiltration at some time t after t_p. The expression for the instantaneous infiltration rate, given a ponded surface condition, for some time t after t_p is:

$$I = \frac{1}{2} S(W_p,\theta_i) \frac{1}{\sqrt{t - t_p + B}} + \tilde{K} \tag{2.1.6}$$

The terms in Eq. (2.1.6) have the same definitions as they do in Eq. (2.1.5).

2.2 Advantages and Disadvantages of the Infiltration Approach

The advantages of the infiltration approach lie with its more realistic portrayal of a local runoff event. For example, consider the initial abstraction of the SCS approach, which is fixed as 20% of the total watershed storage. Although this can be revised due to antecedent moisture conditions (AMC), it can only be done in a very limited manner. There are only three distinct possible values of I_a for a given watershed, although in reality it may experience an I_a of magnitude anywhere between those for AMC I and AMC III. The infiltration approach offers much greater flexibility in this regard because the term $(\tilde{\theta}-\theta_i)$ can handle continuous variation in initial soil moisture and, more importantly, the computation of ponding time explicitly shows the influence of rainfall intensity. Pre-event influences on runoff are better represented than with the SCS method, and the role of rainfall intensity during the event operates as well. The SCS method never has rainfall intensity come into play. The infiltration approach offers a model for abstraction of rainfall from the beginning of an event more consonant with field and laboratory observations.

Post-ponding by the infiltration approach also rests on firmer theoretical ground than the SCS method. Since an infiltration capacity curve is established, this defines the maximum rate at which water may enter the soil. If the rainfall rate falls to a value below this capacity curve, no runoff occurs. By contrast, it was shown in Eq. (1.2.7) that the SCS method will predict excess rainfall as long as precipitation occurs.

The major disadvantage to the use of an infiltration approach to predict runoff is that one must have estimates of soil parameters like $\tilde{\theta}$, $\tilde{K}$, H_f for a watershed if the equations are to be implemented. Such information is not readily available in any reference, and so one must use rainfall-runoff records to calibrate physical parameters for a watershed. This automatically precludes the use of an infiltration approach with an ungaged watershed, unless one is lucky enough to have information from a nearby similar catchment.

II. THE CORRESPONDENCE BETWEEN CURVE NUMBER AND HYDRAULIC SOIL PARAMETERS

3. Basis of a Correspondence

3.1 Soil Parameters to be Correlated with CN

An imposing number of unknown soil parameters appear in the equations introduced in Section 2.1. However, on closer inspection one discovers that one needs only two parameters to characterize the infiltration characteristics of a watershed. For example, $\tilde{\theta}$, θ_i, and H_f

appear on face to be independent soil descriptors. However, they always appear together and their joint influence on runoff can be expressed by the storage suction factor:

$$S_f = (\tilde{\theta}-\theta_i)H_f$$

The only other soil parameter needed is $\tilde{K}$, the hydraulic conductivity at natural saturation. All other terms in the equations can be found using $\tilde{K}$ and S_f and the storm time and intensity characteristics, e.g., $S(\theta_i)$, t_p, W_p, r^*, $S(W_p,\theta_i)$ and B. The problem of finding a correspondence boils down to identifying a CN given a certain parameter pair $(\tilde{K}, S_f)$.

3.2 Parameter Equivalence for a Single Event

If one wishes to define an equivalence between a given $(\tilde{K}, S_f)$ pair and some curve number, a reasonable criterion would be the requirement that the same quantity of water be abstracted from a storm whether the computations are done by SCS method or by infiltration approach. In addition, it was pointed out in Section 1.2 that the SCS method gives its most realistic infiltration rate for a constant rainfall event, so it makes sense to use one as the basis of a CN - $(\tilde{K}, S_f)$ equivalence.

Figure 6 illustrates a constant rainfall event and the manner by which the two respective approaches abstract rainfall. The total abstraction by SCS method is given by the expression:

$$RET + W = I_a + \frac{S(P-I_a)}{P-I_a+S} \tag{3.2.1}$$

This is the same as Eq. (1.2.5) except that retention (RET) due to interception and depression storage has been added to both sides. The total abstraction by infiltration approach can be written as:

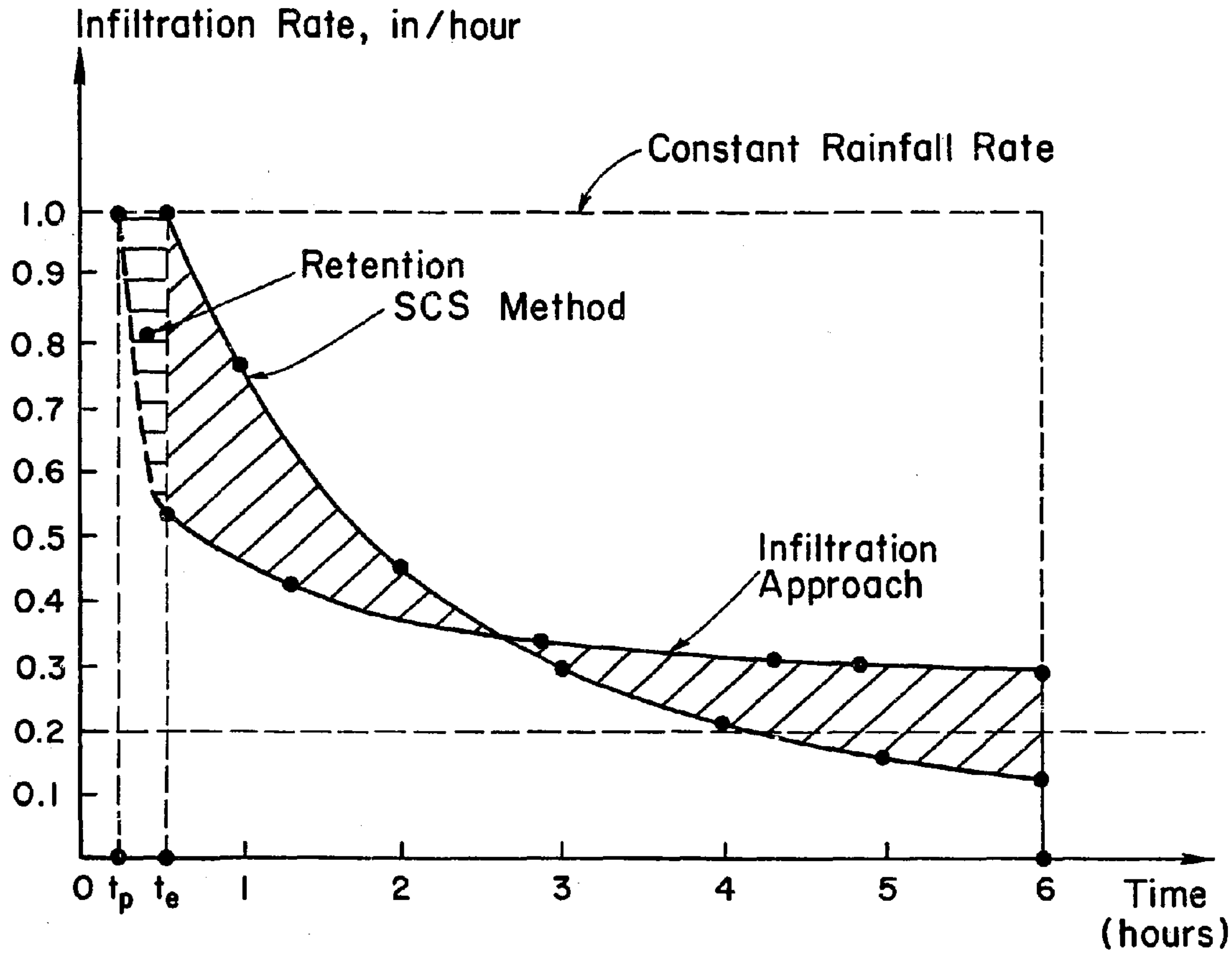

Figure 6. Comparison of infiltration rates by the SCS method and the infiltration approach. (1 inch = 25.4 mm)

$$RET + W = RET + \int_0^{t_D} I \, d\tau = RET + W_p$$

$$+ S(\theta_i) \left(\frac{r^*}{r^*-1}\right) \left[\sqrt{t_D - t_p + \frac{t_p}{2} \left(\frac{r^*}{r^*-1}\right)^3} - \sqrt{\frac{t_p}{2} \left(\frac{r^*}{r^*-1}\right)^3}\,\right] + \tilde{K}(t_D - t_p) \qquad (3.2.2)$$

where t_D is the storm duration, I is the infiltration rate, and all other symbols have been previously defined.

If Eqs. (3.2.1) and (3.2.2) are set equal to one another, the condition for equal total abstraction by both methods has been set. Expressing symbolically this equality, one obtains:

$$RET + W_p + S(\theta_i)\left(\frac{r^*}{r^*-1}\right) \left\{\sqrt{t_D - t_p + \frac{t_p}{2} \left(\frac{r^*}{r^*-1}\right)^3} - \sqrt{\frac{t_p}{2} \left(\frac{r^*}{r^*-1}\right)^3}\,\right\} + \tilde{K}(t_D - t_p)$$

$$= I_a + \frac{S(P-I_a)}{P-I_a+S} \qquad (3.2.3)$$

The solution of Eq. (3.2.3) for S requires one reasonable assumption, namely that AMC II and field capacity soil moisture represent the same watershed wetness condition. In fact, field capacity soil moisture content is a central value between saturation and wilting point, and AMC II is defined simply as the condition of average watershed wetness, so such an assumption is probably not too risky.

The influence of interception and depression storage, lumped together in the retention term, must also be dealt with. If a value is available for a certain watershed type of interest, this could be used. On the other hand assuming a value of retention equal to 0.1 inch (2.54 mm) for all cases would probably be fair, based on the values reported in the literature (Musgrave and Holtan, in Chow, pp. 12-25, Table 12-5; USDA Technical Bulletin No. 1518, p. 12; Viessman et al., pp. 63 and 67).

If one assumes a specific event of cumulative depth P, duration t_D and rainfall intensity $r = (P/t_D)$, then the only unknowns left in Eq. (3.2.3) are I_a and S. One is at first tempted to make use of the SCS relation:

$$I_a = 0.2S$$

but a glance at Figure 1 should be enough to decide against using this very rough approximation. Instead, the initial abstraction may be solved for first by writing Eq. (3.2.3) for the time interval from $t = 0$ to $t = t_e$, and making the substitution $t_e = (I_a/r)$. This equality will be:

$$RET + W_p + S(\theta_i)(\frac{r*}{r*-1}) \{\sqrt{\frac{I_a}{r} - t_p + \frac{t_p}{2} (\frac{r*}{r*-1})^3} - \sqrt{\frac{t_p}{2} (\frac{r*}{r*-1})^3}\}$$

$$+ \tilde{K} (\frac{I_a}{r} - t_p) = I_a \qquad (3.2.4)$$

It is nonlinear with a single unknown, I_a. It may be solved in an iterative fashion with a suitable initial approximation for I_a, such as $W_p + 1$. One may define the function F such that:

$$F = RET + W_p + S(\theta_i)(\frac{r*}{r*-1})\{\sqrt{\frac{I_a}{r} - t_p + \frac{t_p}{2} (\frac{r*}{r*-1})^3} - \sqrt{\frac{t_p}{2}(\frac{r*}{r*-1})^3}\}$$

$$+ \tilde{K} (\frac{I_a}{r} - t_p) - I_a \qquad (3.2.5)$$

The proper value of I_a is the one that makes $F = 0$. The iterative solution is found by solving for the correction to I_a, ΔI_a, until it is of insignificant size:

$$F = 0 = (F)_o + (\frac{dF}{dI_a})_o \Delta I_a \qquad (3.2.6)$$

The subscript o indicates that the function has been evaluated at the previous approximation for I_a. (See Wolf, 1974, p. 23).

Once a value for I_a has been reached, the only remaining unknown is S. Substituting into Eq. (3.2.3), the value of S is readily obtained. And since S is merely a transform of CN, an equivalence has been established between the $(\tilde{K}, S_f)$ pair, selected a priori, and the curve number ultimately solved for.

One comment is in order at this point. Just as CN is a single parameter describing the runoff characteristics of an entire watershed, the equivalent $(\tilde{K}, S_f)$ are likewise *lumped* parameters which represent the *overall average* infiltration characteristics of the watershed. If an infiltrometer test were run at some specific spot in the catchment, it is unlikely that the observed hydraulic conductivity would match that found to be equivalent (along with S_f) to the CN of the watershed.

3.3 Parameter Equivalence for a Range of Events

The preceding section showed how a CN-$(\tilde{K}, S_f)$ equivalence can be arrived at for a single event. However, just as the SCS did not develop a curve number for a soil-cover complex by observing a single rainfall-runoff event, a true CN-$(\tilde{K}, S_f)$ correspondence must be based on calculations for storms representing a range of depths, durations and intensities. Because of the prominent role of the rainfall rate, r, in computing ponding time and post-ponding infiltration, the S found using one storm will not be the same as that found for another storm of different magnitude, even if the same $\tilde{K}$ and S_f are used in both cases. Therefore, one must find the best value of S over a range of representative storm values.

Assuming a representative set of rainfall events can be defined (see discussion in section on data sources employed in this study) a best value of S for a chosen pair of $\tilde{K}$ and S_f can be found in the following manner. Using the same assumptions made with respect to retention and field capacity in section 3.2, a value of I_a may be found by Eq. (3.2.4) for each rainfall event. Using these values, one may next write an equation for each event with a single unknown, S. Applying the method of least squares, a best fit value of S can be computed over all events. The following is a mathematical outline of the least squares solution for S. First define, for shorthand's sake,

$$C = RET + \int_0^{t_D} I d\tau$$

This is the total abstraction by infiltration approach. For each event, the difference from a perfect match of abstracted quantities is the residual, ρ:

$$\rho = I_a + \frac{S(P-I_a)}{P-I_a+S} - C$$

Written in common denominator form the expression for the residual becomes:

$$\rho = \frac{S(I_a+P_d-C)+P_d(I_a-C)}{P_d + S}$$

or

$$\rho = \frac{a\ S + b\ P_d}{P_d + S} \qquad (3.3.2)$$

where

$$P_d = P-I_a$$
$$a = (I_a+P_d-C)$$
$$b = (I_a-C)$$

The quantities a and b are readily evaluated for all events. The sum of the squares of the residuals, for N events, is written as

$$\sum_{i=1}^{N} \rho_i^2 = \sum_{i=1}^{N} \left(\frac{a_i S + b_i P_{d_i}}{P_{d_i} + S}\right)^2 \qquad (3.3.3)$$

To minimize the sum of the squared residuals, the derivative with respect to the unknown, S, is taken and set equal to zero. The value of S satisfying this equation is the least squares value of S.

$$\frac{d}{dS}\left(\sum_{i=1}^{N} \rho_i^2\right) = \sum_{i=1}^{N} \frac{d}{dS}(\rho_i^2) = \sum_{i=1}^{N} \frac{d}{dS} \left(\frac{a_i S + b_i P_{d_i}}{P_{d_i} + S}\right)^2 = 0$$

Applying the rules of differentiation, one obtains:

$$\sum_{i=1}^{N} \frac{S(a_i^2 P_{d_i} - a_i b_i P_{d_i}) + a_i b_i P_{d_i}^2 - b_i^2 P_{d_i}^2}{(P_{d_i} + S)^3} = 0 \qquad (3.3.4)$$

Eq. (3.3.4) may be written more compactly if one defines the terms A_i and B_i such that:

$$A_i = (a_i^2 P_{d_i} - a_i b_i P_{d_i}) = a_i (a_i - b_i) P_{d_i}$$

$$B_i = (a_i b_i P_{d_i}^2 - b_i^2 P_{d_i}) = b_i (a_i - b_i) P_{d_i}^2$$

Naming the resulting compact expression as function G yields:

$$G = \sum_{i=1}^{N} \frac{SA_i + B_i}{(P_{d_i} + S)^3} = 0 \qquad (3.3.5)$$

Eq. (3.3.5) may now be manipulated to yield an expression explicit in S. However, an iterative solution for S may be achieved if one begins with a reasonable first guess at the value S and successively solves for a correction ΔS:

$$G = 0 = (G)_o + \left(\frac{dG}{dS}\right)_o \Delta S \qquad (3.3.6)$$

The subscript o in Eq. (3.3.6) indicates that the function so denoted has been evaluated at the initial approximation for S. The expression for the first derivative of G with respect to the unknown, S, is:

$$\frac{dG}{dS} = \sum_{i=1}^{N} \left[\frac{A_i P_{d_i} - 2 SA_i - 3 B_i}{(P_{d_i} + S)^4} \right] \tag{3.3.7}$$

The quantity ΔS in Eq. (3.3.6) is solved for and added to the previous estimate of S. This is done until the magnitude of the correction ΔS is insignificant.

If a $(\tilde{K}, S_f)$ pair can be identified for each major soil type from sand to clay, the preceding least squares method can be used to compute an equivalent S. Any S is readily transformed into a CN, so the resulting set of CN - $(\tilde{K}, S_f)$ equivalences can be used as the skeleton of a complete table of correspondence for values of CN from 1 to 100.

A computer program, named SCSEXT, was written to perform the necessary calculations to find a least-squares S for a given $(\tilde{K}, S_f)$ pair and a range of rainfall events. In addition to performing the operations described in this section, the program includes checks to ensure that events are not considered where the hydraulic conductivity is greater than the rainfall rate, nor that the time to the end of initial abstraction exceeds the storm duration time. A brief description of SCSEXT, along with a listing, is provided in the appendix of this report.

4. Data Required for Establishment of a CN - $(\tilde{K}, S_f)$ Equivalence

4.1 Soil Data Sources

In order to define a set of CN - $(\tilde{K}, S_f)$ equivalences in the manner outlined in Section 3.3, and implemented in program SCSEXT, one needs as a starting point a set of $(\tilde{K}, S_f)$ values representative of the major soil textural classes. Such a set was put together from both published and unpublished reports of investigators of soil moisture properties.

Since it was desired to establish the CN - ($\tilde{K}$, S_f) correspondence for conditions of field capacity soil moisture conditions (AMC II), a natural starting point was to find values of the moisture deficit, ($\tilde{\theta}-\theta_{fc}$), for soil textural classes. (Recall the definition of the storage suction factor as $S_f = (\tilde{\theta}-\theta_i)H_f$). The values employed in this study were drawn from the USDA-ARS Technical Bulletin No. 1518 (1975), p. 5.

Estimates of H_f, the effective capillary drive (or wetting front suction) for soil texture classes were reported by Brakensiek, Engleman, and Rawls (1979) in a recent SCS-AR Cooperative Research Progress Report. In their work relating initial abstraction to soil infiltration, they made their estimates of H_f using published soil moisture vs. capillary pressure data (Holtan et al., 1968; Rawls et al., 1976) as a starting point. They first estimated the Brooks and Corey constants (1964), ψ_b and λ, using the function:

$$S_e = (\psi_b/\psi)^\lambda \tag{4.1.1}$$

where $S_e = \frac{\theta-\theta_r}{\phi-\theta_r}$, is the effective saturation; θ is the soil water content; θ_r is the residual soil water content; ϕ is the soil porosity; ψ is the capillary pressure, [L]; ψ_b is the bubbling, or air entry, pressure, [L]; and λ is the pore-size distribution index.

The best value of θ_r was obtained by systematically varying it until the highest correlation between S_e and ψ was found. Then, a linear form of Eq. (4.1.1) was obtained by taking the logarithm of both sides. This form of the equation was used to find least squares estimates of ψ_b and λ. With these values, an equation derived by Brakensiek (1977) was then used to estimate the effective capillary drive, H_f. That equation is:

$$H_f = \frac{\eta}{\eta-1} \frac{\psi_b}{2} \tag{4.1.2}$$

where

$$\eta = 3 + 2\,\lambda$$

The Brakensiek, Engleman, and Rawls progress report also cited values of hydraulic conductivity at natural saturation, $\tilde{K}$, as they were reported by Strait, Saxton and Papendick (1978) in an unpublished release.

The values of all soil parameters used in establishing the CN -($\tilde{K}$, S_f) correspondence are displayed in Table 6.

Table 6. Hydraulic parameters of major soil textural classes. (1 inch = 25.4 mm)

Soil #	Soil Textural Class	H_f(in)[1]	$(\tilde{\theta}-\theta_{fc})$[2]	$\tilde{K}$(in/hr)[3]	$S_f = (\tilde{\theta}-\theta_{fc})H_f$
1	clay	9.40	0.07	0.013	0.66
2	silty clay	11.88	0.09	0.02	1.07
3	sandy clay	6.05	0.12	0.03	0.73
4	silty clay loam	11.20	0.08	0.04	0.90
5	clay loam	8.12	0.13	0.04	1.06
6	sandy clay loam	5.55	0.13	0.06	0.72
7	loam	6.95	0.14	0.13	0.97
8	silt loam	10.11	0.11	0.26	1.11
9	sandy loam	5.55	0.19	0.43	1.05
10	loamy sand	3.90	0.27	1.18	1.05

[1]Estimates from Brakensiek, Engleman, and Rawls (1979), SCS-AR Cooperative Research Progress Report, "Relating Initial Abstraction, I_a, to Soil Infiltration."
[2]Values reported in USDA-ARS Technical Bulletin No. 1518, 1975, p. 5.
[3]Values reported by Strait, Saxton and Papendick (1978) in an unpublished release cited by Brakensiek et al in [1].

4.2 Rainfall Data Sources

The Soil Conservation Service does not report the rainfall-runoff events used to develop its curve numbers in NEH-4, nor does it give any reference to where these records may be found. The SCS does state that its curve numbers were determined by plotting rainfall depth versus runoff depth for the event producing the annual maximum runoff event each year in its experimental watersheds. Since the curve numbers were derived in the early to mid 1950's, the period of record for the experimental watersheds was presumably on the order of fifteen to twenty years. For these reasons it was decided to use rainfall frequency maps of depth and duration for storms with return periods in the range of 1 to 20 years.

Although it is true, in the field, that a maximum runoff event is rarely associated with the annual maximum rainfall event, this is due to the influence of variable soil moisture conditions prevailing through the year. It is possible that one inch of rain with wet antecedent conditions could produce more runoff than three inches of rain would if it fell on a very dry watershed. However, for purposes of establishing the $CN - (\tilde{K}, S_f)$ correspondence, field capacity soil moisture is assumed for all events. Therefore a set of rainfall events with return periods from 1 to 20 years should offer a reasonable set of inputs to generate runoff events of the same order of magnitude as those which might actually be observed in a twenty year period of record.

The principal rainfall data reference used in this study was Weather Bureau Technical Paper No. 40, a rainfall frequency atlas of the United States. An example of the type of map found in this atlas is shown in Figure 7. An additional source employed was a similar set of maps issued by the Denver Regional Council of Governments. Figure 8 shows an example of one of these. These references were used to make up data sets for return periods of 1, 5, 10, 15, and 20 years and durations of 3, 6, 12, and 24 hours. Probability paper like that in Figure 9 was

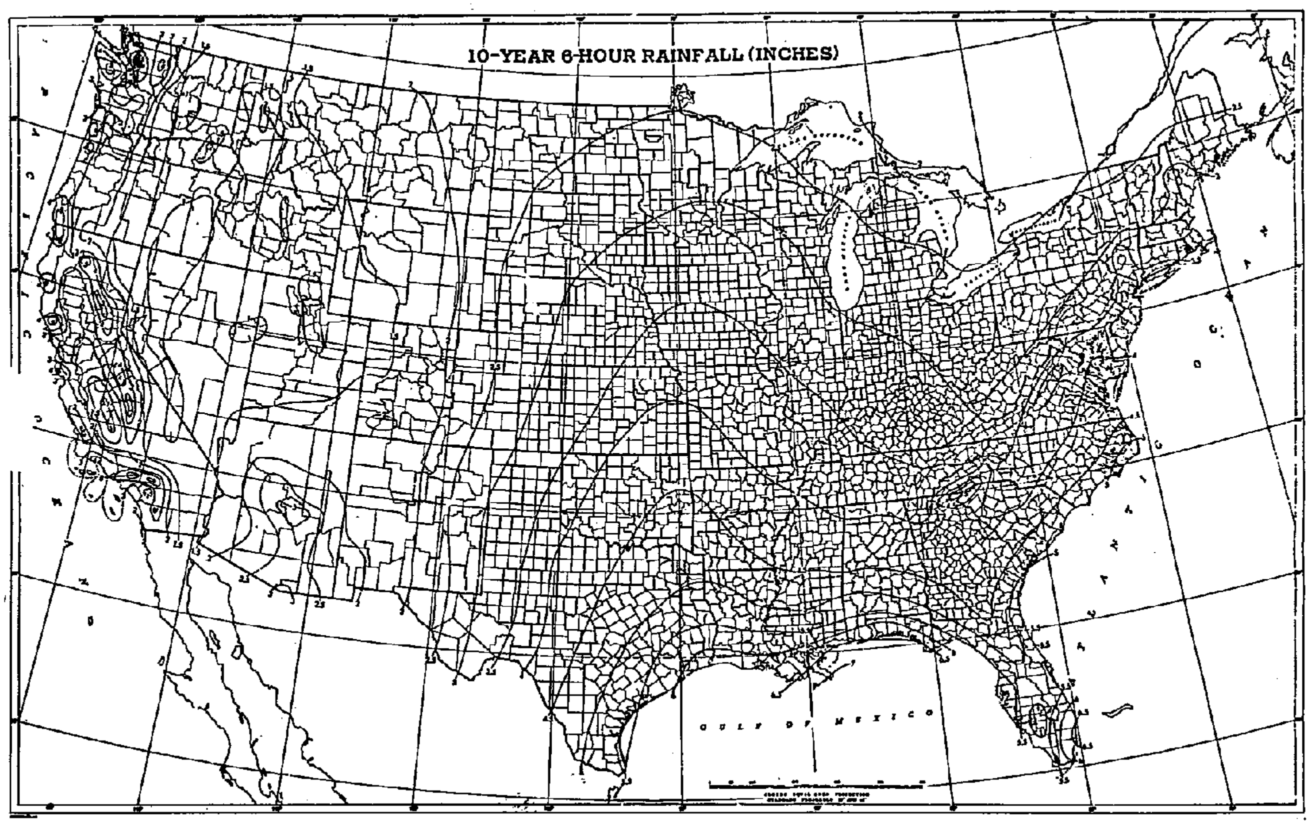

Figure 7. Example of rainfall frequency maps found in T.P. 40. (1 inch = 25.4 mm)

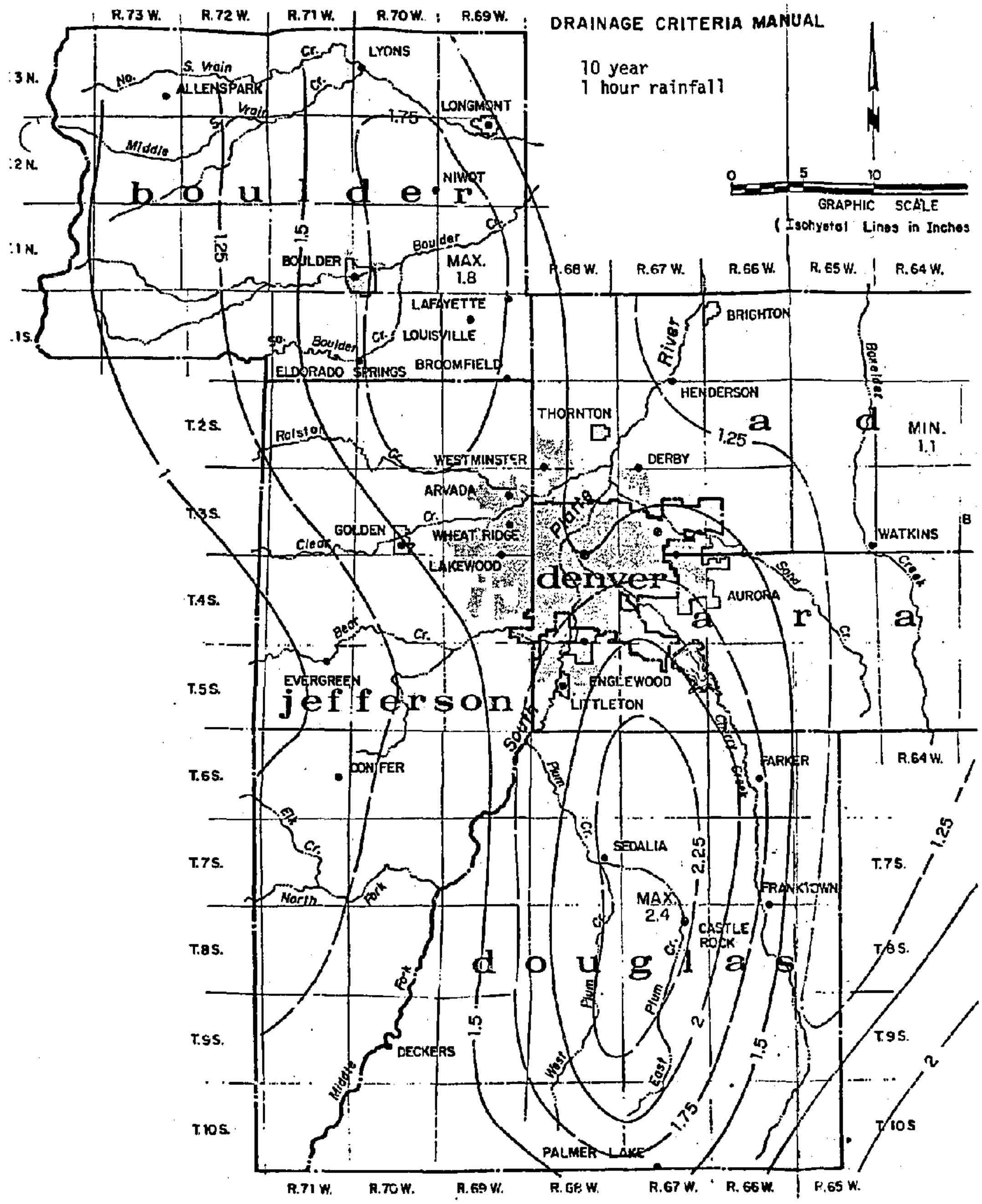

Figure 8. Example of a rainfall frequency map issued by the Denver Regional Council of Governments. (1 inch = 25.4 mm)

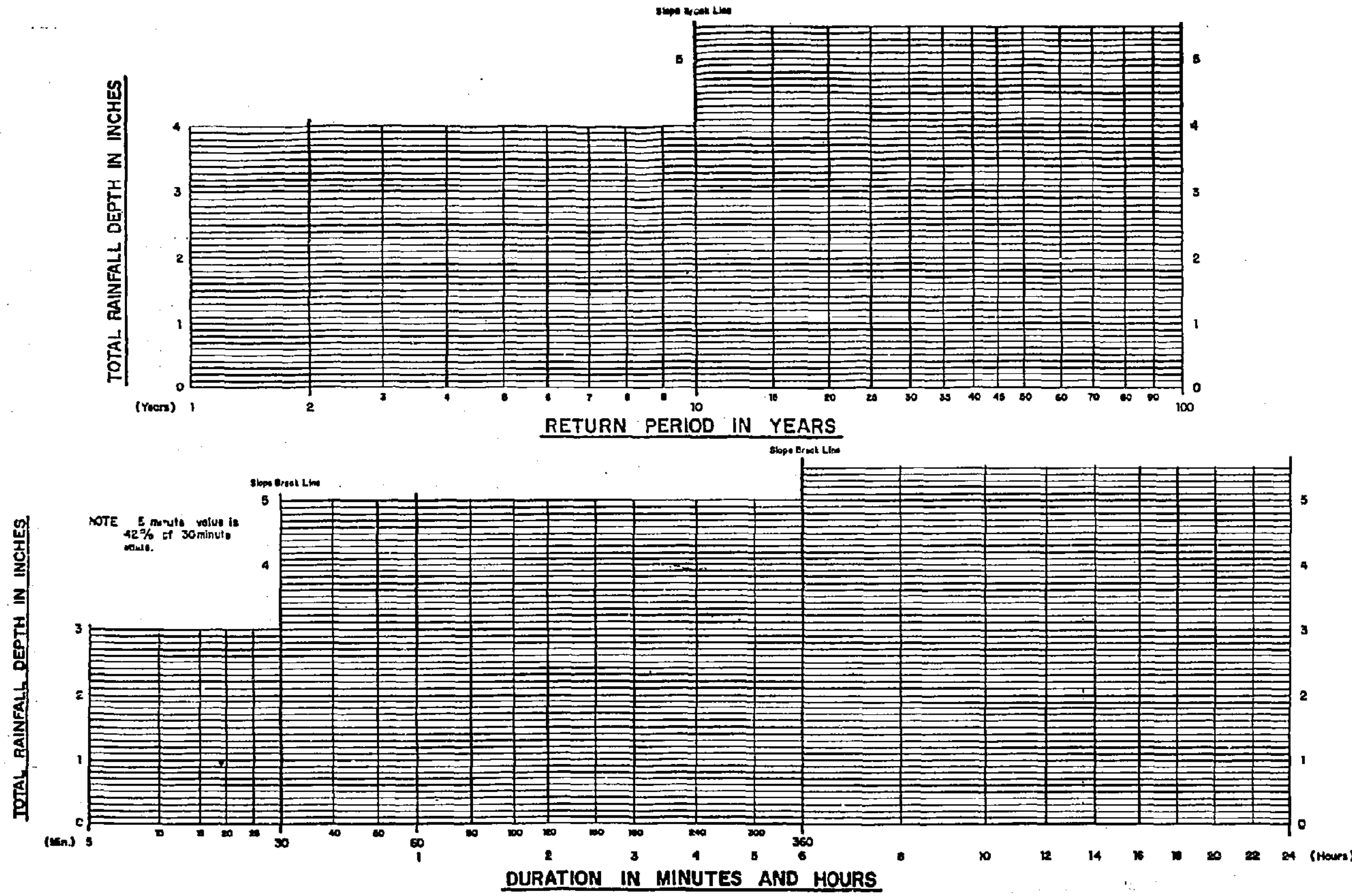

Figure 9. Example of probability paper used in preparation of rainfall data sets.
(1 inch = 25.4 mm)

used to interpolate depths for durations and frequencies not shown explicitly on a map. Because of the sensitivity of the infiltration equations to rainfall intensity, data sets were made up from a variety of locations around the U.S. to assess the influence of this parameter on the CN - ($\tilde{K}$, S_f) correspondences obtained. The locations chosen were Central Oklahoma; Upstate New York; Denver, Colorado; and Miami, Florida. They were chosen to offer a sampling of the range of rainfall intensities likely to be encountered throughout the United States. Tables 7-10 present the data sets.

5. Analysis of CN - ($\tilde{K}$, S_f) Correspondence Results

5.1 Results Obtained with Program SCSEXT

Using program SCSEXT and the data presented in Section 4, sets of CN - ($\tilde{K}$, S_f) equivalences were computed. The results are presented in Table 11. Since the computer program does not compute runoff for events where the rainfall rate is less than $\tilde{K}$, nor when the time of duration is less than the time to end of initial abstraction, a problem was encountered when using the parameters of soil classes 7 through 10. For these textural classes, the rainfall data from Oklahoma, New York and Colorado was not intense enough to produce runoff in the majority of cases. For this reason, the Miami data set was drawn up. Study of the maps in T.P. 40 indicated that in nearly every case, for a given return period and duration, the Miami region had the greatest depth of rain in the U.S. Since rainfall intensities were arrived at by simply dividing cumulative depth by storm duration, the Miami data set had the greatest values. Thus, even for short return periods, the Miami data were capable of generating runoff for soil types with large values of hydraulic conductivity. Of the twenty events in this set, a reasonable

Table 7. Rainfall data for Central Oklahoma, from Weather Bureau Technical Paper No. 40. (1 inch = 25.4 mm)

Central Oklahoma			
Return Period (yr)	Depth (in)	Duration (hr)	Intensity (in/hr)
1	2.88	24	0.12
5	4.56	24	0.19
10	5.52	24	0.23
15	6.00	24	0.25
20	6.24	24	0.26
1	2.76	12	0.23
5	4.08	12	0.34
10	5.04	12	0.42
15	5.40	12	0.45
20	5.76	12	0.48
1	2.22	6	0.37
5	3.48	6	0.58
10	4.20	6	0.70
15	4.44	6	0.74
20	4.80	6	0.80
1	1.80	3	0.60
5	2.94	3	0.98
10	3.60	3	1.20
15	3.90	3	1.30
20	4.11	3	1.37

Table 8. Rainfall data for Upstate New York, from Weather Bureau Technical Paper No. 40. (1 inch = 25.4 mm)

Upstate New York			
Return Period (yr)	Depth (in)	Duration (hr)	Intensity (in/hr)
1	2.40	24	0.10
5	3.60	24	0.15
10	4.08	24	0.17
15	4.32	24	0.18
20	4.56	24	0.19
1	1.92	12	0.16
5	3.00	12	0.25
10	3.48	12	0.29
15	3.72	12	0.31
20	3.84	12	0.32
1	1.74	6	0.29
5	2.46	6	0.41
10	3.00	6	0.50
15	3.30	6	0.55
20	3.48	6	0.58
1	1.29	3	0.43
5	2.01	3	0.67
10	2.49	3	0.83
15	2.70	3	0.90
20	2.79	3	0.93

Table 9. Rainfall data for Denver, Colorado, from maps of the Denver Regional Council of Governments and Weather Bureau Technical Paper No. 40. (1 inch = 25.4 mm)

Denver, Colorado			
Return Period (yr)	Depth (in)	Duration (hr)	Intensity (in/hr)
1	1.20	24	0.05
5	2.16	24	0.09
10	2.88	24	0.12
15	3.12	24	0.13
20	3.36	24	0.14
1	1.20	12	0.10
5	2.04	12	0.17
10	2.64	12	0.22
15	2.76	12	0.23
20	2.88	12	0.24
1	1.08	6	0.18
5	1.68	6	0.28
10	2.28	6	0.38
15	2.46	6	0.41
20	2.58	6	0.43
1	0.84	3	0.28
5	1.50	3	0.50
10	1.74	3	0.58
15	2.10	3	0.70
20	2.19	3	0.73

Table 10. Rainfall data for Miami, Florida, from Weather Bureau Technical Paper No. 40. (1 inch = 25.4 mm)

Miami, Florida			
Return Period (yr)	Depth (in)	Duration (hr)	Intensity (in/hr)
1	4.56	24	0.19
5	7.92	24	0.33
10	9.12	24	0.38
15	10.08	24	0.42
20	10.80	24	0.45
1	4.08	12	0.34
5	6.72	12	0.56
10	8.04	12	0.67
15	8.52	12	0.71
20	8.88	12	0.74
1	3.48	6	0.58
5	5.58	6	0.93
10	6.48	6	1.08
15	7.08	6	1.18
20	7.62	6	1.27
1	3.00	3	1.00
5	4.59	3	1.53
10	5.19	3	1.73
15	5.70	3	1.90
20	6.00	3	2.00

Table 11. Curve numbers obtained for soil textural classes with rainfall data from Oklahoma, New York, Colorado and Florida. (1 inch = 25.4 mm)

Soil Class	K (in/hr)	S_{ffc} (in)	$S(\theta_{fc}) = \sqrt{2KS_f}$ (in/hr$^{\frac{1}{2}}$)	CN, Central Oklahoma	No. of events based upon	CN, Upstate New York	No. of events	CN, Denver, Colorado	No. of events	CN, Miami, Florida	No. of events
1 clay	0.013	0.66	0.131	94.77	20	94.69	20	94.82	20		
2 silty clay	0.02	1.07	0.207	91.60	20	91.35	20	91.64	19		
3 sandy clay	0.03	0.73	0.209	89.97	20	89.50	20	89.89	19		
4 silty clay loam	0.04	0.90	0.268	86.70	20	86.09	20	87.33	18		
5 clay loam	0.04	1.06	0.291	86.08	20	85.56	20	87.06	17		
6 sandy clay loam	0.06	0.72	0.294	82.71	20	82.02	19	86.17	16		
7 loam	0.13	0.97	0.502							67.06	19
8 silt loam	0.26	1.11	0.760							55.10	16
9 sandy loam	0.43	1.05	0.950							52.75	12
10 loamy sand	1.18	1.05	1.574							39.15	1

number produced runoff to be able to determine a CN for soils 7-9. For soil 10, loamy sand, the Miami rainfall produced only one runoff event and the computed CN was rejected.

5.2 Generalization of Results for All Curve Numbers

Using the specific CN - $(\tilde{K}, S_f)$ equivalences reported in Section 5.1 as a framework, one may develop regression equations to generalize these results for all CN. Figure 10 shows a plot of hydraulic conductivity, $\tilde{K}$, against curve number, CN. Figure 11 shows a similar plot of sorptivity at field capacity, $S(\theta_{fc})$ versus CN. Points with circles around them represent correspondences found with rainfall data from Central Oklahoma, Upstate New York, and Denver, Colorado. Points with squares about them are equivalences for soil textures with high hydraulic conductivity which could only be found with the very intense Miami rainfall data. The lines drawn in show the simple regression equations used to generalize these results. It was reasoned that $\tilde{K}$ must go to zero when CN = 100, because in this case all rainfall runs off. Therefore, the regressions for hydraulic conductivity and sorptivity were constrained to go to zero when CN = 100. The line for the points where CN < 57 on the $\tilde{K}$ - CN plot is simply that defined by the two Miami points with CN of 55.10 and 52.75. The point of intersection satisfies both equations used to fit the $\tilde{K}$ - CN plot.

Using the regression equations, a full table of correspondence (Table 12) was constructed to give an equivalent $(\tilde{K}, S_f)$ for each CN between 1 and 100. Starting with a CN, a value of $\tilde{K}$ is computed from the appropriate regression equation. Next, for the same CN, a sorptivity is calculated in a similar manner. The storage suction factor is then readily computed as $S_f = [S(\theta_{fc})]^2/[2\tilde{K}]$.

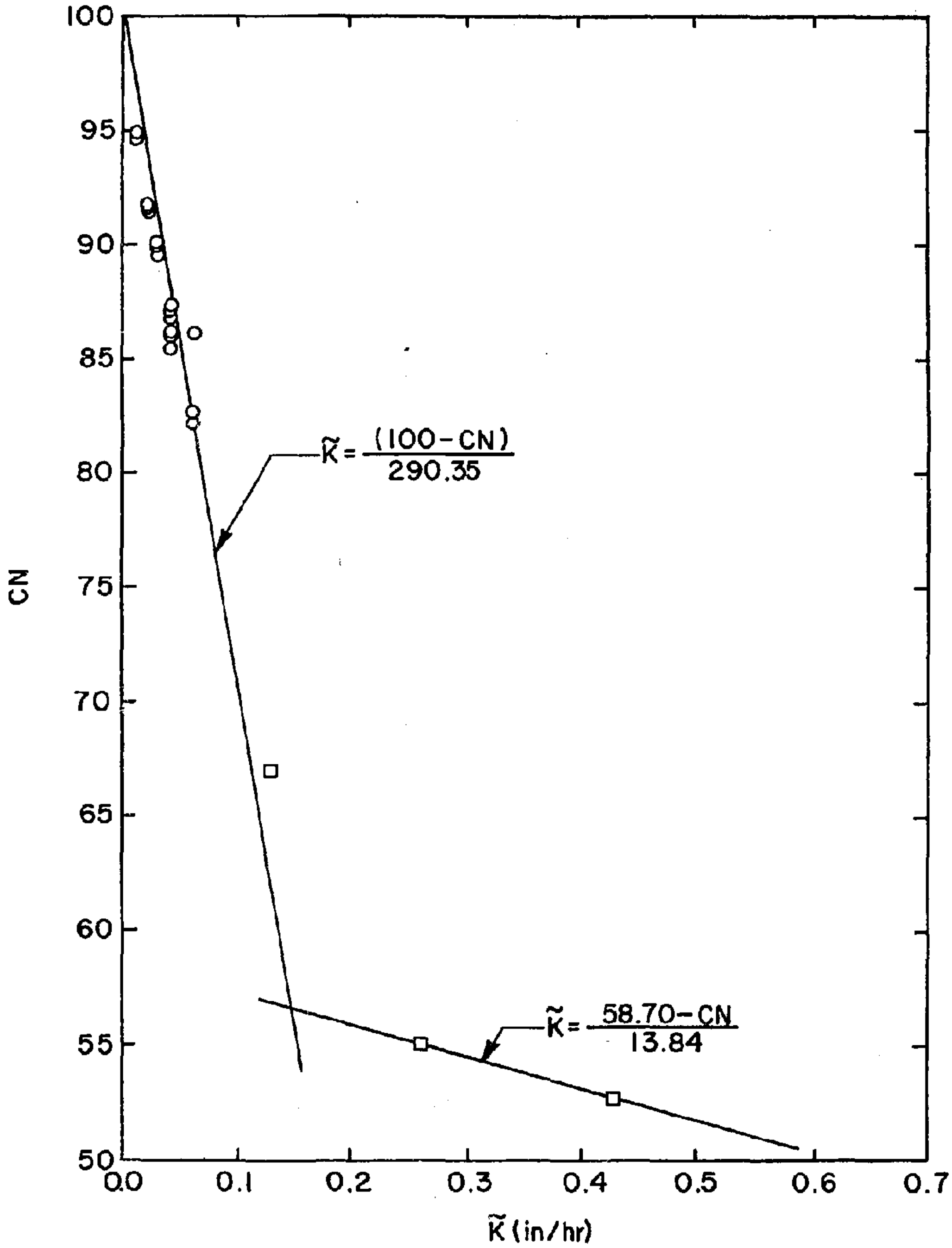

Figure 10. Plot of hydraulic conductivity versus curve number computed by SCSEXT.

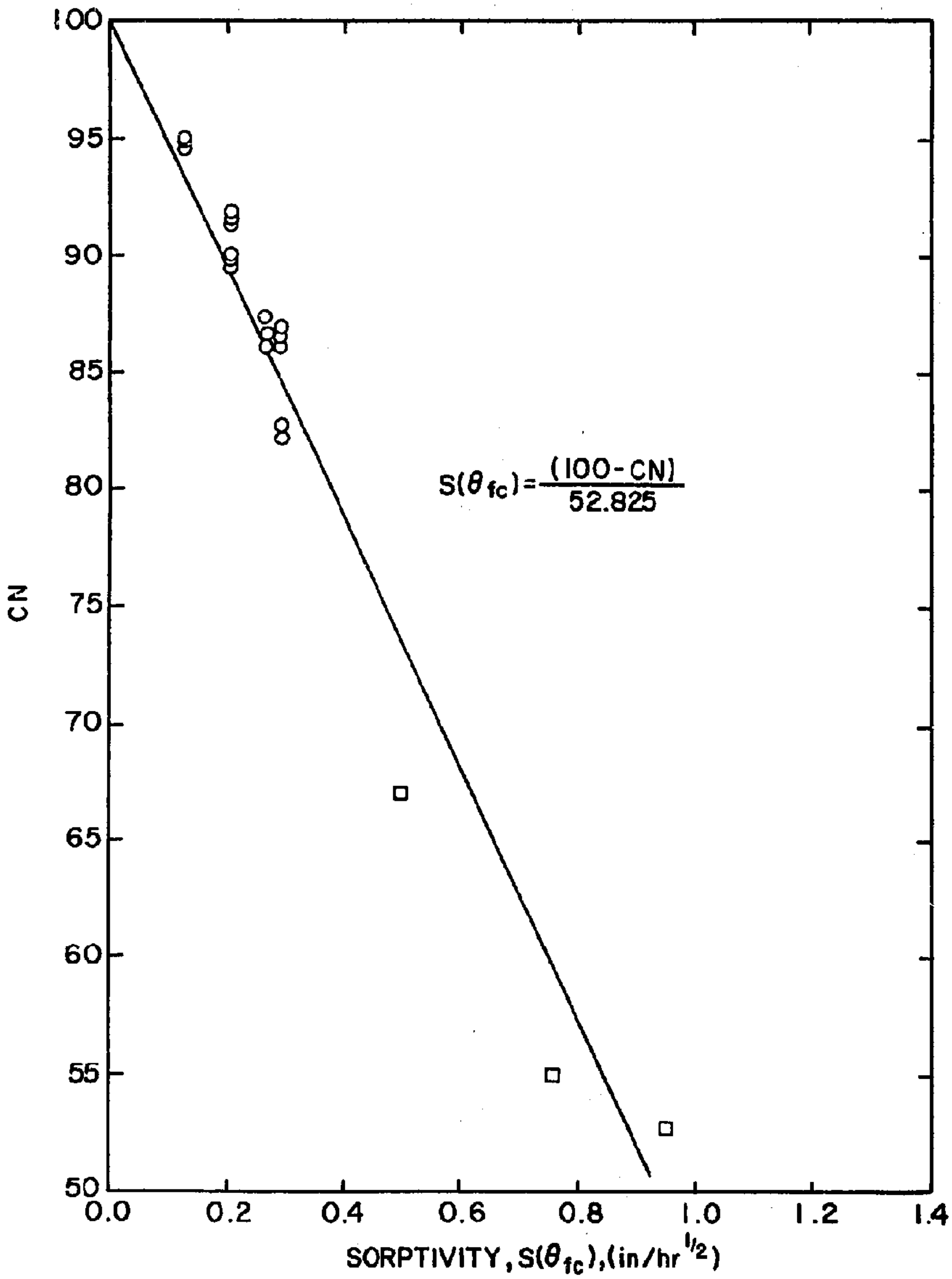

Figure 11. Plot of sorptivity versus curve number computed by SCSEXT.

Table 12. Table of correspondence, CN - ($\tilde{K}$, S_f). (1 inch = 25.4 mm)

CURVE NUMBER	KT(IN/HR)	SF(IN)	SORPTIVITY(IN/HR**1/2)
100.0	0.000	I	0.0000
99.0	.003	.052	.0189
98.0	.007	.104	.0379
97.0	.010	.156	.0568
96.0	.014	.208	.0757
95.0	.017	.260	.0947
94.0	.021	.312	.1136
93.0	.024	.364	.1325
92.0	.028	.416	.1514
91.0	.031	.468	.1704
90.0	.034	.520	.1893
89.0	.038	.572	.2082
88.0	.041	.624	.2272
87.0	.045	.676	.2461
86.0	.048	.728	.2650
85.0	.052	.780	.2840
84.0	.055	.832	.3029
83.0	.059	.884	.3218
82.0	.062	.936	.3407
81.0	.065	.988	.3597
80.0	.069	1.041	.3786
79.0	.072	1.093	.3975
78.0	.076	1.145	.4165
77.0	.079	1.197	.4354
76.0	.083	1.249	.4543
75.0	.086	1.301	.4733
74.0	.090	1.353	.4922
73.0	.093	1.405	.5111
72.0	.096	1.457	.5301
71.0	.100	1.509	.5490
70.0	.103	1.561	.5679
69.0	.107	1.613	.5868
68.0	.110	1.665	.6058
67.0	.114	1.717	.6247
66.0	.117	1.769	.6436
65.0	.121	1.821	.6626
64.0	.124	1.873	.6815
63.0	.127	1.925	.7004
62.0	.131	1.977	.7194
61.0	.134	2.029	.7383
60.0	.138	2.081	.7572
59.0	.141	2.133	.7761
58.0	.145	2.185	.7951
57.0	.123	2.697	.8140
56.0	.195	1.778	.8329
55.0	.267	1.357	.8519
54.0	.340	1.116	.8708
53.0	.412	.961	.8897
52.0	.484	.853	.9087
51.0	.556	.773	.9276
50.0	.629	.713	.9465
49.0	.701	.665	.9655
48.0	.773	.627	.9844
47.0	.845	.595	1.0033
46.0	.918	.569	1.0222
45.0	.990	.548	1.0412
44.0	1.062	.529	1.0601
43.0	1.134	.513	1.0790
42.0	1.207	.500	1.0980
41.0	1.279	.488	1.1169
40.0	1.351	.477	1.1358
39.0	1.423	.468	1.1548
38.0	1.496	.461	1.1737
37.0	1.568	.454	1.1926
36.0	1.640	.447	1.2115
35.0	1.712	.442	1.2305
34.0	1.785	.437	1.2494
33.0	1.857	.433	1.2683
32.0	1.929	.429	1.2873
31.0	2.001	.426	1.3062
30.0	2.074	.423	1.3251
29.0	2.146	.421	1.3441
28.0	2.218	.419	1.3630
27.0	2.290	.417	1.3819
26.0	2.363	.415	1.4009
25.0	2.435	.414	1.4198
24.0	2.507	.413	1.4387
23.0	2.579	.412	1.4576
22.0	2.652	.411	1.4766
21.0	2.724	.411	1.4955
20.0	2.796	.410	1.5144
19.0	2.868	.410	1.5334
18.0	2.941	.410	1.5523
17.0	3.013	.410	1.5712
16.0	3.085	.410	1.5902
15.0	3.158	.410	1.6091
14.0	3.230	.410	1.6280
13.0	3.302	.411	1.6469
12.0	3.374	.411	1.6659
11.0	3.447	.412	1.6848
10.0	3.519	.412	1.7037
9.0	3.591	.413	1.7227
8.0	3.663	.414	1.7416
7.0	3.736	.415	1.7605
6.0	3.808	.416	1.7795
5.0	3.880	.417	1.7984
4.0	3.952	.418	1.8173
3.0	4.025	.419	1.8363
2.0	4.097	.420	1.8552
1.0	4.169	.421	1.8741

It should be remembered that the table of correspondence contains values for field capacity soil moisture conditions (AMC II).

Although values are extrapolated for CN as low as 1, an inspection of Tables 2 and 3 shows that the great majority of soil-cover complexes have curve numbers in the range 60-100. This is also the range for which there are the most points of correspondence for defining the regressions.

Listings are provided in the appendix for the computer programs used to find the regression equations (CFIT) and to fill in the table of correspondence (TABLE).

5.3 Relationship Observed Between Initial Abstraction (I_a) and Storage (S)

It is instructive to use the results of SCSEXT to make a log-log plot of S vs. I_a in the manner of Figure 1, which was constructed by the SCS from field observations in small (less than 10 acres) watersheds. Figure 12 shows such a plot made from the initial abstractions and least-square S values computed in SCSEXT. The scatter in Figure 12 generated by infiltration equations appears to be of the same pattern as the observed scatter shown in Figure 1. This similarity seems to suggest that a ponding time approach to computing the quantity of water abstracted at the beginning of a storm will account for much of the variability of initial abstraction observed in experimental watersheds. It is the sensitivity of a ponding time calculation to rainfall intensity which will produce large variability in the magnitude of abstracted rain even though soil moisture is the same in every case. This feature of using an infiltration approach to compute excess rainfall recommends itself as a more realistic alternative to standard SCS procedures.

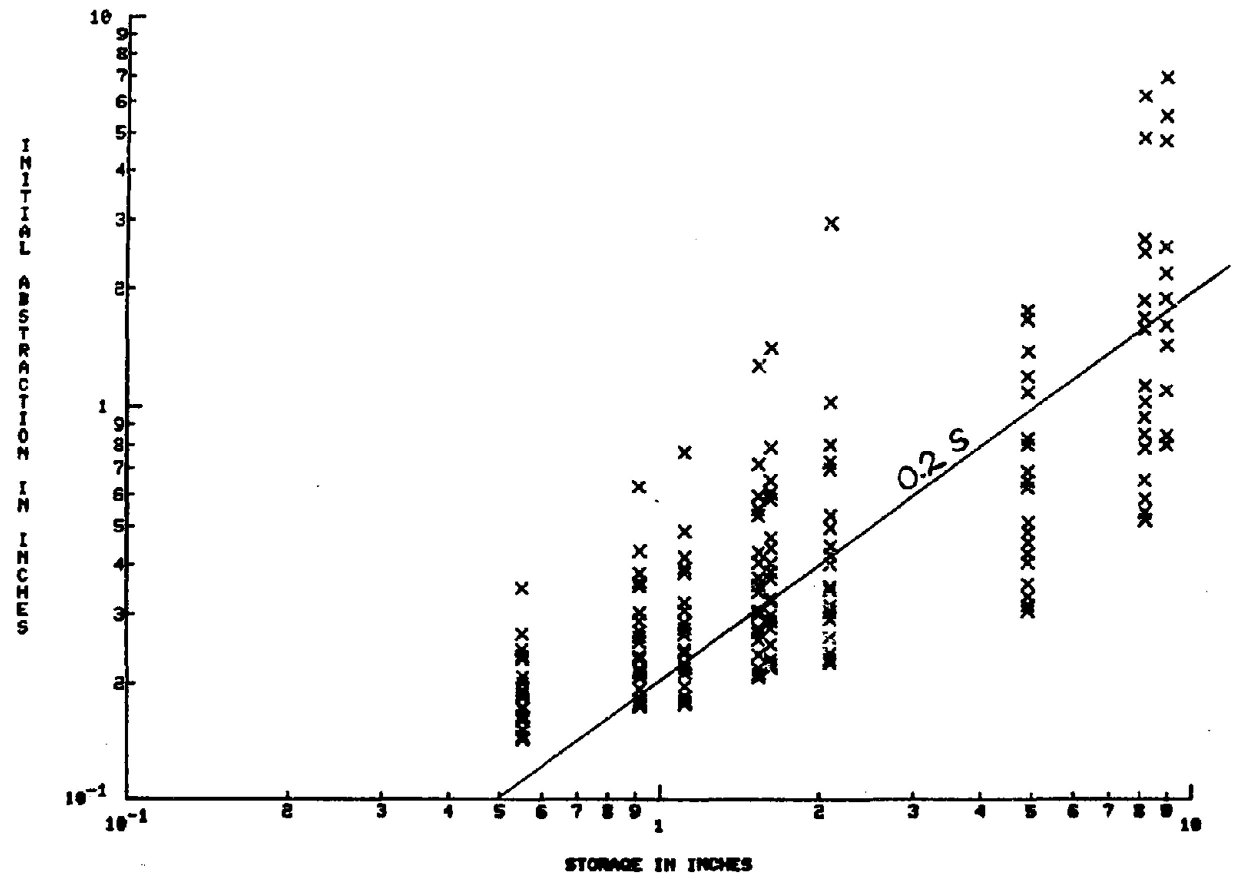

Figure 12. Initial abstraction vs. storage.

5.4 Removal of Bias in Table of Correspondence

Logical reasoning and preliminary tests using the correspondence presented in Table 12 suggest that it contains a bias. As explained in Sections 3.2 and 3.3 of this report, the CN - $(\tilde{K},S_f)$ equivalence was established using events during which the rainfall rate is assumed to be uniform. However, the SCS first defined curve numbers based on observed natural storms for which the rainfall rate certainly was not constant. For this reason it was decided to undertake an analysis of the impact of this assumption in establishing the CN - $(\tilde{K},S_f)$ correspondence.

Time distributions as presented by Huff (1967) were imposed on the storms for Central Oklahoma (Table 7) and Miami, Florida (Table 10). Peak rainfall was set to occur in the second quartile for storms of duration less than 12 hours, in the third quartile for 12 hour storms and in the fourth quartile for 24 hour storms, in accordance with the observations reported by Huff. For each major soil textural class presented in Table 6, an infiltration approach employing Eqs. (2.1.4) and (2.1.5) was applied to compute the cumulative depth of excess precipitation for each event. Soil parameters from classes 1 through 6 were used with the Oklahoma storms, and parameters from classes 7 through 10 were used with the Miami rainfall data. For each soil textural class a CN was calculated by the method of least-squares using the selected cumulative depths of precipitation, the calculated cumulative depths of excess rain and Eq. (1.1.4). The results of this analysis are presented in Table 13. These CN which may be called the "variable rainfall CN," were plotted against the "equivalence or constant rainfall CN" for each textural class for purposes of comparison. This plot is presented in Figure 13.

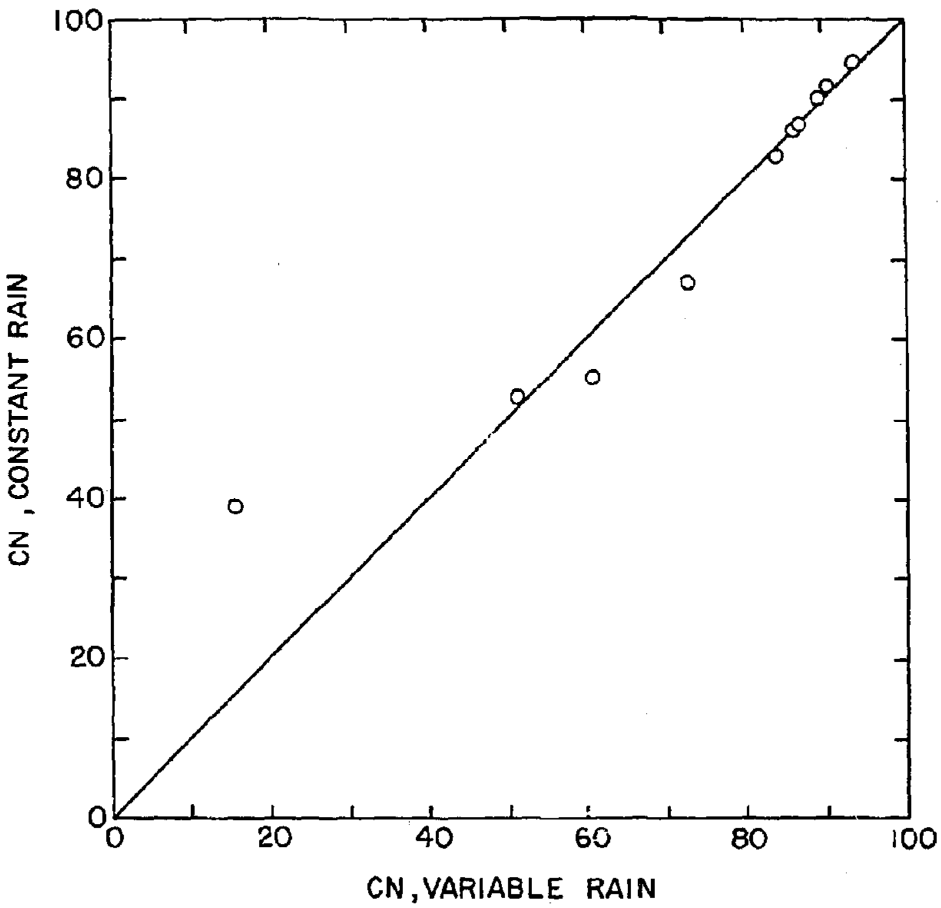

Figure 13. Variable rainfall CN versus equivalence CN for ten soil textural classes.

Table 13. Curve numbers found for major soil textural classes for the case of variable rainfall rate. (1 inch = 25.4 mm)

Soil#	Textural Class	$\tilde{K}$ (in/hr)	S_f (in)	CN
1	clay	0.013	0.66	94.1
2	silty clay	0.02	1.07	90.7
3	sandy clay	0.03	0.73	89.4
4	silty clay loam	0.04	0.90	86.7
5	clay loam	0.04	1.06	86.1
6	sandy clay loam	0.06	0.72	84.1
7	loam	0.13	0.97	72.8
8	silt loam	0.26	1.11	60.8
9	sandy loam	0.43	1.05	51.3
10	loamy sand	1.18	1.05	15.6

Although Figure 13 is suggestive of a trend, there are not enough points from which to generalize. To carry this investigation further, values of soil parameters from Table 12 were used to generate a more dense collection of least-squares, variable rainfall curve numbers. These results are presented in Table 14, and Figure 14 shows a plot of the variable rainfall CN versus the constant rainfall CN. The relationships seen in Figure 14 shows that in the range of CN from 53 to 83, the corresponding soil parameters from Table 12 will produce runoff behavior characteristic of much "tighter" watersheds if variable rainfall is applied. For curve numbers less than 53, Table 12 infiltration parameters will produce less runoff, if variable rainfall is applied, than one would expect for a given curve number.

These trends seem to stem from the assumption of $I_a = 0.2S$ in the original curve numbers derived by the SCS, and the dissimilar way in which the initial abstraction is modeled by an infiltration approach, depending upon whether rainfall intensity is constant or variable. In this study, initial abstraction by the infiltration approach was taken to be the quantity infiltrated up to ponding time, plus 0.1 inch surface

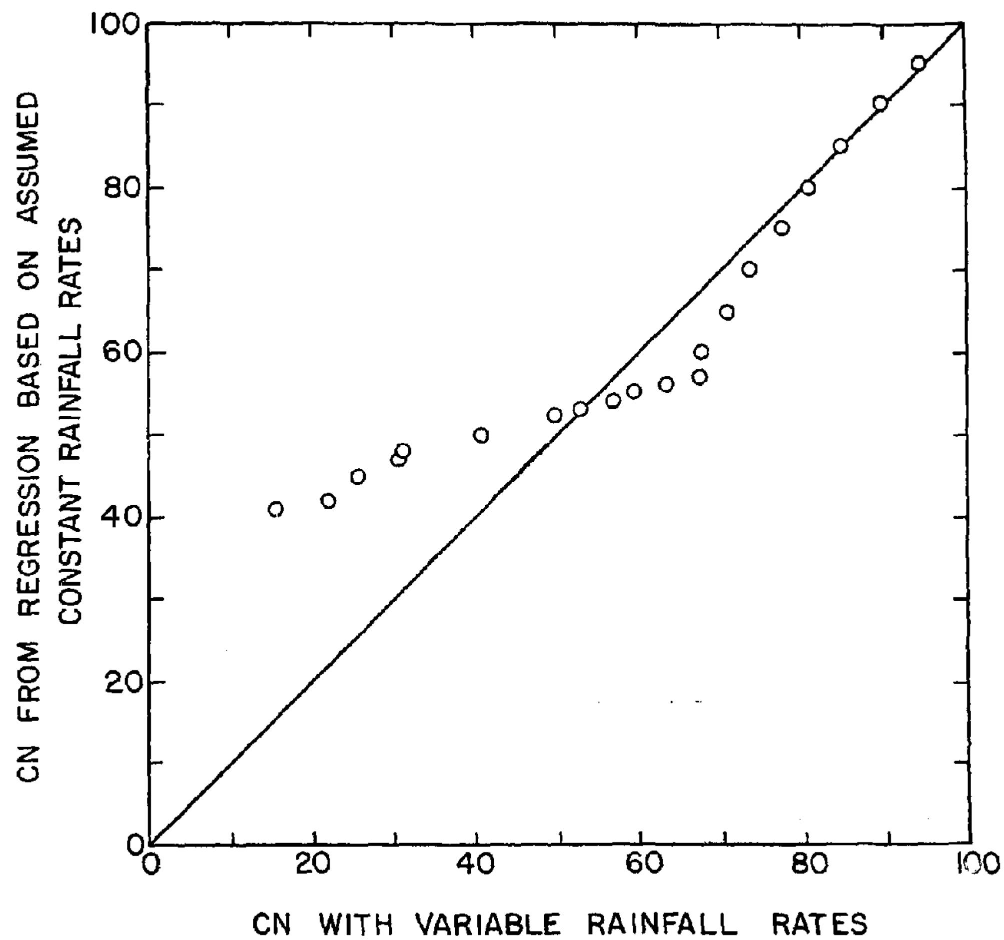

Figure 14. CN found with variable rainfall rates versus CN from Table 12.

Table 14. Least-squares curve numbers found for variable rainfall intensity events.

Constant Rainfall Regression CN	$\tilde{K}$ (in/hr)	S_f (in/hr)	Least-Squares Variable Rainfall CN
95	0.017	0.260	94.4
90	0.034	0.520	89.8
85	0.052	0.780	84.9
80	0.069	1.041	80.9
75	0.086	1.301	77.7
70	0.103	1.561	73.6
65	0.121	1.821	70.9
60	0.138	2.081	67.6
57	0.123	2.697	67.4
56	0.195	1.778	63.3
55	0.267	1.357	59.5
54	0.340	1.116	56.7
53	0.412	0.961	52.7
52	0.484	0.853	49.7
50	0.629	0.713	40.8
48	0.773	0.627	31.1
47	0.845	0.595	30.5
45	0.990	0.548	25.5
42	1.207	0.500	21.9
41	1.279	0.488	15.6

retention, plus the quantity infiltrated in the time it takes to accumulate the surface retention (see Figure 2). For a given set of infiltration parameters, ($\tilde{K}$,S_f), and a storm of a certain depth and duration, the initial abstraction will tend to be larger if computed for an assumed constant rainfall rate than if it is computed for a variable rainfall pattern with the peak occurring in the second quartile. (Half the storms used in this analysis had peak rainfall in the second quartile; one fourth each had peaks in the third and fourth quartiles.)

Returning to Figure 14, it can be seen that for CN > 83, there is good agreement regardless of the assumed rainfall pattern. These CN are characteristic of very tight watersheds, and initial abstraction is probably consistently much less than 0.2S under extreme storm condtions. Because the infiltration parameters are so small for these values of CN, initial abstraction will be very small and satisfied very quickly by an infiltration approach for any type of rainfall pattern, constant or otherwise.

For watersheds with CN in the range of 53 to 83, naturally occurring initial abstractions are still likely to be less than 0.2S, but not so much that the rainfall pattern is irrelevant when modeling them by an infiltration approach. Infiltration parameters found to be equivalent to CN in this range will be too "tight" if a constant rainfall pattern is assumed due to the tendency to overestimate the initial abstraction in this case.

Naturally occurring initial abstractions are likely greater than 0.2S for watersheds with CN $<$ 53. An infiltration approach with assumed constant rainfall seems to underestimate these large early abstractions, and establishes an equivalence with CN (based on equal amounts of total abstraction) by overestimating infiltration after the initial abstraction. This results in overestimates of infiltration parameters, particularly $\tilde{K}$.

It must be admitted that the explanation offered here for the apparent discrepancy between CN for constant and variable rainfall is somewhat speculative. A full analysis of the relative magnitudes of initial abstraction (as computed by infiltration approach) for different rainfall patterns would be especially instructive. Nonetheless, the nature of the discrepancy has been identified and steps may be taken to overcome it.

Figure 15 shows a nomograph developed from the data plotted in Figure 14. Its use will permit the utilization of the correspondence of Table 12 for cases of variable rainfall while avoiding any apparent bias. If one enters Figure 15 along the abscissa with a watershed's CN based on soils and land use, traces vertically to the dark curved line and then left to the ordinate, one may read off the CN to be used when entering the table of correspondence (Table 12). This procedure is illustrated in Figure 15 for the case of a land use CN equal to 72. The equivalent CN, for use with a variable rainfall pattern, is found to be 65.4. Entering Table 12, the appropriate infiltration parameters

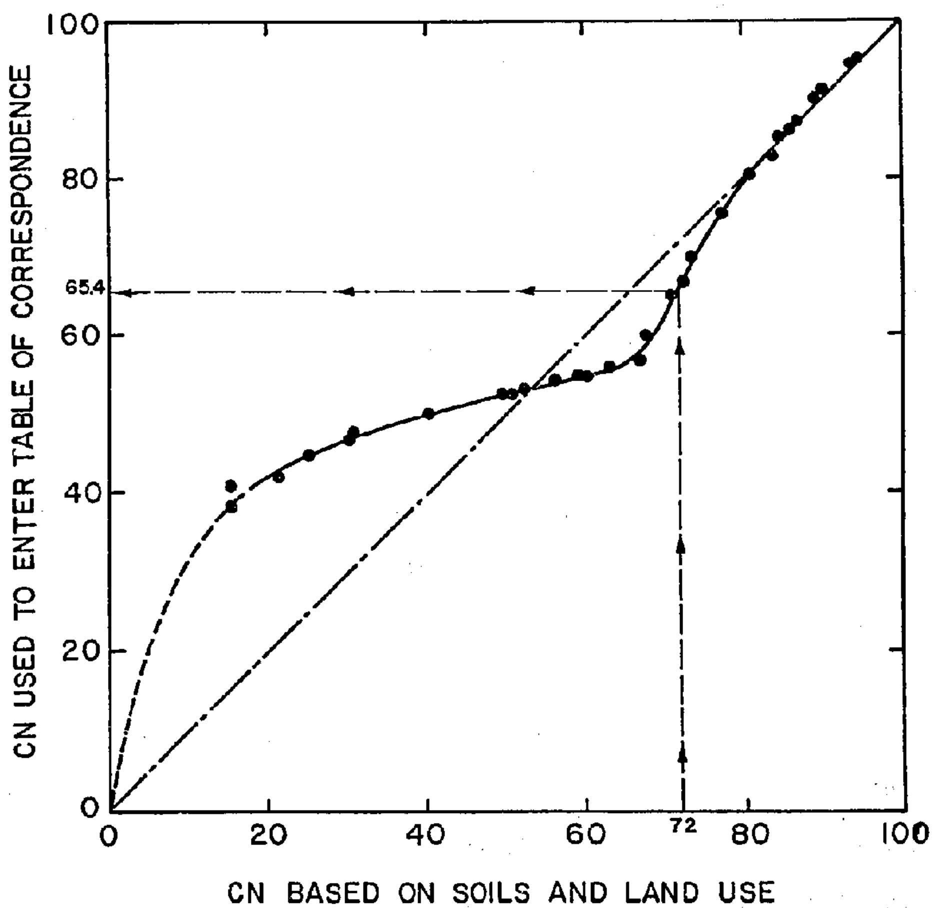

Figure 15. Nomograph for removal of bias in CN - $(\tilde{K},S_f)$ correspondence.

to be used are found by interpolation to be $\tilde{K} = 0.119$ in/hr and S_f = 1.800 inch.

III. IMPLEMENTATION

6. Utility of the CN - ($\tilde{K}$, S_f) Correspondence

With the correspondences reported in this document, a new approach for estimating runoff from ungaged watersheds is available to the hydrologist. Using soil maps, air photos, topographic maps and visual inspection, a curve number (AMC II) can be determined for a watershed of interest by standard SCS procedures. Next this CN based on soils and land use is converted via Figure 15 to a CN to be used to enter the table of correspondence to determine the watershed infiltration parameters. Then, the equivalent ($\tilde{K}$, S_f) can be read off the table of correspondence (Table 12) and an infiltration approach may be used to compute an excess rainfall pattern, given some rainfall event of interest. The excess rain may then be routed to the watershed outlet by some method of the hydrologist's choosing, such as the SCS dimensionless unit hydrograph.

A companion User's Manual for the Fortran program XSRAIN gives a detailed account of how it computes excess rain and runoff hydrographs for ungaged watersheds. The manual also includes an example of hand calculation of excess rainfall by the infiltration approach. The manual is meant to be self-contained, with all necessary tables therein for determination of hydrologic soil groups, curve numbers and equivalent hydraulic soil parameters. This second document with title "User's Manual for XSRAIN: a FORTRAN IV Program for Prediction of Runoff from Unpaged Watersheds" will be distributed by FHWA shortly after the production of this report.

REFERENCES

Aron, G., A. C. Miller, and D. F. Lakatos. 1977. Infiltration formula based on SCS curve number. Journal of the Irrigation and Drainage Division, ASCE, December 1977.

Brakensiek, D. L. 1977. Estimating the effective capillary pressure in the Green and Ampt infiltration equation. Water Resources Research 13(3):68-682.

Brakensiek, Engleman, and Rawls. 1979. SCS-AR Cooperative Research on Hydrologic Modeling. Progress Report FY 1979, unpublished.

Brooks, R. H. and A. T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper 3, Colorado State University, Fort Collins, 27 p.

Green, W. H. and G. A. Ampt. 1911. Studies on soil physics, 1. Flow of air and water through soils. Journal of Agricultural Sciences, Vol. 4, pp. 1-24.

Holtan, H. N., C. B. England, G. P. Lowless, G. A. Schumaker. 1968. Moisture-tension data for selected soils on experimental watersheds. ARS41-144, USDA-ARS, 609 p.

Mein, R. G. and C. L. Larson. 1973. Modeling infiltration during a steady rain. Water Resources Research Journal, Vol. 9, No. 2, pp. 384-394.

Morel-Seytoux, H. J. 1978. Derivations of equations for variable rainfall infiltration. Water Resources Research, Vol. 14, No. 4, August 1978, pp. 561-568.

Morel-Seytoux, H. J. 1979. Infiltration. Encyclopedia of Soil Science, Part 1, pp. 223-237. Edited by Rhodes W. Fairbridge. Dowden, Hutchinson and Ross, Inc., Publishers, Stroudsburg, PA.

Musgrave and Holtan, in Chow, V. T., Handbook of Hydrology, p. 12-25, Table 12-5.

Rawls, W., P. Yates, and L. Ashmussln. 1976. Calibration of selected infiltration equations for the Georgia Coastal Plain, ARS-S-113, USDA-ARS, 110 p.

Smith, R. E. 1976. Approximations for vertical infiltration rate patterns. Transactions, American Society of Agricultural Engineers, Vol. 19, No. 3, 1976, pp. 505-509.

Smith, R. E. 1978. A proposed infiltration model for use in simulation of field-scale watershed hydrology. Prepared for the ARS Nonpoint Pollution Modeling Workshop, February 14-16, 1978, 10 p.

Smith, R. E. and K. G. Eggert. 1978. Discussion of Aron, et al., 1977. Appearing in the Journal of the Irrigation and Drainage Division, ASCE, December 1978, pp. 462-464.

Soil Conservation Service, National Engineering Handbook, Section 4, Hydrology, August 1972, Washington, D.C.

Strait, S., K. Saxton, and R. I. Papendick. 1978. Pressure and hydraulic conductivity curves for various soil textures (unpublished release), 1978. Cited by Brakensiek et al. in SCS-AR Cooperative Research Progress Report FY1979.

U.S. Department of Agriculture, Agricultural Research Service, Technical Bulletin No. 1518, USDAHL-74 Revised Model of Watershed Hydrology, December 1975, Washington, D.C.

Viessman, W., J. W. Knapp, G. L. Lewis, and T. E. Harbaugh. 1977. Introduction to Hydrology. IEP-Dun-Donnelly, Harper and Row, Publishers, New York, 704 p.

Weather Bureau, U.S. Department of Commerce, Technical Paper No. 40, Rainfall Frequency Atlas of the United States, May 1961, 71 p.

Wolf, P. R., Adjustment Computations, 1974, University of Wisconsin, Madison, Wisconsin, 263 p.

APPENDIX

In this section, the description of two computer programs are presented.

Program SCSEXT is for finding an equivalent SCS curve number for specified hydraulic soil parameters over a number of rainfall events.

Program CFIT is for finding the regression between SCS curve number and hydraulic conductivity subject to certain constraints.

Brief Description of Program SCSEXT

Program SCSEXT was written to find an equivalent curve number for specified hydraulic soil parameters, $\tilde{K}$ and S_f, over a number (M) of rainfall events, also specified.

The program begins by reading in the number of soils to be considered, NS, and the rainfall rates and durations (RR and RTD) of the M user specified events. Retention (interception and depression storage) is set equal to 0.10 inch (2.54 mm) for all cases. The counter MMT is set equal to zero; it will record the total number of events over all soils.

The program next enters loop 12, whose index is SOIL. SOIL is incremented from one through NS, the number of soil texture classes being considered. Thus, the operations in loop 12 are performed for one soil type at a time. After reading the hydraulic conductivity, KT, the storage suction factor, SF, and the first guess for storage, S, for a soil, loop twelve initializes the R and TD vectors by setting them equal to the RR and RTD vectors. Next it considers which events (R, TD) cannot be used with the soil type specified by KT and SF due to the fact that the rainfall rate is less than KT, or the ponding time is greater than the rainfall duration. This is accomplished in loop 29. N is the number of events thrown out and MM the number retained. Subscripts of event-specific variables, (such as R, TD, RSTAR, TP) are revised accordingly.

After a few simple preliminary calculations, the total abstraction according to infiltration equations, C1, is calculated in loop 17.

In loop 45, an iterative solution for the initial abstraction, IA2, is found by Newton's method for each event of R and TD. With this value of IA2, a time to end of initial abstraction, TE2, is also computed for each event. A check is made by comparing TE2 with TD for every event, and if TE2 is greater than TD, the event is discarded, and subscripts are revised accordingly for TE2, IA2, R, TD, C1, P, RSTAR, RATIO, TP, PPI. The number of events thrown out by this check is NN.

With values of IA2 for each event retained, the iterative calculations are made for finding the least-squares storage, S, in loops 26 and 25. With the calculation of this S, the equivalence between infiltration parameters and the SCS method has been reached for a specific soil type. Results are printed out and S is stored in the STO and STOR arrays for future reference. Initial abstraction values are stored in ALLIA. The dimensions of STOR and ALLIA are MMT, the total number of events over all NS soil types.

At this point, the "12 CONTINUE" card is hit and the preceding operations are performed for a new soil texture type, with its own values of KT, S_f and first guess S.

After the operations of loop 12 have been done for all NS of the specified soil types, subroutine MAPA gives a log-log plot of initial abstraction versus storage using the values in STOR and ALLIA. MAPA is a library subroutine on the system at Colorado State University, and is probably not found on other systems. It is a subroutine for producing data plots on a line printer.

Finally, in loop 82, curve numbers are computed from the storage values in STO and results are printed out.

The following pages contain definitions of FORTRAN symbols used in SCSEXT, as well as a listing of the program.

Fortran Symbol	Math Symbol	Definition (1 inch = 25.4 mm)
M		Number of rainfall events
NS		Number of soil types
RR(1)...RR(M)	r	Input rainfall rates (in/hr)
RTD(1)...RTD(M)	t_D	Input duration times (hr)
RET		Retention: the combination of interception and depression storage (in)
MMT		Total number of events used over <u>all</u> (NS) soil types ($\sum_{i=1}^{NS} MM_i$)
SOIL		Index of loop 12; as it increments, a new soil type is taken up
KT	$\tilde{K}$	Hydraulic conductivity at natural saturation (in/hr)
SF	S_f	Storage suction factor (in)
R(1)...R(MM)	r	Rainfall rates actually used with soil type of consideration (in/hr)
TD(1)...TD(MM)	t_D	Duration times actually used with soil type of consideration (hr)
N		Number of events discarded because $r < K$ or $t_D < t_p$
NN		Number of events discarded because $t_e > t_D$
MM		MM = M - N - NN; number of events retained
RSTAR	$r^* = (r/\tilde{K})$	Rainfall rate normalized with respect to $\tilde{K}$
TP(K)	t_p	Ponding time for 'Kth' event (hr)
RATIO(K)	$r^*/(r^*-1)$	Convenience term for 'Kth' event

Fortran Symbol	Math Symbol	Definition (1 inch = 25.4 mm)
P(K)	$P = r\ t_D$	Total depth of precip. for 'Kth' event (in)
PPI(K)	$Wp = rt_p$	Pre-ponding cumulative infiltration depth (in)
SORP	$S(\theta_i) = \sqrt{2K\tilde{S}_f}$	Green and Ampt sorptivity ($in/hr^{1/2}$)
C1(I)		Total event abstraction for the 'Ith' event by infiltration approach (in)
IA2(J)	I_a	Initial abstraction for 'Jth' event (in)
ITER		Iteration counter in routine to find I_a
H(J)	F	Function which goes to zero when solution for I_a is reached, for 'Jth' event
DH(J)	dF/dI_a	First derivative with respect to I_a
DIA2	ΔI_a	Incremental correction to previous guess of I_a
TE2(J)	t_e	Time to end of initial abstraction for the 'Jth' event
A(I),B(I)		Convenience terms in the solution for storage, SS for the Ith event alone
SS(I)		Storage if only 'Ith' event considered
PD(I)	P_d	Difference ($P-I_a$) for the Ith event (in)
LA(I)	$a = (I_a+P_e-C)$	Convenience term in solution for least-squares S, for Ith event
LB(I)	$b = (I_a-C)$	Convenience term in solution for least-squares S, for Ith event
ITERS		Iteration counter in computation of S

Fortran Symbol	Math Symbol	Definition
SUMFUNC	$G = \sum_{i=1}^{N} \frac{SA_i+B_i}{(P_{d_i}+S)^3}$	Function which goes to zero when solution S is found
SUMDRIV	$\frac{dG}{dS}$	First derivative of G with respect to S
BA(I)	$A_i=(a_i P_{d_i}^2 - a_i b_i P_{d_i})$	Convenience term for Ith event
BB(I)	$B_i=(a_i b_i P_{d_i}^2 - b_i^2 P_{d_i}^2)$	Convenience term for Ith event
NUMER		Convenience term in calculation of SUMDRIV
DENOM		Convenience term in calculation of SUMDRIV
DELESS	ΔS	Incremental correction to previous estimate of S (in)
STO(SOIL)		Storage, S, for a particular soil type denoted by the index SOIL
STOR(1)...STOR(MM)		Array where S values for all soil types are stored. Each soil type has its S repeated MM times. Used with MAPA line printer plot subroutine
ALLIA(1)...ALLIA(MMT)		Array of all initial abstraction values for all soil types for all retained events. Used with STOR(MMT) in MAPA to print a plot of I_a vs. S.
BEGIN		Index in STOR and ALLIA where values for a particular soil type are begun to be stored
MAPA		CSU subroutine to get a data plot on the line-printer
CN(1)...CN(NS)		Curve number for the respective (1 through NS) soil texture types

```
      PROGRAM SCSEXT(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
      INTEGER BEGIN
      REAL KO,L,LA,LB,NUMER
      INTEGER SOIL
      REAL KT,IA2
      DIMENSION 20),LA(20),LB(20),BA(20),BB(20)
      DIMENSION STO(12),MT(8),CN(12)
      DIMENSION RR(20),RTD(20),TD(20),C1(20),IA2(20),TE2(20)
      DIMENSION MTT(8)
      DIMENSION ALLIA(120),STOR(120),SS(20)
      DIMENSION H(20),DH(20),B(20),A(20),P(20),RATIO(20),R(20),TP(20),
     1RSTAR(20),PPI(20)
      DATA XTT,YTT,MTT/"STORAGE   ","IA        ","          INITIAL ABS
     1TRACTION (IA - INCHES) VS. STORAGE (S - INCHES)          "/
C
C     M IS THE NUMBER OF RAINFALL-DURATION EVENTS BEING CONSIDERED
C
      M=20
C
C     READ NS, THE NUMBER OF SOILS CONSIDERED
C
      READ (5,99) NS
   99 FORMAT(I5)
C
C     READ IN RAINFALL AND DURATION VECTORS
C
      DO 11 I=1,M
      READ (5,10) RR(I),RTD(I)
   10 FORMAT(2F10.3)
   11 CONTINUE
C
C     SET RETENTION VALUE
C
      RET=0.10
C
      MMT=0
      DO 12 SOIL=1,NS
      PRINT 13
   13 FORMAT(2X,21(1H*),/)
      PRINT 14,SOIL
   14 FORMAT(2X,"SOIL NUMBER",I5)
C
C     READ HYDRAULIC CONDUCTIVITY, STORAGE SUCTION FACTOR, AND
C     FIRST GUESS S
C
      READ (5,9) KT,SF,S
    9 FORMAT(3F10.3)
      PRINT 15,KT,SF,S
   15 FORMAT(2X,"KT=",F10.3,2X,"SF=",F10.3,/,2X,"FIRST GUESS S =",F10.3,
     1/)
```

```
C
C     INITIALIZE RAINFALL AND DURATION VECTORS FOR A PARTICULAR SOIL
C
      DO 16 I=1,M
      R(I)=RR(I)
   16 TD(I)=RTD(I)
C
C     THROW OUT EVENTS WHERE RAINFALL RATE .LE. HYDRAULIC CONDUCTIVITY
C     OR PONDING TIME .GT. TIME OF DURATION
C
      N=0
      DO 29 K=1,M
      RSTAR(K)=R(K)/KT
      TP(K)=SF/(R(K)*(RSTAR(K)-1.))
      PRINT 18,R(K),TD(K),TP(K)
   18 FORMAT(2X,"RAINFALL RATE =",F10.3,2X,"IN/HR",5X,"DURATION =",F10.3
     1,2X,"HR",5X,"PONDING TIME=",F10.3,2X,"HR")
C
C     REVISE SUBSCRIPTS, N IS NUMBER OF EVENTS THROWN OUT
C
      R(K-N)=R(K)
      TD(K-N)=TD(K)
      RSTAR(K-N)=RSTAR(K)
      TP(K-N)=TP(K)
C
C     TEST R AGAINST KT AND TP AGAINST TD
C
      IF(R(K).LE.KT)GO TO 19
      IF(TP(K).GT.TD(K))GO TO 62
      GO TO 29
   19 PRINT 20
   20 FORMAT(2X,"RAINFALL RATE LESS THAN HYDRAULIC CONDUCTIVITY OF TH SO
     1IL - RUNOFF DOES NOT OCCUR")
      GO TO 64
   62 PRINT 63
   63 FORMAT(2X,"PONDING TIME GREATER THAN TIME OF DURATION - RUNOFF DOE
     1S NOT OCCUR")
   64 N=N+1
   29 CONTINUE
C
C     MM IS THE NUMBER OF EVENTS RETAINED
C
      MM=M-N
C
C     CALCULATE RATIO AND TOTAL PRECIPITATION
C     CALCULATE PRE-PONDING INFILTRATION (PPI)
C
      PRINT 33
   33 FORMAT(1X,5(1H*),/)
      DO 34 K=1,MM
      RATIO(K)=RSTAR(K)/(RSTAR(K)-1.)
      P(K)=R(K)*TD(K)
      PPI(K)=R(K)*TP(K)
   34 CONTINUE
C
C     CALCULATE SORPTIVITY
C
      SORP=SQRT(2.*KT*SF)
      PRINT 60,SORP
   60 FORMAT(/,2X,"SORPTIVITY =",F10.4)
C
C     CALCULATE TOTAL ABSTRACTION BY INFILTRATION EQUATION, (CI)
C
      DO 17 I=1,MM
      CI(I)=RET+PPI(I)+SORP*RATIO(I)*(SQRT(TD(I)-TP(I)+0.5*(RATIO(I)
     1**3)*TP(I))-SQRT(0.5*(RATIO(I)**3)*TP(I)))+KT*(TD(I)-TP(I))
   17 CONTINUE
C
```

```
C
C     PART TWO - SOLVING FOR INITIAL ABSTRACTION
C
C
C     ENFORCE CONDITION OF EQUAL AMOUNTS ABSTRACTED AT END OF INITIAL
C     ABSTRACTION TO FIND IA2 FOR EACH OF MM EVENTS
C
      NN=0
      DO 45 J=1,MM
C
C     SET INITIAL APPROX FOR IA2(J)
C
      IA2(J)=PPI(J)+1.0
      ITER=0
C
C     ITERATE TO A SOLUTION FOR IA BY NEWTONS METHOD
C
   46 H(J)=R(J)*TP(J)+SORP*RATIO(J)*(SQRT((IA2(J)/R(J))-TP(J)+0.5*(RATIO
     1(J)**3)*TP(J))-SQRT(0.5*(RATIO(J)**3)*TP(J)))+KT*((IA2(J)/R(J))-TP
     2(J))-IA2(J)+RET
      DH(J)=((SORP*RATIO(J))/(2.*R(J)*SQRT((IA2(J)/R(J))-TP(J)+0.5*(RATI
     1O(J)**3)*TP(J))))+(1./RSTAR(J))-1.
      IF(ABS(DH(J)).LE.1.0E-10)GO TO 45
      DIA2=-(H(J)/DH(J))
      IA2(J)=IA2(J)+DIA2
      ITER=ITER+1
      IF(ITER.GT.10)GO TO 47
C
C     TEST MAGNITUDE OF DIA2
C
      IF(ABS(DIA2).GT.0.010)GO TO 46
      GO TO 66
   47 PRINT 48,J
   48 FORMAT(2X,"TEN ITERATIONS WITHOUT CONVERGENCE IN ATTEMPT TO CALCUL
     1ATE IA2(",I2,")")
      GO TO 45
C
C     CALCULATE TIME TO END OF IA2
C
   66 TE2(J)=IA2(J)/R(J)
C
C     REVISE SUBSCRIPTS. NN IS THE NUMBER OF EVENTS THROWN OUT
C
      TE2(J-NN)=TE2(J)
      IA2(J-NN)=IA2(J)
      R(J-NN)=R(J)
      C1(J-NN)=C1(J)
      P(J-NN)=P(J)
      RSTAR(J-NN)=RSTAR(J)
      RATIO(J-NN)=RATIO(J)
      TP(J-NN)=TP(J)
      PPI(J-NN)=PPI(J)
      TD(J-NN)=TD(J)
C
C     TEST TE2 AGAINST TD
C
      IF(TE2(J).GE.TD(J))GO TO 65
      GO TO 45
   65 PRINT 67
   67 FORMAT(2X,"TE2.GE.TD,EVENT SKIPPED")
      NN=NN+1
   45 CONTINUE
      MM=MM-NN
      PRINT 30,MM
   30 FORMAT(2X,I5,2X,"EVENTS WITH R.GT.KT , TP.LE.TD AND TD.GT.
     1TE2")
C
```

```
C     MMT IS THE CUMULATIVE NUMBER OF EVENTS BEING CONSIDERED
C     OVER ALL SOILS
C
      MMT=MMT+MM
      PRINT 69,MMT
   69 FORMAT(2X,"CUMULATIVE NUMBER OF EVENTS CONSIDERED, MMT =",I3)
      DO 68 K=1,MM
      PRINT 59,K,RSTAR(K),K,RATIO(K),K,TP(K),K,P(K),K,PPI(K)
   59 FORMAT(2X,"RSTAR(",I2,")=",F10.3,5X,"RATIO(",I2,")=",F10.3,
     15X,"TP(",I2,")=",F10.3,5X,"P(",I2,")=",F10.3,5X,"PPI(",I2,
     2")=",F10.3)
   68 CONTINUE
C
C     CALCULATE STORAGE USING IA2
C
      DO 24 I=1,MM
      A(I)=P(I)-C1(I)
      B(I)=IA2(I)*(P(I)-IA2(I)+C1(I))-C1(I)*P(I)
C
C     FIND STORAGE FOR EACH PARTICULAR EVENT
C
      SS(I)=-B(I)/A(I)
   24 CONTINUE
C
C     CALCULATE LEAST SQUARES STORAGE OVER ALL EVENTS
C
      DO 26 I=1,MM
      PD(I)=P(I)-IA2(I)
      LA(I)=IA2(I)+PD(I)-C1(I)
   26 LB(I)=IA2(I)-C1(I)
C
      ITERS=0
   27 SUMFUNC=0.
      SUMDRIV=0.
      ITERS=ITERS+1
      IF(ITERS.GT.10)GO TO 31
      DO 25 I=1,MM
      BA(I)=((LA(I)**2)*PD(I))-(LA(I)*LB(I)*PD(I))
      BB(I)=(LA(I)*LB(I)*(PD(I)**2))-((LB(I)**2)*(PD(I)**2))
      SUMFUNC=SUMFUNC+((BA(I)*S+BB(I))/((PD(I)+S)**3))
      NUMER=(BA(I)*((PD(I)+S)**3))-(3.*(S*BA(I)+BB(I))*((PD(I)+S)**2))
      DENOM=((PD(I)+S)**6)
      SUMDRIV=SUMDRIV+(NUMER/DENOM)
   25 CONTINUE
      DELESS=-SUMFUNC/SUMDRIV
      S=S+DELESS
      IF(DELESS.GE.0.001)GO TO 27
      GO TO 32
   31 PRINT 35
   35 FORMAT(/,2X,"TEN ITERATIONS WITHOUT CONVERGENCE FOR S",/)
   32 CONTINUE
```

```
C
C     PRINT OUT RESULTS
C
      PRINT 33
      DO 41 I=1,MM
      PRINT 51,I,IA2(I),I,TE2(I),I,SS(I)
   51 FORMAT(2X,"IA2(",I2,")=",F10.3,3X,"TE2(",I2,")=",F10.3,3X,
     1"SS(",I2,")=",F10.3)
   41 CONTINUE
      PRINT 33
      PRINT 28,S,RET
   28 FORMAT(2X,"SOIL STORAGE =",F10.3,2X,"RETENTION =",F10.3)
      PRINT 33
      STO(SOIL)=S
      BEGIN=MMT-MM+1
      DO 70 K=BEGIN,MMT
   70 STOR(K)=S
      DO 71 K=1,MM
      ALLIA(BEGIN)=IA2(K)
   71 BEGIN=BEGIN+1
   12 CONTINUE
      IF(NS.LT.3)GO TO 101
      CALL MAPA(5,STOR,ALLIA,1,MMT,XMIN,XMAX,YMIN,YMAX,XTT,YTT,MTT,4)
  101 PRINT 33
      DO 82 I=1,NS
      CN(I)=1000./(STO(I)+10.)
      PRINT 83,I,STO(I),I,CN(I)
   83 FORMAT(2X,*STO(*,I2,*)=*,F10.3,3X,*CN(*,I2,*)=*,F10.3)
   82 CONTINUE
  100 STOP
      END
```

Program CFIT

Program CFIT was written to find the regression between curve number, CN, and hydraulic conductivity, $\tilde{K}$, subject to the constraint that at CN = 100, $\tilde{K}$ = 0.0 in/hr. It was also used for sorptivity vs. CN.

A list of the Fortran symbols used and their definitions follows, along with a listing of CFIT.

CFIT Symbols

Fortran Symbol	Definition
N	Number of soil types for which there is a K and CN
KT(I)	$\tilde{K}$, the hydraulic conductivity ('Ith' soil)
CN(I)	Curve number, ('Ith' soil)
B(I)	Convenience term, B(I) = 100 - CN(I)
MAPA	CSU subroutine to give a data plot on the line printer
CLSQ	Subroutine to compute constrained least-squares
A1	Slope of regression line found in CLSQ
K(I)	Estimated hydraulic conductivity found with regression computed in CLSQ, 'Ith' soil
STDER	subroutine to compute standard error of estimate

CLSQ Symbols

Fortran	Definition
X	$\tilde{K}$, the hydraulic conductivity or other parameter to be estimated from CN
B(I)	Convenience term, B(I) = 100 - CN(I)
BX	Product, for 'Ith' soil, of B(I) times X(I)
X2	X2 = X(I)**2
M	Slope of regression line

STDER Symbols

Fortran	Definitions
X(I)	'Known' value of parameter
Y(I)	Value of parameter estimated by regression
RO(I)	Squared difference between X(I) and Y(I)
SUMRO	Sum of squared residuals
SD	Standard error of estimate
M	Number of soil types for which values of X and Y are available

```
      PROGRAM CFIT(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
      DIMENSION KT(12),CN(12),K(12),MT(8),B(20)
      DIMENSION MTT(8)
      REAL K,KT,M
      DATA XTT,YTT,MTT/"KT","CN","PLOT OF STORAGE VS. CALCULATED
     1 COEFFICIENTS"/
      DATA XT,YT,MT/"K","CN","PLOT OF STORAGE VS. PREDICTED
     1 COEFFICIENTS"/
      READ(5,14)N
   14 FORMAT(I5)
      DO 101 I=1,N
      READ(5,10)KT(I),CN(I)
   10 FORMAT(2F10.4)
  101 CONTINUE
      DO 102 I=1,N
      B(I)=100.-CN(I)
      WRITE(6,11)I,KT(I),I,CN(I)
   11 FORMAT(2X,*KT(*,I2,*)=*,F10.4,5X,*CN(*,I2,*)=*,F10.4)
  102 CONTINUE
      CALL MAPA(5,KT,CN,1,N,XMIN,XMAX,YMIN,YMAX,XTT,YTT,MTT,1)
      CALL CLSQ(N,B,KT,A1)
      WRITE(6,100)A1
  100 FORMAT(2X,"REGRESSION LINE: KT=(100-CN)/",F10.3)
      DO 103 I=1,N
  103 K(I)=B(I)/A1
      DO 104 I=1,N
      WRITE(6,12)I,K(I)
   12 FORMAT(2X,*K(*,I2,*)=*,F7.3)
  104 CONTINUE
      CALL STDER(N,KT,K,SD)
      WRITE(6,13)SD
   13 FORMAT(2X,"STANDARD ERROR OF ESTIMATE=",E12.5)
      CALL MAPA(5,K,CN,1,N,XMIN,XMAX,YMIN,YMAX,XT,YT,MT,1)
      STOP
      END
```

```
      SUBROUTINE CLSQ(N,R,X,M)
      DIMENSION B(20),X(20)
      REAL M
      BX=0.
      X2=0.
      DO 1 I=1,N
      BX=BX+(B(I)*X(I))
      X2=X2+(X(I)**2)
    1 CONTINUE
      M=BX/X2
      RETURN
      END
      SUBROUTINE STDER(M,X,Y,SD)
      DIMENSION X(20),Y(20)
      SUMRO=0.0
      DO 14 I=1,M
      RO=(X(I)-Y(I))**2
      SUMRO=SUMRO+RO
   14 CONTINUE
      SD=SQRT(SUMRO/FLOAT(M-1))
      RETURN
      END
```

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.