PART 5

REVIEWS AND COMMENTS DURING PREPARATION OF DRAFT OF MANUAL

Reviewers

In late 1988, drafts of the three major sections of the manual relating to rainfall-runoff modeling; that is, rainfall criteria, rainfall losses, and unit hydrographs, were available. In December 1988, copies of these drafts were sent out to various professionals for the purpose of receiving critical review. A letter to the Flood Control District dated 30 December 1988 (Appendix 5-A) lists the individuals that were solicited to perform such a review, and that letter indicates which draft section(s) each individual was asked to review. A copy of the letter that was sent to each reviewer is contained in Appendix 5-A.

Comments

Either written or verbal review comments were received from reviewers. Dr. Herman Bouwer forwarded the draft review copy to Dr. Kenneth Renard and Dr. Bouwer requested that Dr. Renard provide a review. Subsequently, review comments were received from Dr. Renard.

The written review comments that were received and the subsequent correspondence with several of the reviews is contained in the following appendices:

APPENDIX	
5-B	Dr. Walter Rawls
5-C	Dr. Leonard Lane
5-D	Dr. Kenneth Rennard (for Dr. Herman Bouwer)
5-E	Mr. Harry Millsaps (for Mr. Robin McArthur)
5-F	Dr. Herb Osborn
5-G	Mr. C.O. Clark

Written review comments and suggestions were carefully considered, and when appropriate, comments and suggestions were incorporated into subsequent drafts of the manual.

Verbal review comments were received from the following:

Mr. John Pedersen
Mr. Art Cudworth
Dr. David Woolhiser
Mr. V. Ottozawa-Chatupron.

These verbal review comments were received in office visits with these individuals and records of such comments are not available. Mr. Pedersen had several questions, comments, and suggestions that were either resolved in our discussions or were incorporated in revisions to the manual. Mr. Cudworth had been instrumental in supplying data and serving as an advisor in the preparation of the S-Graph Report (Sabol, 1987) and his review comments were minimal. Dr. Woolhiser's comments were of a more conceptual nature relating to the general procedure that was being proposed in the manual. No significant concerns were reported by those three reviewers. Mr. Ottozawa-Chatupron's responses were more in regard to the use of those techniques in an ADOT Highway Drainage Design Manual that was being prepared at that time. His comments, being related to another project, are not contained, herein.

APPENDIX 5-A

Letters of Request for Reviews

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. Joe Rumann
Hydrologist
Flood Control District of Maricopa County
3335 West Durango
Phoenix, Arizona 85009

Dear Joe:

Enclosed in the draft of the Rainfall Losses section of the Maricopa County Hydrology Manual. Every time that I read this I have a desire to add, delete, or change something. I think that I will quit reading it and let others take over. As we discussed, I sent copies of the drafts of the various sections to qualified individuals for their review and comment. I have asked reviewers to concentrate on certain sections and I have provided other sections to some reviewers for their general information only. This is summarized:

Reviewer (1)	Rainfall (2)	Rainfall Losses (3)	Unit Hydrographs (4)
John Pedersen, Corps of Eng., LA	R	I	R
Art Cudworth, USBR, Denver		R	R
Robin McArthur, SCS, Phoenix	R	R	R
Dave Woolhiser, ARS, Tucson	I	I	I
Leonard Lane, ARS, Tucson	I	R	I
Herb Osborn, ARS (retired)	R		
Walter Rawls, ARS, Beltsville		R	
Herman Bouwer, U.S. Water Cons. Lab., Phoenix		R	
V. Ottozawa-Chatupron, ATRC Phoenix	I	I	I
C.O. Clark (retired), Oklahoma			R

R - Review is requested
I - For information of reviewer. Review and comments are not requested

I will be returning on 3 February 1989 and I will contact you the week of 6 February. Hopefully all reviews can be completed during my absence, and we can finish the manual early next year.

The signed contracts are also enclosed. Thanks for taking care of this. I do appreciate and enjoy having the opportunity to continue to work with you and others at the Flood Control District.

Best wishes for 1989.

Sincerely yours,

George V. Sabol

Enclosures:
1. Copy of review package
2. Copies of letters to reviewers
3. Signed copies of contract (5)

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. John Pedersen, P.E.
U.S. Army Corps of Engineers
Los Angeles District
P.O. Box 2711
Los Angeles, California 90053-2325

Dear John:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

Your assistance by reviewing the Rainfall and Unit Hydrograph Procedures section would be greatly appreciated. I have also enclosed the Rainfall Losses section for your general information, and your review of this section is also encouraged but not requested

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me and Mr. Joe Rumann at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft sections of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. Art Cudworth
Hydrology Branch
U.S. Bureau of Reclamation
Engineering and Research Center
P.O. Box 25007
Denver, Colorado 80225

Dear Art:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

Your assistance by reviewing the Rainfall Losses and Unit Hydrograph Procedures sections would be greatly appreciated.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft sections of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. Robin McArthur
Soil Conservation Service
201 E. Indianola Ave.
Suite 200
Phoenix, Arizona 85012

Dear Mr. McArthur:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

Your assistance by reviewing the Rainfall, Rainfall Losses, and Unit Hydrograph Procedures sections would be greatly appreciated.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me and Mr. Joe Rumann at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft sections of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Dr. David Woolhiser
Arid Lands Watershed Management Research Unit
200 E. Allen Road
Tucson, Arizona 85719

Dear Dave:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

As we discussed in your office on 7 December, whatever level of review that you can provide of this material will be greatly appreciated, but do not feel under any obligation to undertake this task. I have enclosed the Rainfall, Rainfall Losses, and Unit Hydrograph Procedures sections for your information and possible review.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me and Mr. Joe Rumann at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft sections of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Dr. Leonard Lane
Arid Lands Watershed Management Research Unit
200 E. Allen Road
Tucson, Arizona 85719

Dear Leonard:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

As we discussed on 7 December, your assistance by reviewing the Rainfall Losses section would be greatly appreciated. I have also enclosed the Rainfall and Unit Hydrograph Procedures sections for your general information, and your review of these sections is also encouraged but not requested.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me and Mr. Joe Rumann at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft sections of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Dr. Herb Osborn
2341 South Lazy A Place
Tucson, Arizona 85713

Subject: Maricopa County Hydrology Manual and
ADOT Highway Drainage Design Manual

Dear Herb:

As you may be aware, the Flood Control District of Maricopa County is preparing a Hydrology Manual for use in Maricopa County, and the Arizona Department of Transportation is preparing a Highway Drainage Design Manual for use throughout the state of Arizona. I have talked to you on several occasions about data from Walnut Gulch and about rainfall criteria for use within Maricopa County and Arizona. The Rainfall section of the Maricopa County Hydrology Manual has been drafted, and I would appreciate it if you could review this and provide comments to me. Keep in mind that this is for Maricopa County but I would also like your comments in regard to using the same, or similar type of rainfall criteria for use throughout Arizona in the ADOT Highway Drainage Design Manual.

I apologize for not talking to you about this in advance of this letter, but I have not been successful in contacting you by phone during the holidays. I visited Dave Woolhiser and Leonard Lane in Tucson on 7 December. I had planned to call you that day but I was unexpectedly called away from Tucson on other matters and I couldn't talk to you. I am sending the Rainfall, Rainfall Losses, and Unit Hydrograph Procedures sections to Dave for his information and possible review, contingent on his time for such a review. Leonard has agreed to review the Rainfall Losses section. Your review of the Rainfall section would be very valuable because of your familiarity with the subject and your expertise in this area. I realize that you have retired from the ARS, and I'm sure that I could provide some amount of consulting fee to you for this review.

I will be out of the country from 1 January through 5 February.

When I return I will contact you regarding this. Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosure: Rainfall section of Maricopa County Hydrology Manual

Copy: Mr. Joe Rumann, Flood Control District of Maricopa County
Mr. V. Ottozawa-Chatupron, Arizona Transportation Research Center

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. Walter Rawls
ARS, U.S. Dept. of Agriculture
Agri. Research Center - West
Bldg. 007, Rm. 137
Beltsville, MD 20705

Dear Walter:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of a section of the draft of that manual.

As we previously discussed, your assistance by reviewing the Rainfall Losses section would be greatly appreciated.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft section of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Dr. Herman Bouwer
U.S. Water Conservation Lab.
4331 E. Broadway
Phoenix, Arizona 85040

Dear Herman:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review, if possible.

You or your staff may be interested in the Rainfall Losses section and I would appreciate any review and comment that you would wish to make. However, do not feel under any obligation to undertake this task.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft section of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. V. Ottozawa-Chatupron
Senior Research Engineer
Arizona Transportation Research Center
College of Engineering
Arizona State University
Tempe, Arizona 85287

Subject: Maricopa County Hydrology Manual and
ADOT Highway Drainage Design Manual

Dear Ott:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

I am enclosing the Rainfall, Rainfall Losses, and Unit Hydrograph Procedures sections for your information and review. You may wish to consider your review in regard to the ADOT Highway Drainage Design Manual and these are submitted to you as a supplement to the Task 1 Interim Report.

I will call you in February to receive any comments and suggestions that you may have, or you may mail them to me and Mr. Joe Rumann at your convenience.

Thank you in advance for your cooperation.

Sincerely yours,

George V. Sabol

Enclosures: Copy of draft section of Hydrology Manual as noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County
Mr. Richard Perry, NBS/Lowry
Mr. Doug Sovern, MWE
Mr. Robert Ward

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

30 December 1988

Mr. C.O. Clark
Consulting Engineer
2121 E. 22nd Place
Tulsa, OK 74114

Dear Mr. Clark:

I haven't taken the opportunity to communicate with you since your letter of 14 May 1988. It is my privilege to once more write to you and to make both a personal and professional request to review the enclosed. The Flood Control District of Maricopa County, Arizona is presently preparing a Hydrology Manual. As you will notice from the enclosed, the Flood Control District is recommending two unit hydrograph procedures, one of which is the Clark Unit Hydrograph. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of the Unit Hydrograph Procedures section of that manual. You can send your comments and suggestions to me. I will be unavailable until after 6 February so there is no urgency for this.

Thank you in advance for your cooperation and assistance.

I hope all is well with you, and I look forward to the opportunity to meet you someday.

Sincerely yours,

George V. Sabol

Enclosures: As noted.

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

APPENDIX 5-B

Review Comments and Correspondence with Dr. Walter Rawls

United States Department of Agriculture
Agricultural Research Service
Beltsville Area
Beltsville Agricultural Research Center
Beltsville, Maryland 20705

March 23, 1989

SUBJECT: Review of Rainfall Losses Section of Hydrology Manual

TO: George Sabol
1351 E 141 st. Ave.
Brighton, CO 80601

FROM: Walter J. Rawls Walter Rawls
Hydrologist

The above section is well put together and I only have a few comments which you might want to consider. First you might want to add the effect of rocks in the soil on hydraulic conductivity (see attached publication). Second, you might want to add a table grouping soil textures into hydrologic soil groups, see attached. Finally, since curve numbers are still majorly used, you might want to use fig. 2 relating curve number hydrologic condition saturated hydraulic conductivity.

PAPER NO. PNR-84-203

MODIFYING SCS HYDROLOGIC SOIL GROUPS AND CURVE NUMBERS FOR RANGELAND SOILS

D. L. Brakensiek
Res. Hydraulic Eng.
USDA-ARS
NW Watershed Res. Center
Boise, ID

W. J. Rawls
Hydrologist
USDA-ARS
Hydrology Lab.
Beltsville, MD

G. R. Stephenson
Geologist
USDA-ARS
NW Watershed Res. Center
Boise, ID

For presentation at the 1984 Annual Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS
PACIFIC NORTHWEST REGION

Cavanaugh's Motor Inn
Kennewick, WA
September 26-28, 1984

SUMMARY:

Procedures are proposed for determining SCS hydrologic soil groups and curve numbers for rangeland soils. The procedures utilize the SCS Soils-5 data base and previously developed infiltration research results. An example for the USDA-ARS Reynolds Creek research watershed in Idaho is presented.

American Society of Agricultural Engineers

St. Joseph, Michigan 49085

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The Society is not responsible for statements or opinions advanced in papers or discussions at its meetings. Papers have not been subjected to the review process by ASAE editorial committees; therefore, are not to be considered as refereed.

Modifying SCS Hydrologic Soil Groups and Curve Numbers for Rangeland Soils[1]

D. L. Brakensiek, W. J. Rawls, and G. R. Stephenson[2]

Alternative determinations of SCS hydrologic soil groups (HSG) and runoff curve numbers (CN) procedures are presented along with examples. The procedure utilizes the SCS Soils-5 data base. Use of this data base is facilitated by SIRS (Soils Information Retrieval Systems) facilites use of this data base.

SOILS DATA

The SCS Soils-5 file represents the largest and most available U.S. soils data bank. SIRS has now greatly facilitated access to Soils-5. Since the Soils-5 data file does not include certain soil water properties such as percent sand, R. B. Grossman of the National Soils Survey Laboratory, SCS, Lincoln, Nebraska, developed expressions for calculating these quantities from the Soils-5 data. He cautions that the exactness of the approximations may vary and that they should only be used if measurements for particular properties are unavailable.

Table 1 presents Soils-5 property entries from SIRS for the Searla soil series (found on the Reynolds Creek watershed in Idaho). We have added a letter code for reference to the following calculations. Necessary soil properties which we require but are not available on SOILS 5 are: Z1, the percent of fragments < 250 mm, > 2 mm by weight, and Z5, the percent sand.

These can be calculated from the Grossman expressions as,

$$Z1 = E + \left[\left(1 - \frac{E}{100}\right)(100 - G)\right], \qquad (1)$$

where

E = percent fraction greater than 3 inches (E),
G = percent material less than 3 inches passing sieve #10 (G),
and

---

[1]Contribution from the USDA, Agricultural Research Service; Northwest Watershed Research Center, 270 South Orchard, Boise, ID 83705, and Hydrology Laboratory, Room 139, Building 007, BARC-West, Beltsville, MD 20705.

[2]Research Hydraulic Engineer, Northwest Watershed Research Center, Boise, ID 83705, Hydrologist, Hydrology Laboratory, Beltsville, MD 20705, and Geologist, Northwest Watershed Research Center, Boise, ID 83705.

TABLE 1. SOILS-5 FILE FOR SEARLA SOIL SERIES

--*-*-*-*-*-*-*-*-*

searla (id0929)cool

mlra(s): 25
rev. th,ghl , 12-82
calcic argixerolls, loamy-skeletal, mixed, frigid

the searla series consists of very deep well drained soils that formed in colluvium from sedimentary rocks on mountains. elevation is 5500 to 6900 feet. aap is 14 to 16 ihes. mast is 42 to 45 f. ffs is 50 to 70 days. vegetation is mountain big sagebrush and bluebunch wheatgrass. typically the surface layer is brown gravelly loam 15 inches thick. the subsoil is yellowish brown very gravelly clay loam to 32 inches. the substratum is white very gravelly loam and very pale brown very gravelly sandy loam to 60 inches. slopes are 30 to 60 percent.

--*-*-*-*-*-*-*-*-*

searla (id0929)cool

A depth (in.)	B texture	C unified	D aashto	E fract > 3in (pct)	F percent of material less than 3 in passing sieve no. 4	G 10	H 40	I 200	J liquid limit	K plast'y index	M clay %<2mm	N moist bulk density (g/cm3)
0-15	gr-l	sm-sc,gm-gc	a-4	5-10	65-85	60-80	45-60	35-50	25-30	5-10	12-20	1.40-1.50
15-32	grv-cl	gc	a-2	5-15	45-60	35-50	25-40	20-35	30-40	10-15	27-35	1.40-1.50
32-60	grv-l,grv-sl	gm-gc	a-1,a-2	0-15	35-60	25-50	15-35	10-30	25-30	5-10	10-22	1.50-1.60

O permea- bility (in/hr)	P available water (in/in)	Q soil reaction (ph)	R salinity mmhos/cm	S shrink- swell	T erosion factors k	U t	V wind erod. group	W organic matter (pct)
0.6-2.0	0.13-0.16	6.6-7.3	-	low	.15	2	6	2-4
0.2-0.6	0.10-0.13	6.6-7.3	-	low	.10			
0.6-2.0	0.05-0.09	7.4-8.4	< 2	low	.05			

$$Z5 = 100 - \frac{100\ I}{G} \qquad (2)$$

where

I = percent material less than 3 inches passing sieve #200 (I).

PROPOSED HYDROLOGIC SOIL GROUP (HSG) PROCEDURES

Our procedure for determining the HSG is based on knowing the percent sand and clay, and soil porosity. If Soils-5 data are used, then the percent sand (Z5) is calculated by equation (2).

Calculation of the soil porosity from the moist bulk density (N), if not given in Soils-5, is computed as follows:

1 - Enter Fig. 1 with the percent sand (Z5) and clay (M) and read the mineral bulk density.

2 - Use the equation in Fig. 1 to calculate the Soil Bulk Density (SBD) with an appropriate percent of organic matter (OM) (W).

3 - Calculate the total porosity as,

Porosity = 1 - SBD/2.65.

If the Soils-5 data contains bulk density, then calculate the porosity from that value. With the inputs of percent sand and clay and porosity, enter the computer program shown in Table 2 to determine the fine earth fabric saturated conductivity, KS. Table 3 presents a sample output. For our purposes, only the KS from the output is needed.

With the saturated hydraulic conductivity (KS) known, determine the hydrologic soil group (HSG) from Table 4. Rangeland soils may require a modification due to conditions, such as stone or coarse fragment content, soil compaction, or frozen soils. These modifications are considered in the next section. The saturated conductivity limits for A, B, C, and D were taken from Musgrave (1955).

Wood and Blackburn (1984) indicated that the hydrologic soil groupings should be "greatly modified" for use in arid and semiarid rangelands, especially to make more use of surface soil properties.

RANGELAND SOIL MODIFICATIONS

Coarse Materials

Rangeland soils, such as those on the Reynolds Creek Watershed, contain significant amounts of coarse fragments. From work by Bouwer and Rice (1983) and unpublished SCS Soils-5 based equations, developed by Grossman (1983), a relationship was developed for calculating the soil porosity for the bulk soil containing coarse fragments,

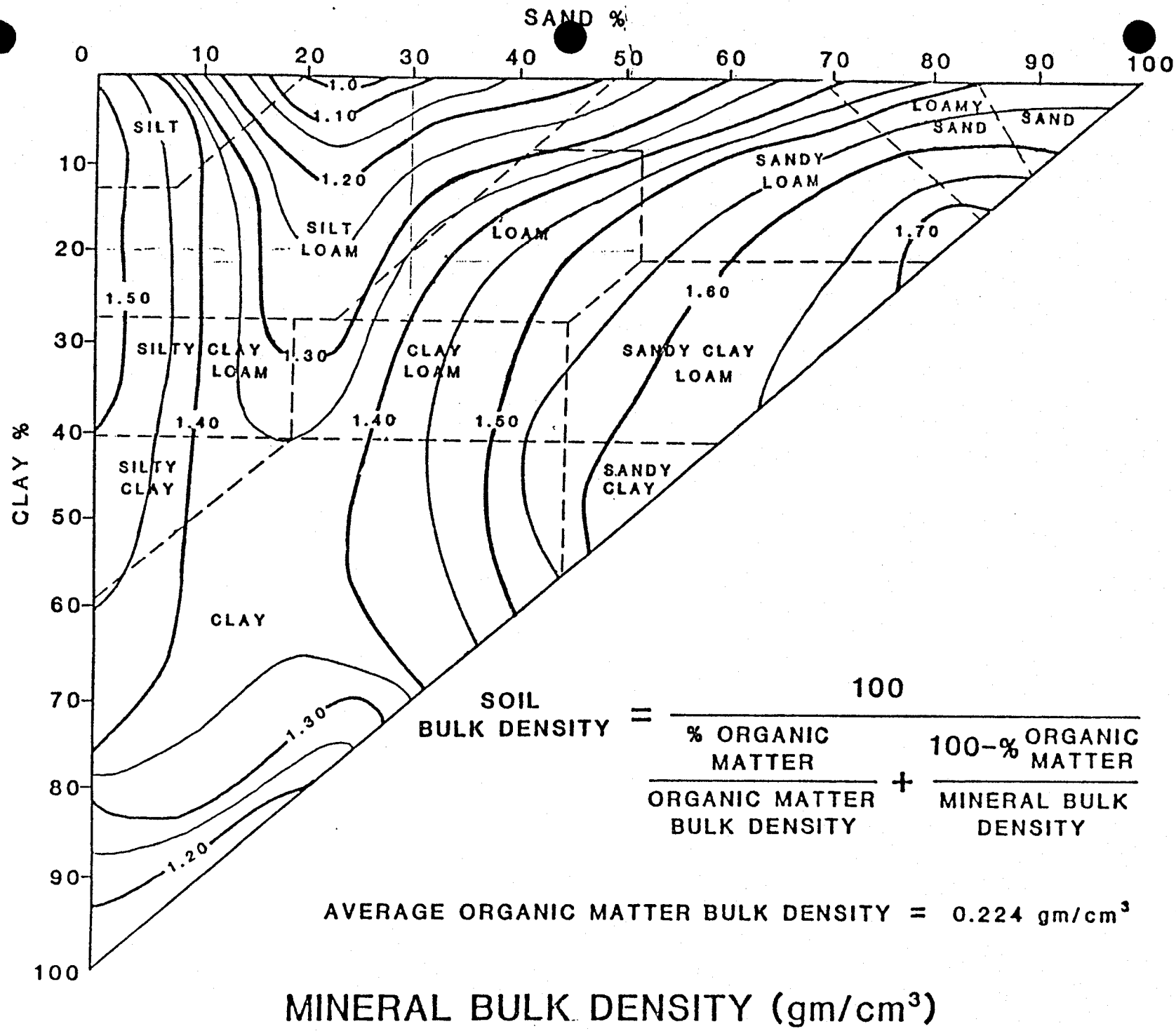

Fig. 1--Determination of soil bulk density.

TABLE 2. PROGRAM TO FIND SOIL PARAMETERS

POR = POROSITY PS = PERCENT SAND = % SAND PC = PERCENT CLAY = % CLAY

```
      REAL*4 Ks,Yf,Qe,Qr,Yb,LAM
      CHARACTER*1 ANS
10    WRITE(6,20)
20    FORMAT(/,/,5X,'$ ENTER THE POROSITY: ',$)
      ACCEPT*, POR
      IF(POR .LT. 0.0 .OR. POR .GT. 1.0) GO TO 150
30    WRITE(6,40)
40    FORMAT(/,5X,'$ ENTER THE % OF SAND: ',$)
      ACCEPT*, SAND
      IF(SAND .LT. 5.0 .OR. SAND .GT. 70.0) GO TO 170
50    WRITE(6,60)
60    FORMAT(/,5X,'$ ENTER THE % OF CLAY: ',$)
      ACCEPT*, CLAY
      IF(CLAY .LT. 5.0 .OR. CLAY .GT. 60.0) GO TO 190
      PS=SAND
      PC=CLAY

    EQUATIONS DESCRIBING GREEN-AMPT PARAMETER CHARTS

      Qe=0.01162-0.001473*PS-0.002236*PC+0.98402*POR+0.0000987*PC**2
     1+0.003616*PS*POR-0.010859*PC*POR-0.000096*PC**2*POR-0.002437*
     2POR**2*PS+0.0115395*POR**2*PC

      Yf=6.5309-7.32561*POR+0.001583*PC**2+3.809479*POR**2+0.000344*
     1PS*PC-0.049837*PS*POR+0.001608*PS**2*POR**2+0.001602*PC**2*
     2POR**2-0.0000136*PS**2*PC-0.003479*PC**2*POR-0.000799*PS**2*POR

      Yf = EXP(Yf)

      Ks=19.52348*POR-8.96847-0.028212*PC+0.00018107*PS**2-0.0094125*
     1PC**2-8.395215*POR**2+0.077718*PS*POR-0.00298*PS**2*POR**2-
     20.019492*PC**2*POR**2+0.0000173*PS**2*PC+0.02733*PC**2*POR+
     30.001434*PS**2*POR-0.0000035*PC**2*PS

      Ks = EXP(Ks)

      Qr=-0.0182482+0.00087269*PS+0.00513488*PC+0.02939286*POR
     1-0.00015395*PC**2-0.0010827*PS*POR-0.00018233*(PC**2)*
     2(POR**2)+0.00030703*(PC**2)*POR-0.0023584*(POR**2)*PC

      LAM=-0.7842831+0.0177544*PS-1.062498*POR-0.00005304*PS**2
     1-0.00273493*PC**2+1.11134946*POR**2-0.03088295*PS*POR
     2+0.00026587*(PS**2)*(POR**2)-0.00610522*(PC**2)*(POR**2)
     3-0.00000235*(PS**2)*PC+0.00798746*(PC**2)*POR-0.00674491
     4*(POR**2)*PC

      LAM = EXP(LAM)
```

TABLE 2. PROGRAM TO FIND SOIL PARAMETERS (CONT.)

```
      Yb=5.3396738+0.1845038*PC-2.48394546*POR-0.00213853*
      1PC**2-0.04356349*PS*POR-0.61745089*PC*POR+0.00143598
      2*(PS**2)*(POR**2)-0.00855375*(PC**2)*(POR**2)-0.00001282*
      3(PS**2)*PC+0.00895359*(PC**2)*POR-0.00072472*(PS**2)*POR
      4+0.0000054*(PC**2)*PS+0.50028060*(POR**2)*PC

      Yb = EXP(Yb)
---------------
      BARTHD=.1535-.0018*PS+.0039*PC+.1943*POR
      BAR15 =.0370-.0004*PS+.0044*PC+.0482*POR

    OUTPUT SECTION

      WRITE(6,70) POR,SAND,CLAY
 70   FORMAT(/,/,/,12X,'POROSITY',5X,'% SAND',5X,'% CLAY',/,
      112X,F7.5,6X,F6.2,5X,F6.2)
      WRITE(6,80) Qe
 80   FORMAT(/,/,5X,'EFFECTIVE POROSITY = ',F7.4)
      WRITE(6,85) LAM
 85   FORMAT(/,5X,'POROSITY INDEX      = ',F7.4)
      WRITE(6,90) Yf
 90   FORMAT(/,5X,'WETTING FRONT CAPILLARY PRESSURE = ',F10.4,' cm')
      WRITE(6,100) Ks
 100  FORMAT(/,5X,'SATURATED HYDRAULIC CONDUCTIVITY = ',F10.5,' cm/hr')
      WRITE(6,110) BARTHD
110   FORMAT(/,5X,'ONE THIRD BAR WATER CONTENT      = ',F10.4)
      WRITE(6,120) BAR15
120   FORMAT(/,5X,'15 BAR WATER CONTENT             = ',F10.4)
      WRITE(6,125) Qr
125   FORMAT(/,5X,'RESIDUAL WATER CONTENT           = ',F10.4)
      WRITE(6,126) Yb
126   FORMAT(/,5X,'BUBBLING PRESURE                 = ',F10.4,' cm')
      WRITE(6,130)
 130  FORMAT(/,/,/,5X,'$ WOULD YOU LIKE TO CALCULATE ANY MORE?(y/n) ',$)
      READ(5,140) ANS
 140  FORMAT(A1)
      IF(ANS .EQ. 'Y' .OR. ANS .EQ. 'y') GO TO 10
      STOP

    ERROR CHECKING

 150  WRITE(6,160)
 160  FORMAT(/,/,5X,'ERROR IN POROSITY,  value must be > 0 and < 1')
      GO TO 10
 170  WRITE(6,180)
 180  FORMAT(/,/,5X,'ERROR IN PERCENTAGE OF SAND, value must be > 5 and
      1 < 70')
      GO TO 30
 190  WRITE(6,200)
 200  FORMAT(/,/,5X,'ERROR IN PERCENTAGE OF CLAY, value must be > 5 and
      1 < 60')
      GO TO 50
      END
```

TABLE 3. SAMPLE OUTPUT

```
RUN SOILS

   $ ENTER THE POROSITY: 0.45

   $ ENTER THE % OF SAND: 39

   $ ENTER THE % OF CLAY: 16

         POROSITY      % SAND      % CLAY
         0.45000        39.00       16.00

   EFFECTIVE POROSITY =  0.3788

   POROSITY INDEX     =  0.3460 (GREEN AND AMPT λ)

   WETTING FRONT CAPILLARY PRESSURE =    21.1312 cm (GREEN AND AMPT ψf)

   SATURATED HYDRAULIC CONDUCTIVITY =    0.59637 cm/hr

   ONE THIRD BAR WATER CONTENT      =     0.2331

   15 BAR WATER CONTENT             =     0.1135

   RESIDUAL WATER CONTENT           =     0.0710 (GREEN AND AMPT Θr)

   BUBBLING PRESURE                 =    27.4790 cm

   $ WOULD YOU LIKE TO CALCULATE ANY MORE?(y/n) N

FORTRAN STOP
```

Table 4.--SCS hydrologic soil groups for saturated conductivity (KS) classes.

HSG (KS cm/hr)	Description
A (0.76-1.14)[1]	(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 (0.38-0.76)	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 (0.13-0.38)	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer than impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D (0.0-0.13)	(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.

[1]It is assumed that a KS greater than 1.14 cm/hr is an "A" soil.

$$\phi_c = (1 - \frac{Z1}{100}) / (\frac{1}{\phi} - \frac{Z1}{100}) \quad (3)$$

where

ϕ_c = the bulk soil porosity (with coarse fragments),
ϕ = fine earth fabric, < 2 mm, porosity, and
Z1 = percent by weight of the soil material > 2 mm and < 250 mm,

where Z1 is calculated from Soils-5 data by equation (3). The value of ϕ is the porosity determined from Fig. 1 by the procedure described in the text or taken from the Soils-5 data file.

Equation (4) was also derived from the results of Bouwer and Rice (1983). The saturated conductivity can be calculated for the soil containing coarse fragments, K_c, from the conductivity of the fine earth fraction, KS, and the percent by weight of coarse fragments, Z1. If Z1 is not known it is calculated by equation (1).

$$K_c = (1 - \frac{Z1}{100}) KS \quad (4)$$

The value of K_c is entered in Table 4 and a hydrologic soil group is determined for the bulk soil. The computer program in Table 2 can be entered with ϕ_c to determine bulk soil properties other than the saturated hydraulic conductivity, which is determined by equation (4). Equation (4) is also similar to one derived by Peck and Watson[3]. Additional research on gravels in soils is presented by Dunn and Mehuys (1984).

Compacted Soils

Soil bulk densities can change as a function of land use which induce compaction. As the bulk density increases the bulk soil porosity will decrease, which may change the HSG. Our procedure is simply to change the original bulk density by the percent change and compute a new porosity. The program in Table 2 is entered with a new porosity, and the calculated KS value is used in Table 4 to determine the HSG.

FROZEN SOILS

Frozen soil conditions frequently occur on rangelands. The following procedure was developed by Lee (1983) from his study of a frozen soil. He related the ratio of the frozen soil saturated conductivity $(KS)_f$ to the unfrozen soil KS as a function of antecedent soil water content. We have expressed his

[3]Peck, A. J., and J. D. Watson. 1979. Hydraulic conductivity and flow in non-uniform soil. Unpublished paper, presented at the Workshop on Soil Physics and Field Heterogeneity, Canberra, Australia, p. 31-36.

antecedent soil water factor as a percent of field capacity. One-third bar water contents are also estimated in our computer program. Equations (5a,b) present Lee's relationships,

$$(KS)_f/KS = 1.89 - 0.023\ (\%\ \text{of FC}), \quad \%FC < 78 \tag{5a}$$

and

$$= 0.1 \quad , \quad \%F > 78. \tag{5b}$$

For example, if it is estimated that the antecedent soil water content when the ground is frozen was 50 percent of field capacity, then by equation (5a)

$$(KS)_f/KS = 0.74.$$

Thus, if the original hydrologic soil group was "B", KS = 0.45 cm/hr, then

$$(KS)_f = 0.33 \text{ cm/hr}$$

and the HSG determined from Table 4 would be reduced to a "C" soil. Equations (5a,b) should be used very cautiously, since they are based on laboratory tests of only one soil texture. However, they do indicate the hydrologic importance of frozen soils.

SURFACE ROCK COVER

A thesis study by Dadkhah (1979) indicated that rock cover on the soil surface, from 0 percent to 20 percent, decreased the SCS curve number by nearly 10 percent. Apparently surface rock cover is a signficant factor to consider on rangeland curve number hydrology, but more research is needed to quantify its effect. The same thesis study also investigated the interactions of rock cover, vegetation cover, and soil compaction.

RANGELAND RUNOFF CURVE NUMBERS

Standard SCS procedures for determining rangeland CN's are given in Tables 8.1, 8.2, and 9.1 of their Hydrology Guide (SCS 1972). Inputs are land use treatment or practice, hydrologic condition, and hydrologic soil group (HSG). The HSG can be estimated by our procedure.

We propose an alternative procedure which uses the KS parameter directly, rather than the hydrologic soil group. We developed Fig. 2 by combining Tables 8.1, 8.2, and 9.1, and our Table 4. Fig. 2 would be entered with the estimated KS value and with an estimated hydrologic condition (HC), i.e., cover class. We are suggesting that HC can be estimated from percent cover. Based on SCS Table 8.2, the cover classes were defined as shown in Fig. 2 for bare, poor, fair, and good cover. The lines in Fig. 2 were oriented with the four points in their Table 9.1 representing the curve numbers for a bare, poor, fair and good HC plotted versus the mid-point KS for each HSG. For interpretation between classes, we developed the following equation assuming the average cover percent shown in Fig. 2 for each class.

$$CN = 96.38 - 0.158C - 19.84K - 0.397KC \tag{6}$$

where

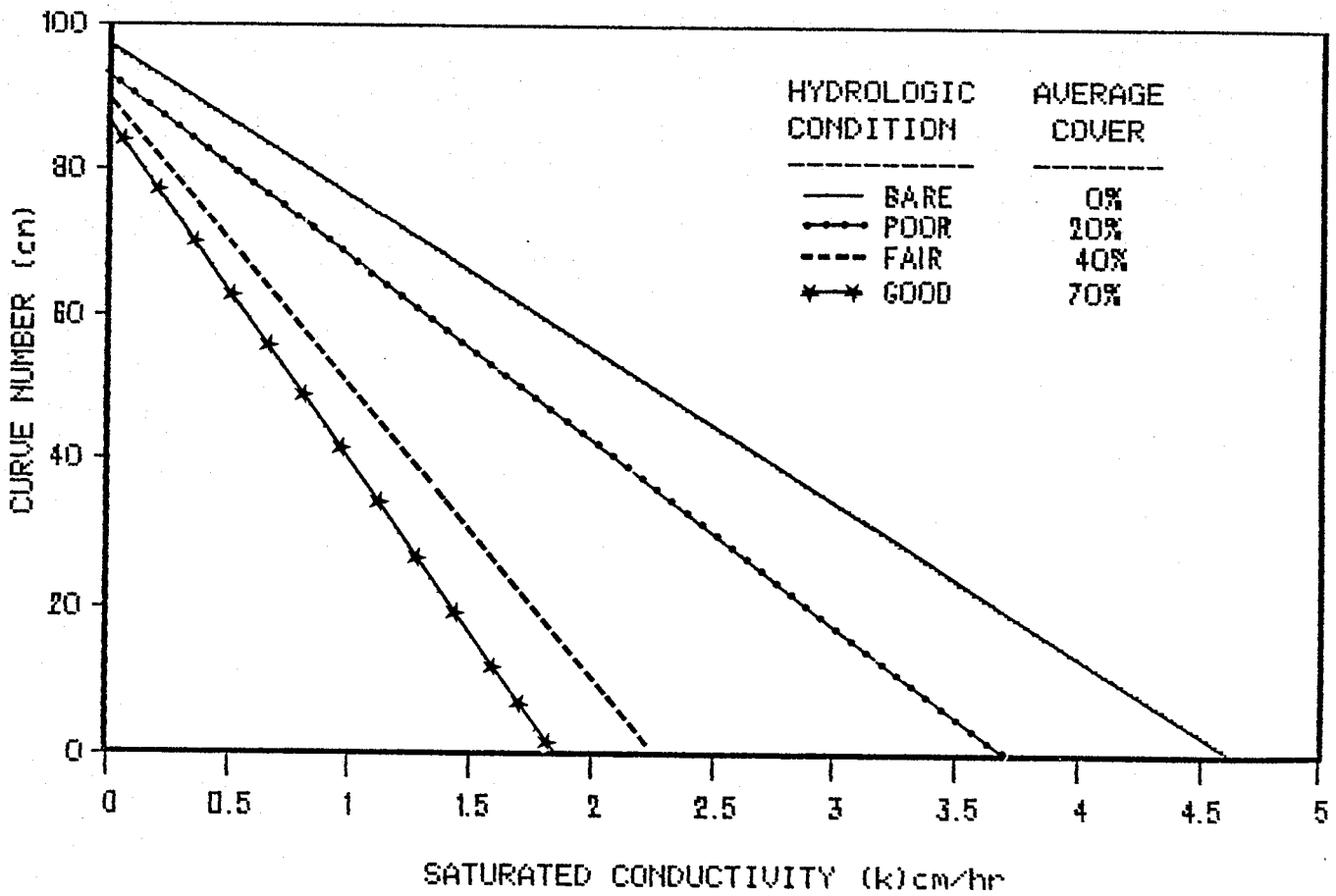

Fig. 2--Rangeland curve numbers as a function of saturated conductivity for cover classes.

CN = Curve Number,
C = total cover in percent, and
K = saturated conductivity, cm/hr.

EXAMPLES

Given: Reynolds Creek Soils-5 data for Searla (id0929) cool

(1) Find - percent sand

Sand (%) = Z5 = 100 - 100 I/G

I = percent material < 3" passing #200 sieve = 35 - 50 percent
G = percent material < 3" passing #10 sieve = 60 - 80 percent.

Using the midpoint value for I and G

Sand (%) = 100 - 100 (42.5/70)
= 39 percent.

(2) Find - percent by weight of material > 2 mm and < 250 mm = Z1

$$Z1 = E + \left[\left(1 - \frac{E}{100}\right)(100-G)\right]$$

E = percent fraction > 3 inches
G = percent material < 3 inches passing the #10 sieve.

From Soils-5

E = 5 - 10 percent
G = 60 - 80 percent

$$Z1 = 7.5 + \left[\left(1 - \frac{7.5}{100}\right)(100 - 70)\right]$$

Z1 = 35 percent.

(3) Find - Hydrologic Soil Group

From the Soils-5, the percent clay (M) is 12 - 20 with the mid-value of 16 percent and the percent of sand (Z5) is 39 percent.

The measured moist bulk density (N) is 1.4 - 1.5 with a mid-value of 1.45.

From our computer program

KS = 0.60 cm/hr.

Referring to Table 4, this soil is Hydrologic Soil Group B.

If we assume a total cover of 30 percent cover, the calculated curve number is

CN = 72.

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3 April 1989

Mr. Walter Rawls
ARS, U.S. Dept. of Agriculture
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Subject: FCDMC Hydrology Manual

Dear Walter:

Thank you for your review comments of 23 March 1989. I will incorporate your suggestions into the manual. I have one question for which I would like your response. This is in regard to the values of the Green and Ampt parameters for loam and silt loam in Table 2 of Green-Ampt Infiltration Parameters from Soils Data by Rawls, Brakensiek, and Miller (ASCE, Hyd. Engineering, Vol. 109, No. 1). Specifically, on the table the value of hydraulic conductivity for loam is 0.34 cm/hour and for silt loam is 0.65 cm/hour, and the capillary pressures are 8.89 cm and 16.68 cm, respectively. Since loam generally has a higher sand content than silt loam I would think that these values should be reversed, and that loam would have a greater hydraulic conductivity than silt loam. Is there some reason for this anomaly, or is there a possible error in this table?

Sincerely yours,

George V. Sabol

Enclosure: Copy of Table 2

Copy: Mr. Joe Rumann, Flood Control District of maricopa County

George
you are correct the numbers were transposed
Walter

FIG. 1.—Distribution of Soils

in which θ = soil water content, in cubic centimeters per cubic centimeter; θ_r = residual saturation, in cubic centimeters per cubic centimeter; ϕ = total porosity, in cubic centimeters per cubic centimeter; ψ_b = bubbling pressure, in centimeters; ψ = capillary pressure, in centimeters; and λ = the pore-size distribution index.

The Green and Ampt parameters can be calculated from the estimated Brooks and Corey constants as follows: The wetting front capillary pressure term, ψ_f, is calculated by (2)

$$\psi_f = \frac{2\lambda + 3}{2\lambda + 2}\left(\frac{\psi_b}{2}\right) \quad \text{(4)}$$

The effective porosity, θ_e, is calculated as

$$\theta_e = \phi - \theta_r \quad \text{(5)}$$

in which ϕ = the total porosity, in cubic centimeters per cubic centimeter, and is calculated from bulk density and particle density; and θ_r = the residual soil-water content, in cubic centimeters per cubic centimeter. The Green and Ampt hydraulic conductivity, K, based on Bouwer's (4) findings that it is one-half the saturated hydraulic conductivity, is calculated as

$$K = \frac{K_s}{2} \quad \text{(6)}$$

in which the saturated conductivity, K_s, is calculated by an equation (Ref. 5) derived by substituting the Brooks and Corey equation into the Childs, Collis-George permeability integral (6) given by

$$K_s = a\frac{\phi_e^2}{\psi_b^2}\left[\frac{\lambda^2}{(\lambda + 1)(\lambda + 2)}\right] \quad \text{(7)}$$

in which a = a constant representing the effects of various fluid con-

TABLE 2.—Green and Ampt Parameters According to Soil Texture Classes and Horizons

Soil texture class (1)	Horizon (2)	Sample size (3)	Total porosity, ϕ, in cubic centimeters per cubic centimeters (4)	Effective porosity, θ_e, in cubic centimeters per cubic centimeters (5)	Wetted front capillary pressure, ψ_f,[a] in centimeters (6)	Hydraulic conductivity, K,[b] in centimeters per hour (7)
Sand[c]		762	0.437 (0.374–0.500)[d]	0.417 (0.354–0.480)	4.95 (0.97–25.36)	11.78
	A	370	0.452 (0.396–0.508)	0.431 (0.375–0.487)	5.34 (1.24–23.06)	
	B	185	0.440 (0.385–0.495)	0.421 (0.365–0.477)	6.38 (1.31–31.06)	
	C	127	0.424 (0.385–0.463)	0.408 (0.365–0.451)	2.07 (0.32–13.26)	
Loamy sand		338	0.437 (0.363–0.506)	0.401 (0.329–0.473)	6.13 (1.35–27.94)	2.99
	A	110	0.457 (0.385–0.529)	0.424 (0.347–0.501)	6.01 (1.58–22.87)	
	B	49	0.447 (0.379–0.515)	0.412 (0.334–0.490)	4.21 (1.03–17.24)	
	C	36	0.424 (0.372–0.476)	0.385 (0.323–0.447)	5.16 (0.76–34.85)	
Sandy loam		666	0.453 (0.351–0.555)	0.412 (0.283–0.541)	11.01 (2.67–45.47)	1.09
	A	119	0.505 (0.399–0.611)	0.469 (0.330–0.608)	15.24 (5.56–41.76)	
	B	219	0.466 (0.352–0.580)	0.428 (0.271–0.585)	8.89 (2.02–39.06)	
	C	66	0.418 (0.352–0.484)	0.389 (0.310–0.468)	6.79 (1.16–39.65)	
Loam		383	0.463 (0.375–0.551)	0.434 (0.334–0.534)	8.89 (1.33–59.38)	0.34
	A	76	0.512 (0.427–0.597)	0.476 (0.376–0.576)	10.01 (2.14–46.81)	
	B	67	0.512 (0.408–0.616)	0.498 (0.382–0.614)	6.40 (1.01–40.49)	
	C	47	0.412 (0.350–0.474)	0.382 (0.305–0.459)	9.27 (0.87–99.29)	
Silt loam		1,206	0.501 (0.420–0.582)	0.486 (0.394–0.578)	16.68 (2.92–95.39)	0.65
	A	361	0.527 (0.444–0.610)	0.514 (0.425–0.603)	10.91 (1.89–63.05)	
	B	267	0.533 (0.430–0.636)	0.515 (0.387–0.643)	7.21 (0.86–60.82)	
	C	73	0.470 (0.409–0.531)	0.460 (0.396–0.524)	12.62 (3.94–40.45)	
Sandy clay loam		498	0.398 (0.332–0.464)	0.330 (0.235–0.425)	21.85 (4.42–108.0)	0.15
	A	—[e]	— —	— —	— —	
	B	198	0.393 (0.310–0.476)	0.330 (0.223–0.437)	26.10 (4.79–142.30)	
	C	32	0.407 (0.359–0.455)	0.332 (0.251–0.413)	23.90 (5.51–103.75)	
Clay loam		366	0.464 (0.409–0.519)	0.309 (0.279–0.501)	20.88 (4.79–91.10)	0.10
	A	28	0.497 (0.434–0.560)	0.430 (0.328–0.532)	27.00 (6.13–118.9)	
	B	99	0.451 (0.401–0.501)	0.397 (0.228–0.530)	18.52 (4.36–78.73)	
	C	55	0.452 (0.412–0.492)	0.400 (0.320–0.480)	15.21 (3.79–61.01)	
Silty clay loam		689	0.471 (0.418–0.524)	0.432 (0.347–0.517)	27.30 (5.67–131.50)	0.10
	A	65	0.509 (0.449–0.569)	0.477 (0.410–0.544)	13.97 (4.20–46.53)	
	B	191	0.469 (0.423–0.515)	0.441 (0.374–0.508)	18.56 (4.08–84.44)	
	C	39	0.475 (0.436–0.514)	0.451 (0.386–0.516)	21.54 (4.56–101.7)	
Sandy clay		45	0.430 (0.370–0.490)	0.321 (0.207–0.435)	23.90 (4.08–140.2)	0.06
	A	—	— —	— —	— —	
	B	23	0.435 (0.371–0.499)	0.335 (0.220–0.450)	36.74 (8.33–162.1)	
	C	—	— —	— —	— —	
Silty clay		127	0.479 (0.425–0.533)	0.423 (0.334–0.512)	29.22 (6.13–139.4)	0.05
	A	—	— —	— —	— —	
	B	38	0.476 (0.445–0.507)	0.424 (0.345–0.503)	30.66 (7.15–131.5)	
	C	21	0.464 (0.430–0.498)	0.416 (0.346–0.486)	45.65 (18.27–114.1)	
Clay		291	0.475 (0.427–0.523)	0.385 (0.269–0.501)	31.63 (6.39–156.5)	0.03
	A	—	— —	— —	— —	
	B	70	0.470 (0.426–0.514)	0.412 (0.309–0.515)	27.72 (6.21–123.7)	
	C	23	0.483 (0.441–0.525)	0.419 (0.294–0.544)	54.65 (10.59–282.0)	

[a]Antilog of the log mean and standard deviation.
[b]Values for Rawls, et al. (13).
[c]Values for the texture class.
[d]Numbers in ( ) ± one standard deviation.
[e]Insufficient sample to determine parameters.

A Note on Determining Soil Properties for Soils Containing Rock Fragments

D.L. BRAKENSIEK, W.J. RAWLS, AND G.R. STEPHENSON

Many rangeland soils contain a significant rock fraction which may modify soil properties, whereas most published soil and soil water data are for the fine earth fraction. A listing of equations is presented which calculates soil water properties for soils containing a rock fraction. It is seen that standardization is badly needed to describe properties of these soils. Especially needed is standardization to distinguish between bulk densities and particle densities as well as properties on a mass or volume basis. The classification of these soils is discussed by Miller and Guthrie (1984).

Table 1 presents published or derived equations for some common soil and water properties. Most of these relationships were

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Table 1. Soil and water properties.

Soil Property	Expression	Reference
Coarse Fraction:		
	R_m, wet or dry sieving and weighing	Flint and Childs (1984)
	$R_v = (BD_t/BD_{>2}) \bullet R_m$	Flint and Childs (1984)
	$f_v = (\rho_T/\rho_s) \bullet f_m$	Russo (1983)
	$R_m = \dfrac{1 - BD_{<2}/BD_t}{1 - BD_{<2}/BD_{>2}}$	Derived
	$R_v = \dfrac{BD_t - BD_{<2}}{BD_{>2} - BD_{<2}}$	Flint and Childs (1984)
	$\dfrac{R_v}{1 - R_v} = \dfrac{R_m}{(\rho_s/\rho_b)(1-R_m)}$	Derived
Bulk Density:		
	$\rho_b = \rho_T \dfrac{(1 - f_m)}{(1 - f_v)}$	Russo (1983)
	$BD_{<2} = BD_t \dfrac{(1 - R_m)}{(1 - R_v)}$	Flint and Childs (1984)
	$\rho_T = \left[f_m/\rho_s + \dfrac{(1 - f_m)}{\rho_b} \right]^{-1}$	Russo (1983)
Bulk Density:		
	$\rho_T = \left[\dfrac{1 - W}{\rho_s} \quad \dfrac{W}{\rho_b} \right]^{-1}$	Mehuys et al. (1975)
	$d_{(S+A)} = \left[\dfrac{1 - X_w}{d_S} \quad \dfrac{X_w}{d_A} \right]^{-1}$	Berger (1976)
	$\rho_T = (1 - f_v)\rho_b + (f_v)\rho_s$	Russo (1983)
	$BD_t = BD_{<2} + R_v(BD_{>2} - BD_{<2})$	Flint and Childs (1984)
	$BD_{>2} = (1 - P_{>2})PD_{>2}$	Flint and Childs (1984)
	ρ_t, BD_t Irregular Hole Bulk Density Sampler	Flint and Childs (1984) Russo (1983) Cunningham and Matelski (1968)
Water Content:		
	$\theta_w = (1 - R_w)\theta_b + R_w\,\theta_s$	Reinhart (1961) Flint and Childs (1984)
	$W_{vt} = (1 - R_v)W_{v<2} + (R_v)W_{v>2}$	Flint and Childs (1984)
	$W_v = W_m \bullet BD/\rho_w$	Hillel (1971)
Saturated Conductivity:		
	$K_s/K_o = \dfrac{2(1 - a)}{2 + a}$	Dunn and Mehuys (1984)
	$K_t/K_b = (1 - R_w)$	Brakensiek and Rawls (1985)

a, f_v, R_v = Coarse fraction (>2 mm) by volume
$d_{(S+A)}$, ρ_T, BD_t = Bulk density of field bulk soil
d_A, ρ_s, $BD_{>2}$ = Bulk density of coarse fraction (>2 mm)
$(1 - W)$, X_w, f_m, R_m = Coarse fraction by weight
d_s, ρ_b, $BD_{<2}$ = Bulk density of fine fraction (<2 mm)
$P_{>2}$ = Total porosity of coarse fraction
$PD_{>2}$ = Particle density of coarse fraction
W_{vt}, θ_w = Total field water content by volume
$W_{v<2}$, θ_b = Water content of fine fraction by volume
$W_{v>2}$, θ_s = Water content of coarse fraction by volume
$W_{m<2}$ = Water content of fine fraction by weight
K_s, K_t = Saturated conductivity of bulk soil
K_o, K_b = Saturated condutivity of fine fraction
ρ_w = Density of water

Note: All quantities in decimal form.

nner during a rainstorm having excessive intensities.

Four groups, A, B, C, and D, were defined by SCS soil scientists, with numerical limits established by Musgrave (1955). We have assumed that the conductivity parameter, K, of the Green and Ampt infiltration equation, which is approached after prolonged wetting, corresponds to the minimum infiltration rate used in the SCS classification of soils. The Green and Ampt equation is

$$f = K(1 + \frac{\psi_f n}{F}) \qquad (1)$$

where K = conductivity parameter,

ψ_f = wetting front suction parameter,

n = available soil porosity,

f = rate,

and F = accumulated amout.

K is one-half of the saturated conductivity, K_s.

Figure 1 is a soil texture triangle upon which the numerical limits for K have been used to delineate the hydrologic soil groups. This chart is adapted from our work on predicting Green and Ampt parameters from soil texture, organic matter content, and tillage practice factors (Rawls et al. 1983). The zero percent porosity change applies to the initial soil state.

An earlier report of our work presented the following tabulation of soil groups based on average soil texture conductivities:

Hydrologic soil grouping	Soil textures
A	Sand, loamy sand, and sandy loam
B	Silt loam and loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, and clay

This grouping was compared with soil groupings found in the SCS SOIL 5 File and is consistent with their A, B, C, and D classification.

Comparing the tabulation with figure 1 clearly shows the lumping involved in classifying soils only according to a soil texture class. For example using texture class, only, places a silt loam in a B group, whereas using particle size percentages (and organic matter) can place it in any of the four groups. The A and D soil groups are most nearly invariant with respect to soil texture. This lumping would infer inconsistencies in using curve number hydrology as part of a more physical based and distributed watershed model. However, the lumping of soil textures in soil groups is entirely consistent with the way that they were originally derived, that is, from small watershed or plot data.

Figure 1 can be used in curve number hydrology to group soils from available SCS soil survey information. Application of figure 1 to a soil profile containing several horizons of different texture can be handled by using the harmonic mean of the horizon conductivities. This requires definition of an effective or wetted soil depth.

GREEN-AMPT PARAMETERS

Figure 2 presents the Green and Ampt effective porosity parameter. The hydrologic soil groups do not line up with a particular effective porosity value. Figure 3 presents estimates of the Green and Ampt wetting front capillary potential parameter. There is a tendency for hydrologic soil groups to be characterized by a particular wetting front potential, that is, A = 10 cm; B = 20 cm; C = 40 cm; and D = 50 cm.

Even though figures 1, 2, and 3 indicate the SCS hydrologic soil groupings are not uniquely related to soil hydraulic and hydrologic properties, they do show that the Green and Ampt parameters can be estimated from readily available soil properties.

INITIAL ABSTRACTION

An advantage of the infiltration approach is that infiltration prior to runoff can be calculated (Mein and Larson 1971). The component of curve number hydrology, initial abstraction term I_a, is thus calculated rather than assumed to be a fixed percentage of total soil storage.

LAND USE AND TREATMENT

The cover component of the hydrologic soil-cover complex includes land use, land treatment, and land use and treatment class (hydrologic condition). The last appears to refer to the quality of the agronomic condition. We have developed a procedure to incorporate a change in soil porosity, which may result from agronomic practices, into estimating Green and Ampt infiltration parameters. From this result, it can be shown that the hydrologic soil grouping is not a fixed soil parameter but is significantly changed by soil porosity changes.

The physical condition of soil is significantly influenced by practices such as tillage, compaction, consolidation, crusting, incorporation of organic amendments, soil surface roughness, and vegetation cover. These can primarily influence the hydraulic properties of soils through changes in soil porosity. At present, our assumption is that the principal influence of agronomic practice is to change the total soil porosity. The pore-size distribution may also change, but there is little data on this aspect. Rawls et al. (1983), from a search of research data, were able to relate an initial increase in porosity to

were developed by assuming that the soil and rock fraction are each made up of porosity and solids on a mass or volume basis. An excellent discussion for the soil fraction alone is presented by Hillel (1971). At the end of Table 1, the symbols are defined corresponding to the key publications referenced since they are not standard.

References On Stony Soils

Berger, Eli. 1976. Partitioning the parameters of stony soils important in moisture determinations into their constituents. Plant and Soil. 44:201-207.

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Cunningham, R.L., and R.P. Matelski. 1968. Bulk density measurements on certain soils high in coarse fragments. Soil Sci. Soc. Amer. Proc. 32:109-111.

Hillel, Daniel. 1971. Soil and water: physical principles and processes. Academia Press, New York and London.

Mehuys, G.R., L.H. Stolzy, J. Letey, and L.V. Weeks. 1975. Effect of stones on the hydraulic conductivity of relatively dry desert soils. Soil Sci. Soc. Amer. Proc. 39:37-42.

Reinhart, K.G. 1961. The problem of stones in soil-moisture measurement. Soil Sci. Soc. Amer. Proc. 25:268-270.

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The following are in Soil Sci. Soc. of Amer. Spec. Publ. No. 13, "Erosion and Productivity of Soils Containing Rock Fragments," edited by J.D. Nichols, P.L. Brown, and W.J. Grant. 1984.

Dunn, A.J. and G.R. Mehuys. Relationship between gravel content of soils and saturated hydraulic conductivity in laboratory tests, p. 55-64.

Flint, A.L., and S. Childs. Physical properties of rock fragments and their effect on available water in skeletal soils, p. 91-103.

Miller, F.T., and R.L. Guthrie. Classification and distribution of soils containing rock fragments in the United States, p. 1-6.

Relation between Ecological-Range Condition and Proportion of Soil-Surface Types

RICHARD E. ECKERT, JR., FREDERICK F. PETERSON, AND J. TIM BELTON

Abstract

Different kinds of A-horizon soil-surface types occur on loess-mantled xerollic Orthids and Argids in the Intermountain area. Four soil-surface types were identified on sites with potential vegetation of Wyoming big sagebrush [*Artemisia tridentata wyomingensis* Beetle] and Thurber needlegrass [*Stipa thurberiana* Piper]. These surfaces occupy different microtopographic positions and have different morphologies and chemical and physical properties. This study relates differences in the cover of these soil-surface types to ecological-range condition on sites of similar potential. Proportion of the surface type found under shrub or bunchgrass cover varies with range condition. More of the surface associated with shrub cover is found on low condition sites because of greater sagebrush cover. More of the surface associated with bunchgrass cover is found on high condition sites because of greater grass cover. Proportion of the surface types found in the interspace between shrubs also varies with range condition. High condition sites have a greater cover of the soil surface associated with bunchgrass cover and of the soil surface with cryptogam-stabilized microrelief. Conversely, low condition sites have essentially none of the soil surface associated with bunchgrass cover but a large amount of the soil surface with little microrelief. Results are interpreted in terms of watershed stability and natural revegetation potential.

Various ecological sites in the Intermountain area occur on xerollic Orthids and Argids. The A horizons of many of these soils have formed in a thin loess mantle and have distinctive morphologies determined by their parent material, their microtopographic position, and recent vegetation. This loess originated from sediments deposited in large Pleistocene lakes and subsequently exposed to wind transport as the lakes dried (Young and Evans 1986). In Nevada, the area leeward of these former lakes have soils that commonly are capped with loam, very fine sandy loam, or silt loam textured surface soils. This area is informally called the Humboldt Loess Belt and comprises about 8 million ha in central and northern Nevada and extends into southeastern Oregon, southern Idaho, and western Utah.

Four distinctive soil-surface morphological types of A horizons are found on fan piedmonts and basin floors in the Wyoming big sagebrush [*Artemisia tridentata wyomingensis* Beetle]-grass vegetation types in the Humbolt Loess Belt (Eckert et al. 1977) (Fig. 1). These soil-surface types are closely related to their microtopograpic position. A schematic cross-sectional diagram and description of these microtopographic positions are presented in Figure 2 and Table 1, respectively. Similar surfaces have been recognized by Hugie and Passey (1964), Schlatterer (1968), and Stuart et al. (1971, 1973). Postulated genesis of these surface horizons and their morphological attributes such as polygon shape, morphology, vesicularity, polygon microrelief, and surface cracks between polygons have been described (Eckert et al. 1977). Texture, organic matter, bulk density, modulus of rupture, and porosity characteristics of these soil surfaces were described by Wood et al. (1978). Eckert et al. (1978), Stephens (1980), and Wood et al. (1982) have shown that these morphological and physical properties can affect plant and hydrologic responses to rangeland improvement and management practices.

Table 1. Surface soil morphological types and their microtopographic positions.

Surface soil morphological type	Micro-topographic position	Description of microtopographic position
I	Coppice	A semi-conical form, the highest microtopographic elevation.
II	Coppice bench	A flattish or gently sloping area next highest to the coppice, and higher than any adjacent intercoppice or playette, if the latter occur.
III	Intercoppice microplain	A gently sloping or nearly flattish area next lower than the coppice bench. (Absent in some situations).
IV	Playette	A slightly depressed or flat area at the lowest microtopographic elevation and surrounded by coppices, coppice benches, or intercoppice microplains. Absent in some situations).

Authors are range scientist, USDA/ARS, 920 Valley Road, Reno, Nev. 89512; soil scientist, Dep. of Plant Science, Univ. of Nevada, Reno 89557; and former graduate student, Dep. of Range, Wildlife, and Forestry, Univ. of Nevada, Reno 89512. Belton is currently a range conservationist, USDA/FS, Saugus Ranger District, Saugus, Calif. 91350.

This research is the result of cooperative investigations of the USDA-ARS and the Nevada Agr. Exp. Sta. and was funded in part by the USDI-BLM.

Manuscript accepted 26 December 1985.

APPENDIX 5-C

Review Comments and Correspondence with Dr. Leonard Lane

L. J. Lane, Ph.D.
Hydrologist
411 E. Suffolk Dr.
Tucson, AZ 85704
January 4, 1989

Dr. George V. Sabol
Consulting Engineer
1351 East 141 st Avenue
Brighton, CO 80601

Dear George:

Thank you for sending me the sections of the Hydrology Manual for Maricopa County. Obviously you have done a great deal of work and at first glance it looks quite professional.

As we discussed in December, my current assignment is in erosion modeling so that review of the Hydrology Manual will need to be done outside work hours. Even though the job would be done outside work hours, I will need to get permission from our Area Administrator.

I estimate that a professional review of the material will take approximately 2.5 days. For public work such as this, a reasonable rate for my time and that of a technical assistant is $350. per day for a total of $875. If you will write me a letter proposing this agreement, I will attach it to the "Request for Outside Work" form and submit it for approval.

Finally, I commend you for trying to upgrade the technology used in Maricopa County and wish you success with the Manual.

Sincerely,

Leonard

Leonard J. Lane

SSN
526-70-1162

BRIEF RESUME FOR LEONARD J. LANE

NAME: Leonard J. Lane BORN: Tucson, AZ, April 25, 1945

EDUCATION: 1970 B.S. With Distinction, Engineering Math., Univ. Of AZ
1972 M.S. Systems & Industrial Engineering, Univ. of AZ
1975 Ph.D. Hydrology & Water Resources, Colorado State Univ.

PROFESSIONAL EXPERIENCE:

1970-72 Hydrologist, USDA-ARS, Tucson, AZ. Hydrologic research, and rainfall-runoff modeling

1975-81 Hydrologist, USDA-ARS, Tucson, AZ. Hydrologic research, erosion/sedimentation research, participated in development of CREAMS model

1981-82 Staff Member, Los Alamos. Erosion/sedimentation research, contaminant transport and waste management studies

1982-83 Hydrologist, USDA-ARS, Tucson, AZ. Hydrologic modeling, soil-water-plant relationships, infiltration and erosion studies

1983-84 Staff Member, Los Alamos. Waste management studies, USLE and CREAMS erosion studies/modeling, unsaturated flow and transport modeling

1984- Hydrologist, USDA-ARS, Tucson, AZ. Hydrologic/erosion modeling, member of Core Team for USDA Water Erosion Prediction Project (WEPP), Project Leader for WEPP

PROFESSIONAL ACTIVITIES, CONSULTING, AND TEACHING:

Memberships: AGU, ASAE, ASCE, AWRA, BGRG, SRM

Consulting: City of Tucson, Universities (Arizona, San Diego State, Griffith), Los Alamos National Laboratory, Washington State Dept. of Ecology

Teaching: Ph.D. Students: 6 former, 4 current; M.S. Students: 1 former, 2 current; Adjunct Assoc. Professor at University of Arizona

HONORS AND AWARDS:

1. Outstanding performance awards: 1970, 1977, 1987, 1988
2. Tau Beta Pi Engineering Honorary, 1970, Sigma Xi, 1975
3. USDA Superior Service Team Award, 1981
4. Arthur S. Flemming Award, 1982
5. Nominated as Guest Fellow of Royal Society, 1984
6. Mountain States Area Scientist of the Year, 1986

PUBLICATIONS:

Author or coauthor of over 110 publications, 1969-88. (List available on request)

REFERENCES: Available on request.

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

28 February 1989

Dr. Leonard J. Lane
411 E. Suffolk Dr.
Tucson, Arizona 85704

Dear Leonard:

Excuse me for not responding sooner to your letter of 4 January 1989. I was out of the country from 1 January until 3 February and for the last 3 weeks I have tried to catchup.

The Flood Control District of Maricopa County is rewriting the Rainfall section and I will send the revised draft when it is available. It will be essentially the same although I think that there are some errors in the current 2-hr and 24-hr distributions. They are also planning on expanding the text. The 6-hr distribution is the primary distribution and this looks okey. Use the present draft of the Rainfall section to get an idea of what is to come but don't spend much time on this until you get the new draft.

The letter that you requested is enclosed. I agree to your terms and you can consider this my authorization to proceed. I will keep you informed and let me know if I can provide any additional information that you may need.

Sincerely yours,

George V. Sabol

P.S. - I need to gather information on channel transmission losses for the manual. I understand that you have already been in communication with the Flood Control District on this. Could you send me a copy of Chapter 19 of NEH-4? I'll talk to you about your recommendation later. We need something that can be used within the limitations of HEC-1 (RL Card).
I look forward to your assistance with this manual.

GEORGE V. SABOL Ph.D., P.E.
CONSULTING ENGINEER
1351 EAST 141st AVENUE
BRIGHTON, COLORADO 80601
(303) 457-0989

28 February 1989

Dr. Leonard Lane
411 E. Suffolk Dr.
Tucson, Arizona 85704

Dear Dr. Lane:

The Flood Control District of Maricopa County is presently preparing a Hydrology Manual for use in Maricopa County, Arizona. As this is a major undertaking with significant technical, social, and economic implications for Maricopa County, we would appreciate your review of some sections of the draft of that manual.

As we discussed on 7 December 1988, your assistance by reviewing the Rainfall Losses section would be greatly appreciated. I have also enclosed the Rainfall and Unit Hydrograph Procedures sections for your general information, and your review of these sections is also encouraged but not requested.

Your letter of 4 January 1989 indicated an estimated time of 2.5 days at $350 per day for your time plus a technical assistant. These terms are agreed to.

Let me know when you have received approval for this service. I look forward to receiving your review comments.

Sincerely yours,

George V. Sabol

Copy: Mr. Joe Rumann, Hydrologist, Flood Control District of Maricopa County

L. J. Lane
411 E. Suffolk Dr.
Tucson, AZ 85704
302-575-8009
April 3, 1989

Dr. George Sabol
1351 East 141st Avenue
Brighton, CO 80601

Dear George:

Sorry I missed you on the telephone at work today. But, it is just as well as you were calling about the Maricopa County Hydrology Manual and I have agreed to do that work out of the office and on my own time. In the future, I request you call or write me at home about the work I am doing outside of the regular work for ARS. This is to make sure I do not use official time or facilities for private work. Please understand I am not trying to be uncooperative but to live by the letter and spirit of the rules for outside activities.

Now, I understand you will be in Tucson on April 11, 1989 and would like to discuss the Hydrology Manual. Very good. Please let me know where you will be staying and what time would be best for you. We can also meet in my home if this is convenient. As for the review, everything should be ready by that date and we can go over the comments in case you have questions.

Please feel free to call me at home in the evening or on weekends to let me know where we can get together and if there are any other preparations I need to make in the meantime.

Sincerely,

Leonard

Leonard J. Lane

Leonard J. Lane, Ph.D.
Hydrologist
411 E. Suffolk Dr.
Tucson, AZ 85704
602-575-8009

April 11, 1989

Dr. George V. Sabol
Consulting Engineer
1351 East 141st Avenue
Brighton, CO 80601

Dear George:

Enclosed are my review comments and the draft of the Rainfall Losses section of the proposed Hydrology Manual for Maricopa County. Please notice that I went through the draft document and listed my comments by section, page, and paragraph. The most important comments and suggestions are summarized on page 9 at the end of my review comments.

Although my comments are quite critical, they are intended to be constructive and hence I have included suggestions to overcome specific problems identified in the review and suggestions for overall improvement of the Manual. Please do not think I am critical of your effort or the need for an improved technology to predict runoff in the Southwest. Your draft document reflects a high degree of professional effort and your project is in our best professional interest and in the public interest. Therefore, I hope my comments are helpful.

Thank you for the opportunity to review the material and best wishes in your efforts to develop a "new hydrology" for Maricopa County.

Sincerely,

Leonard J. Lane

Leonard J. Lane

enclosures

REVIEW COMMENTS

RAINFALL LOSSES SECTION OF THE
PROPOSED HYDROLOGY MANUAL FOR MARICOPA COUNTY
(Preliminary Draft Dated 29 Dec. 1988)

Comments by: Leonard J. Lane, Ph.D.
Hydrologist
411 E. Suffolk Drive
Tucson, AZ 85704
602-575-8009

Comments are by Section, Page, and Paragraph.

RAINFALL LOSSES

Theory
General

1. p. 1, para 1. Good discussion and introduction of the importance of the chapter. Provides a brief, but good justification of the importance of the section.

2. p. 1, para 2. This discussion is not very clear. Subsequent discussions in the text clear up the uncertainties, but there is no need to start out with uncertainty. Suggest you rewrite this paragraph and include a figure showing rainfall hyetograph, infiltration rate, initial abstractions, etc. A good model is the figure in the SCS Section 4, Hydrology in the National Engineering Handbook.

Surface Retention Loss

1. pp. 1-2, para 1. Interception is not always a " relatively minor contribution ". In some cases it can be quite significant. Suggest you qualify this statement by something like "For purposes of flood studies and for situations normally encountered in Maricopa County, interception is usually small compared with other factors making up the surface retention losses." It is a small point, but you want the Manual to be able to stand up to scientific review.

On the top of p. 2 the text states that the surface retention loss estimates contained in the Manual were obtained from rainfall simulator studies and from the literature. Again, this is not a journal article but it is a professional paper so I suggest citing the key source documents for the specific surface retention loss estimates used in the Manual. Only by citing your sources can you provide permanent and retrievable documentation of the technical basis of the Manual.

Infiltration

1. pp. 2-3. This material appears to be inconsistent with the remainder of the material in the section. For example, why introduce the Horton equation for illustration purposes then abandon it in favor of the Green-Ampt equation later? This is not a literature review, so I suggest you exclude the Horton equation if you do not intend to recommend it. Please talk about infiltration in general and then use the recommended procedures (IL+ULR and Green-Ampt as recommended on p. 5) as approximations to the infiltration process. Limiting discussion only to recommended procedures will help the reader focus on recommended methodology and prevent the perception that the Horton equation is also recommended. Again, the hyetograph-infiltration figure suggested earlier would be of real help here.

2. p. 4 is missing in my copy. Comments will be made when p.4 is received.

3. p. 5, discussion of SCS procedure. My copy is incomplete (no p. 4) but the material on top of p. 5 is good. Except, again please remove reference to Horton equation. Also, a statement that new technology is available and should be utilized might be appropriate here.

4. p. 5, last para. The two recommended procedures just jump out without introductory material. Suggest you include a specific section entitled something like "Recommended Rainfall-Runoff Estimation Methods for Maricopa County". An entry such as this in the table of contents would help the reader.

Green and Ampt Infiltration Equation

1. p. 6, first para. This presentation of the Green-Ampt equation and the way it is solved (eqs. 3 & 4) is not the best way to present the model. I prefer something like the following:

The Green-Ampt infiltration equation is

$$f = Ks + Ks*Ns/F$$

where:

f = infiltration rate (L/T),
Ks = saturated hydraulic conductivity (L/T),
Ns = capillary drive term (L), and
F = cumulative infiltration depth (L).

In this notation, the capillary drive term, Ns, is a function of the average capillary suction at the wetting front, the effective porosity, and the available porosity at the initial water content of the soil.

In equation form,

$$Ns = PHI*Ne*(1-Se)$$

where:

PHI = average capillary suction at the wetting front (L),
Ne = effective porosity, and
Se = relative saturation term equal to 1.0 at saturation of the effective porosity and equal to 0.0 in the oven dry condition.

To be consistent with your eq. 2, we can write (Sf-Si)/Ne which is 1-Se if we assume relative saturation as the final soil saturation in the soil profile above the wetting front.

This formulation of the Green-Ampt equation is included not to suggest you change your description (I recognize you want to stay with the formulation and notation used in HEC-1) but to allow you to compare subsequent calculations made with the above notation with corresponding calculations using your eqs. 1,2 and 3.

References to the solution of the Green-Ampt equation are as follows:

Chu, S. T. 1978. Infiltration during an unsteady rain. Water Resources Research, 14(3):461-466.

Mein, R. G., and Larson, C. L. 1973. Modeling infiltration during a steady rain. Water Resources Research, 9(2):384-394.

Example Calculations You Can Use to Verify Your Green-Ampt Calculations

Following are example calculations you can convert to English units and then compare to corresponding calculations using the HEC-1 type solution to the Green-Ampt equation. I strongly suggest you make the calculations and comparisons. If you do, do not expect the results to be exactly the same because we use different algorithms. However the rates and amounts ought to be comparable to a few percent. The test calculations are for a variable rainfall intensity pattern to test the solution for unsteady rain and are for a bare sandy loam soil in an initially dry condition. You may wish to plot the data from this example (or one like it) and include the results as a worked example in the Manual. In fact, such a test would be good to show that practitioners are using a correct and current calculation routine in material they submit to the County for review.

Finally, the example calculations show the variable tp which is the time to ponding and the point at which the Green-Ampt equation is used to compute rainfall excess. The calculations do not include any interception or other initial abstraction losses not directly resulting from the infiltration calculations.

Test calculations for Rainfall Losses Section
Sandy Loam Soil, Bare, Wilting Point Initial Water Content

Infiltration Parameters:

saturated conductivity , Ks = 11.0000 (mm/hr)
effective matric potential, Ns = 28.7820 (mm)
effective porosity, Ne = .4100 (mm/mm)
relative saturation, Se = 22.0000 (%)

Rainfall Intensity Data:

index	time (min)	rate (mm/hr)			
1	.000	25.400	from time	0.0 to time 10.0	i = 25.4
2	10.000	50.800	"	10.0 to time 20.0	i = 50.8
3	20.000	2.540	"	20.0 to time 45.0	i = 2.54
4	45.000	50.800	"	45.0 to time 60.0	i = 50.8
5	60.000	.000		for times > 60.0	i = 0.0

Infiltration and Rainfall Excess Results:

index	time	rainfall rate (mm/h)	rainfall depth (mm)	infiltration rate (mm/h)	infiltration depth (mm)	excess rate (mm/h)	excess inches
1	.00	25.4000	.0000	25.4000	.0000	.0000	0
2	5.00	25.4000	2.1167	25.4000	2.1167	.0000	0
3	10.00	50.8000	4.2333	50.8000	4.2333	.0000	0
4tp	14.40	50.8000	~~7.9548~~	49.5914	7.9548	1.2085	.0003
5	15.00	50.8000	8.4667	42.0940	8.4545	8.7060	.029
6	20.00	2.5400	12.7000	2.5400	11.9623	.0000	0
7	25.00	2.5400	12.9117	2.5400	12.1740	.0000	0
8	30.00	2.5400	13.1233	2.5400	12.3857	.0000	0
9	35.00	2.5400	13.3350	2.5400	12.5973	.0000	0
10	40.00	2.5400	13.5467	2.5400	12.8090	.0000	0
11tp	45.00	50.8000	13.7583	33.0143	13.0207	17.7857	.0584
12	50.00	50.8000	17.9917	29.6288	15.7718	21.1712	.0695
13	55.00	50.8000	22.2250	27.3439	18.2409	23.4561	.0770
14	60.00	.0000	26.4583	.0000	20.5196	.0000	

Summary:

total rainfall = 26.46 (mm)
duration = 60.00 (min)
infiltration volume = 20.52 (mm)
rainfall excess volume = 5.94 (mm) .2339 in

By my calculations with your equation 3 applied to the period from t = 45 min = 0.75 h to t = 60 min = 1.0 h, the results are

		Equation 3		Chu(1978) Solution	
t(i-1)	t(i)	F(i-1)	F(i)	F(i-1)	F(i)
45.0	50.0	13.0207	15.7701	13.0207	15.7718
50.0	55.0	15.7701	18.2384	15.7718	18.2409
55.0	60.0	18.2384	20.5166	18.2409	20.5196

so that the percent difference after 10 min is

e = ((20.5195-20.5166)/20.5196)*100 = 0.015 ,

a surprisingly close result. Again, I don't know how you compute time to ponding and infiltration for an unsteady rain so I suggest you compare results for the entire storm.

2. p. 6, eq. 4. Equation 4 should read f = delF/delT not delf = delF/delT and f is the average infiltration rate over the time interval T to T + delT.

3. p. 7, para 1. No scientific evidence is presented for the assertion that IA can be as large as 0.35 in (8.9 mm) in flat areas of Maricopa County. The same for the other entries in Table 1. I strongly suggest that the para at top of p. 7 be expanded to include reference to key source documents supporting IA choices and to the actual data on IA, if practical. The value of 0.35 in corresponds to a runoff CN of 85. Coincidence? Or were CN's used to derive the IA values? The Manual should be very explicit on the source of the values in Table 1 or the County will need to defend them later when the procedures in the Manual are challenged.

4. p. 7, para 2. It is not clear from the paragraph if you are saying that time to ponding, tp, and the time when IA is satisfied are synonymous. A good reference for an explanation of the Green-Ampt equation, tp, etc. is:

Skaggs, R. W. and Khaleel R. 1982. Infiltration, Ch. 4 In: Hydrologic Modeling of Small Watersheds, Eds. Haan, C. T., Johnson, H. P., and Brakensiek, D. L., ASAE Monograph No. 5, ASAE, St. Joseph, MI, pp.121-166.

Following Skaggs and Khaleel, the infiltrated volume, Fp, at the time of ponding is:

Fp = Ns/(i/Ks-1)

where i is the rainfall intensity rate when ponding is achieved so that f=i for t < tp. In the example above,

Fp = 28.782/(50.8/11 -1) = 7.9548 mm = 0.31 in

is the amount of rain to reach a ponded condition on the surface and thus reach the time when the infiltration equation can be properly

applied. Before this time when t=tp, the infiltration rate f = i and f = Ks + KsNs/F does not apply. Are you suggesting that:

yes, this one 1. IA is satisfied first then the time to ponding is satisfied as shown above? If so, then the amount of rain required before runoff is produced is IA + Fp = 0.35 + 0.31 = 0.66 in.

or

2. IA is satisfied and at the time IA is satisfied ponding occurs so that f = Ks + KsNs/F applies at exactly the time when the cumulative rainfall equals IA. If F=0.0, then you have division by zero. To be mathematically correct it must be that F>0.0. How can this be if you assume no infiltration as IA is being satisfied? If this is the assumption, somehow tp is reached without infiltration and then runoff starts after IA = 0.35 in of rain has fallen.

If I read the material on p. 7 correctly, there is a logical inconsistency here. If this is the case, it should be corrected. If there is no inconsistency, then I suggest you rewrite the material so it is easier to follow.

5. p. 7, para 3. The silt textural class is left out of Table 2. I suggest you add a line between silt loam and sandy clay loam as follows:

class	xKsat	psif	dry	normal	saturated
silt	0.10	7.5	.33	.14	0

Also, change silty loam in Table 2 to silt loam to be consistent.

6. pp. 8-9, No comments.

7. pp. 10-11, Equations 5-11 and list of variables. The notation and units are confusing, i.e. fraction (0.0 to 1.0) for CAN, BO, etc. but percent for sand. To test the adjustments to Ks provided by eq. 5, i.e., KsADJ = KE = CAN*KEc + OP*KEo, I evaluated them for loamy sand, silt loam, and silty clay for a range in CAN, BC, and BO. If the evaluations are correct given the confusing nature of the variables (by the way a diagram or figure would sure help in explaining the terms listed on p. 11), then the results of applying eq. 5 are summarized in Table R1 below.

Values of canopy cover in Table R1 vary from 0.1 to 1.0, bare soil under the canopy from 0 to .125, and ratio of bare soil outside the canopy from 0 to .90. If I interpret the explanation of variables on pp. 10-11 correctly, then these are reasonable values. Given that these are reasonable values and assuming I evaluated the equations correctly, then the last column of Table R1 shows that the adjusted Ks values, KE, are illogical and unreasonable. For example, in the loamy sand texture class, the KE values decrease with increasing canopy cover and go negative for the other two soils. The negative values result when BO/CAN is much larger than 1, A*(1-BO/CAN) is negative with

absolute value greater than CRC*BO/CAN, and finally when OP*KEo is negative and larger in absolute value than CAN*KEc. If my interpretations and calculations are correct, then this can happen with reasonable parameter values.

I strongly suggest that you construct a table such as Table R1 for all textural classes and for various values of canopy cover and bare soil. If Table R1 is indicative, then you cannot use eq 5 to adjust the parameter values. Even if there were typographical errors in your eqs 5-11 or if I miscalculated, you should carefully check these equations in their limits to make sure the results are reasonable. Complicated regression equations often "blow up" in the limits and should be avoided if possible.

Table R1. Evaluation of KE from eq. 5 for various values of CAN, BC, and BO for three textural classes.

Texture Class	Ks (in/h)	Canopy Cover CAN	Bare Soil Under Canopy BC	Area Outside Canopy BO	Red. Factor SC	% Sand (%) SA	BD	KE (in/h)
Loamy Sand	1.2	0.0	-----Division by zero in eqs. 6 & 7-----					
	1.2	0.1	.045	.90	.89	80.	1.46	5.19
	1.2	0.5	.125	.50	.89	80.	1.46	0.58
	1.2	0.9	.045	.10	.89	80.	1.46	0.28
	1.2	1.0	0.0	0.0	.89	80.	1.46	0.24
Silt Loam	0.25	0.1	.045	.90	.81	25.	1.15	-22.71
	0.25	0.5	.125	.50	.81	25.	1.15	1.89
	0.25	0.9	.045	.10	.81	25.	1.15	5.54
	0.25	1.0	0.0	0.0	.81	25.	1.15	6.44
Silty Clay	0.02	0.1	.045	.90	.73	10.	1.33	-11.70
	0.02	0.5	.125	.50	.73	10.	1.33	0.92
	0.02	0.9	.045	.10	.73	10.	1.33	2.77
	0.02	1.0	0.0	0.0	.73	10.	1.33	3.23

A general suggestion here is to try to simplify the equations used to adjust Ks. The user will not often have data for the amount of bare soil under and outside the canopy. More likely, he will have estimates of <u>total canopy cover</u> and <u>total ground cover</u>. You should probably limit your Ks adjustment equations to only total canopy cover and total ground cover. You should also carefully define these cover terms using diagrams and examples so that there is no ambiguity. If I have trouble understanding this material when taking time to review and study it, the infrequent user is sure to have trouble and produce

inconsistent results. This section must be rewritten to make it of practical value and to reduce the probability of misinterpretation of the Manual. Would it be possible to derive simple parameter adjustment equations using the original data base and not the interpretations embodied in eqs. 5-12 ? Tim Ward (Prof. Civil Engineering, Box 3CE, New Mexico State University, Las Cruces, NM 88003 505-646-3232) has collected infiltration data appropriate for these analyses and I suggest you contact him to obtain reprints and reports describing his data and findings. In any event, without realistic methods to adjust the Green-Ampt parameters to reflect land use and management, the Manual will not be ready for practical, everyday use.

Initial Loss Plus Uniform Loss Rate (IL + ULR)

1. p. 12, paras 2-3. Clear description of the procedure. However, the initial loss (STRTL) and the constant rate (CNSTL) are both dependent upon and derived from the Green-Ampt parameters. The above discussion of the need to make Green-Ampt parameters reasonable and related to land use and management also apply to this method.

2. p. 13. Same comments, good discussion but dependent on how you estimate XKSAT.

Procedure for Estimating Loss Rates

Green and Ampt Method

1. pp. 13-14, steps 1-6 in applying the method. Good outline of how to apply the Green-Ampt method. After the uncertainty in eqs 5-12 is dealt with, I suggest you also include a worked example so the user of the Manual can go through a step by step example to verify that the procedures are being applied correctly.

Initial Loss Plus Uniform Loss Rate Method

1. pp. 14-15. Same comment as above.

SUMMARY OF MOST IMPORTANT COMMENTS & SUGGESTIONS BY REVIEWER

1. Include a definition sketch or figure showing rainfall hyetograph, surface retention losses, time to ponding, and infiltration rate to orient the user and supplement the written descriptions.

2. Include source documents and data, if possible and practical, to justify the values of surface retention loss mentioned on pp. 1-2 and shown in Table 1.

3. Remove reference to Horton eq. and include only descriptions of recommended methods. Include a section in the chapter entitled something like "Recommended Rainfall-Runoff Estimation Methods for Maricopa County".

4. Verify your Green-Ampt infiltration calculations using the example storm and calculations given on p. 4 of this review. Carefully examine the time to ponding calculations to make sure they match those shown in my example.

5. Please rewrite the material on p. 7 of the chapter dealing with the initial abstraction, IA, and its relationship with the time to ponding, tp. Review comment No. 4 on pp. 5-6 of this review deals with the uncertainty in your presentation.

6. You should verify and validate the results of using eqs. 5-12 for all soil textural classes and for a variety of canopy and ground cover following the example calculations given in Table R1 of the review comments. If the Ks adjustment equations do not reproduce reasonable and consistent results, then you should abandon them and derive simpler, and consistent adjustment relationships utilizing estimates of total canopy cover and total ground cover. These steps are essential if the Manual is to be of practical value and if it is to produce consistent results in the limits of its application.

APPENDIX-- BASIC PROGRAMS USED IN REVIEW

PROGRAM NO. 1-- TO COMPUTE INFILTRATION

PROGRAM NO. 2-- TO ADJUST Ks

Program No. 1-- To Compute Infiltration

```
5 REM  PROGRAM TO EVALUATE LI ET AL., 1976 GREEN-AMPT
6 REM  APPROXIMATE SOLUTION
7 REM  DELF = -.5(2F-KS*DELT)+.5[(2F=KS*DELT)^2
8 REM          +8KS*DELT(A + F)]^1/2
9 REM
10 DIM F(100),T(100),RATE(100)
20 REM
30 INPUT "ENTER KS,A,F0,T0,TMAX,DELT ",KS,A,F0,T0,TMAX,DELT
40 T(1) = T0/60.0
50 F(1) = F0
55 DELT = DELT/60.0
60 N = ((TMAX-T0)/60.0)/DELT + 1
70 FOR I=1 TO N
80 D1 = -0.5*(2.0*F(I)-KS*DELT)
90 D2 =  0.5*((2.0*F(I)-KS*DELT)^2 + 8.0*KS*DELT*(A+F(I)))^.5
100 DELF = D1+D2
110 F(I+1) = F(I) + DELF
120 T(I+1) = T(I) + DELT
130 RATE(I+1) = DELF/DELT
140 PRINT"I+1,T(I+1),F(i+1),RATE(I+1)",I+1,T(I+1)*60.0,F(I+1),RATE(I+1)
150 NEXT I
160 END
```

Program No. 2-- To Adjust Ks

```
5 REM PROGRAM TO ADJUST Ks A LA RAWLS, ET AL. 1988
10 REM KsADJ=KE = CAN*KEc + OP*KEo
15 REM KEc=Ks*CF*(BC*CRC/CAN + A*(1-BC/CAN))
20 REM KEo = Ks*(BO*CRC/CAN + A*(1-BO/CAN))
25 REM CF = 1.96*CAN <-- ok on Line 100
30 REM CRC = 6/(5.5/SC + 0.5/B)
35 REM A = EXP(2.82-0.099*SA + 1.94*BD)
40 REM B = 0.0000173*SA^2 - 0.0001575*SA + 0.04595
50 REM
60 PRINT"ENTER FRACTIONS:CANOPY COVER,BARE SOIL UNDER CANOPY/TOTAL AREA"
65 INPUT "CAN,BC",CAN,BC
70 OP = 1.0-CAN
75 INPUT "ENTER BARE SOIL OUTSIDE CANOPY/TOTAL AREA BO",BO
80 INPUT" Ks,SC,SA%,BD ",KS,SC,SA,BD
81 REM CONVERT KS IN/HR TO CM/HR
82 KS = KS*2.54
85 REM CALCULATE THE SUBFACTORS
90 B = 0.0000173*SA^2 - 0.0001575*SA +0.04595
95 A = EXP(2.82 - 0.099*SA + 1.94*BD)
100 CF = 1.0 + 0.96*CAN
105 CRC = 6.0/(5.5/SC + 0.5/B)
110 KO = KS*(BO*CRC/CAN + A*(1.0-BO/CAN))
115 KC = KS*CF*(BC*CRC/CAN + A*(1.0-BC/CAN))
120 KE = CAN*KC + OP*KO
121 REM CONVERT BACK TO IN/HR
125 KS = KS/2.54
126 KC = KC/2.54
127 KO = KO/2.54
128 KE = KE/2.54
130 PRINT "KS,KC,KO,KE",KS,KC,KO,KE
140 PRINT
150 REM
160 END
```

REVIEW COMMENTS TIED TO THIS DRAFT.

from Leonard Lane
29 Dec 88

RAINFALL LOSSES

PRELIMINARY
For Review Only

Theory

General

Rainfall excess is that portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall losses equals precipitation. When performing a flood analysis using a rainfall-runoff model, the determination of rainfall excess is of utmost importance. Rainfall excess integrated over the entire watershed results in runoff volume, and the temporal distribution of the rainfall excess will, along with the hydraulics of runoff, determine the peak discharge. Therefore, the estimation of the magnitude and time distribution of rainfall losses should be performed with the best practical technology, considering the objective of the analysis, economics of the project, and consequences of inaccurate estimates.

Rainfall losses are generally considered to be the result of interception of rainfall by vegetal cover, depression storage on the land surface (paved or unpaved), evaporation of water from the land surface, and infiltration of water into the soil matrix. For the purposes of this Hydrology Manual rainfall losses are classified as either surface retention loss or infiltration. Losses are also often separated into accumulated losses prior to the initiation of surface runoff (initial abstraction), and losses during surface runoff; however, initial abstraction is not identical to surface retention loss because initial abstraction includes some amount of infiltration losses prior to the start of surface runoff.

unclear, add figure see NEH-4 ✓

Surface Retention Loss

Surface retention loss, as used herein, is the summation of all rainfall losses other than infiltration. The major component of this loss is depression storage consisting of rainfall that is captured in puddles, small surface depressions, road gutters, ditches, roofs, and other non-draining surface features. A relatively minor contribution by interception is also considered as a part of the total surface

expand - see comments ✓

retention loss. Estimates of surface retention loss are difficult to obtain and are a function of the physiography and land-use of the area. Estimates of surface retention loss contained in this manual have been obtained from the analysis of rainfall-runoff data, results of rainfall simulator studies conducted on rangelands and turf, and published estimates for such losses.

references

Infiltration

Infiltration is the movement of water from the land surface into the soil. Infiltration is distinguished from percolation in that percolation is the movement of water through the soil subsequent to infiltration. Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, the extent by which percolation can restrict infiltration of rainfall should be carefully evaluated before percolation can be assumed to restrict infiltration for the design rainfalls that are being considered in Maricopa County. For example, hydrologic soil group D has been defined by SCS soil scientists as:

> "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."

This definition indicates that soils in hydrologic soil groups A, B, or C could be classified as D if they are underlain by an impervious strata of clay, caliche, or rock. When these soils are considered in regard to long-duration rainfalls that are the design events for many parts of the United States this definition may be valid. However, when considered for short-duration and relatively small design rainfall depths in Maricopa County this definition could result in under estimation of the rainfall losses for these storms. This is because even a relatively shallow horizon of soil overlaying an impervious layer still has the ability to store a significant amount of infiltrated rainfall. For example, consider the situation where only 4 inches of soil covers an impervious layer. If the effective

porosity is 0.30 then 1.2 inches (4 inches times 0.30) of water can be infiltrated and stored in the shallow soil horizon. For a design rainfall of 6 hours and a rainfall depth of about 4 inches this represents a significant storage volume for infiltrated rainfall. Therefore, for drainage studies in Maricopa County that contain major areas of soil that are classified as hydrologic soil group D, the reason for the soil survey classification as D should be determined. Hydrologic soil group D should be retained for clay soils, soils with a permanent high water table, and rock outcrop. Hydrologic soil group D should probably not be retained in all situations where the classification is based on shallow soils over nearly impervious layers, and site specific studies and sensitivity analyses should be performed to estimate the loss rates that should be used for such soils.

remove Horton discussion

Infiltration of water into the soil is generally believed to follow an exponential decay function as proposed by Horton (1939):

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where f is the infiltration rate at time t,

f_c is the minimum (equilibrium) infiltration rate,

f_o is the initial infiltration rate,

t is the time from start of rainfall,

k is a constant that is dependent upon the soil-vegetation complex, and

e is the base of the Naperian logarithms.

This infiltration function is illustrated in Figure 1. In Figure 1, the infiltration rate is shown to be a continually decreasing function of time and the surface retention loss is shown to be a loss that is independent of and separate from the infiltration of rainfall into the soil. This represents the physical process that is to be simulated in modeling rainfall loss.

The driving force for infiltration is gravity and capillary forces drawing water into and through the pore spaces of the soil matrix.

agencies, consulting engineering firms, and individuals throughout the community. However, the method is limited because of both theoretical and practical deficiencies of the method. Several of the deficiencies of the SCS CN method are:

1. Rainfall losses are independent of the duration of rainfall. That is, for a given depth of rainfall the same rainfall loss results regardless of the duration of rainfall, and the same rainfall excess would be estimated for a given rainfall depth occurring in, for example, either 1 hour or 24 hours.
2. The estimated rainfall loss rate is a function of rainfall intensity. Short periods of high intensity rainfall would often result in large estimates of rainfall losses. This is contrary to the Horton type infiltration relation as illustrated in Figure 1.
3. The infiltration rate approaches zero rather than a minimum infiltration rate, f_c.
4. The initial abstraction of 0.2S is not justified nor is it based on data for hydrologic conditions that are representative of Maricopa County.
5. The selection of CN is too subjective and is based more on traditional acceptance of CN values rather than scientifically substantiated findings.
6. At low rainfalls (less than 4 inches), the estimate of rainfall loss is very sensitive to the selection of CN.

For these reasons the SCS CN method is not recommended for general use in Maricopa County.

Two methods are recommended for use in Maricopa County; these are the initial loss plus uniform loss rate (IL+ULR), and the Green and Ampt infiltration equation. Other methods should be used only if there is technical justification for a variance from this recommendation and if adequate information is available to estimate the necessary parameter values. Use of rainfall loss methods other than those recommended should not be undertaken unless previously approved by the Flood Control District and the local regulatory agency.

Green and Ampt Infiltration Equation

This model, first developed in 1911 by W.H. Green and G.A. Ampt, has since the early 1970s ~~1973~~ received increased interest for estimating rainfall infiltration losses. The model has the form:

$$f = K_s \left(1 + \frac{\psi \times \theta}{F}\right) \qquad (1)$$

$$\cancel{f = K\left(1 + \frac{\psi\phi(S_f - S_i)}{F}\right)}$$

see comments

where f = infiltration rate (L/T),

K = hydraulic conductivity in the wetted zone (the ultimate steady state rate) (L/T),

ψ = average capillary suction in the wetted zone (L),

~~S_f = final soil saturation (volumetric),~~

~~S_i = initial soil saturation (volumetric),~~

~~ϕ = soil porosity, and~~

F = depth of rainfall that has infiltrated into the soil since the beginning of rainfall.

It is important to note that as rain continues, F increases and f approaches K, and therefore, f is inversely related to time. Equation 2 is implicit with respect to f which causes computational difficulties. Eggert (1976) simplified Equation 1 by expanding the equation in a power series and truncating all but the first two terms of the expansion. The simplified solution (Li and others, 1976) is:

$$\Delta F = -.5(2F - K\Delta t) + .5((2F - K\Delta t)^2 + 8K\Delta t(\psi + F))^{1/2} \qquad (3)$$

where t is the computation interval and F is accumulated depth of infiltration at the start of t. The average infiltration rate is:

$$\Delta f = \frac{\Delta F}{\Delta t} \qquad (4)$$

Use of the Green and Ampt equation as coded in HEC-1 involves the simulation of rainfall loss as a two phase process. The first phase is the simulation of the surface retention loss as previously described, and this loss is called the initial loss (IA) in HEC-1.

During this first phase all rainfall is lost (zero rainfall excess generated) during the period from the start of rainfall up to the time that the accumulated rainfall equals the value of IA. It is assumed for modeling purposes, that no infiltration of rainfall occurs during this first phase. Initial loss (IA) is primarily a function of land-use and surface cover, and recommended values of IA for use with the Green and Ampt equation are presented in Table 1. For example, as shown in Table 1 about 0.35 inches of rainfall will be lost to runoff due to surface retention for desert and rangelands on relatively flat slopes in Maricopa County.

check reference

The second phase of the rainfall loss process is the infiltration of rainfall into the soil matrix. For modeling purposes, the infiltration begins immediately after the surface retention loss (IA) is completely satisfied. The three Green and Ampt equation infiltration parameters as coded in HEC-1 are hydraulic conductivity at natural saturation (XKSAT), wetting front capillary suction (PSIF), and volumetric soil moisture deficit at the start of rainfall (DTHETA). The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture), organic matter, and bulk density. The primary soil surface characteristics are vegetation cover, rock cover, and soil crusting. The land management practices are identified as various tillages as they result in changes to soil porosity.

see comment

Values of Green and Ampt equation parameters as a function of soil characteristics alone (bare ground condition) have been obtained from published reports (Rawls and others, 1983; Rawls and Brakensiek, 1983). Average values of XKSAT and PSIF for each of the soil texture classes are shown in Columns (2) and (3) of Table 2 (Rawls and others, 1983). Values of XKSAT and PSIF as a function of percent of sand and percent of clay for soil with 0.5 percent organic matter and base value (unaltered) soil porosity are shown in Figures 2 and 3, respectively (Rawls and Brakensiek, 1983). The values of XKSAT and PSIF from Table 2 should be used if general soil texture classification of the drainage area is available. The values of XKSAT

and PSIF from Figures 2 and 3 can be used if more specific soil texture classification is available from a detailed soil survey for which the percentage of sand and clay has been determined by an appropriate field soil survey. The use of the information in Figures 2 and 3 will require an extensive study of the soil for the drainage area and for most drainage studies only general soil texture classification will be known and the values from Table 2 should be used.

The soil moisture deficit (DTHETA) is a volumetric measure of the soil moisture storage capacity that is available at the start of the rainfall. DTHETA is a function of the effective porosity of the soil. If the soil is saturated at the start of rainfall then DTHETA equals 0.0. If the soil is devoid of moisture at the start of rainfall the DTHETA equals the effective porosity of the soil. Therefore the range of DTHETA is 0.0 to the effective porosity. The porosity of soil as a function of soil texture (percent of sand and percent of clay) is shown in Figure 4 (Brakensiek and others, 1984).

Under natural conditions, soil seldom reaches a state of soil moisture less than the wilting point of vegetation, and a graph of volumetric soil moisture at wilting point as a function of soil texture is shown in Figure 5. Due to the rapid drainage capacity of most soils in Maricopa County the soil would not be expected to be in a state of soil moisture greater than the field capacity at the start of a design storm. A graph of volumetric soil moisture at field capacity as a function of soil texture is shown in Figure 6. However, Maricopa County also has a large segment of its land area under irrigated agriculture and it is reasonable to assume that the design frequency storm could occur during or shortly after certain lands had been irrigated. Therefore, for irrigated lands it would be reasonable to assume that soil moisture could be at or near effective saturation during the start of the design rainfall.

Three conditions for DTHETA have been defined for use in Maricopa County based on the antecedent soil moisture condition that could be expected to exist at the start of the design rainfall. These three

conditions are "Dry" for antecedent soil moisture near the vegetation wilting point; "Normal" for antecedent soil moisture condition near field capacity due to previous rainfall or irrigation applications on nonagricultural lands; and "Saturated" for antecedent soil moisture near effective saturation due to recent irrigation of agricultural lands. Values of DTHETA have been estimated by subtracting the initial volumetric soil moisture for each of the three conditions from the soil porosity. The value of DTHETA "Dry" as a function of soil texture is shown in Figure 7. This figure was prepared by subtracting the wilting point soil moisture on Figure 5 from the soil porosity on Figure 4. The value of DTHETA "Normal" as a function of soil texture is shown in Figure 8. This figure was prepared by subtracting the field capacity soil moisture on Figure 6 from the soil porosity on Figure 4. The value of DTHETA "Saturated" is always equal to 0.0 because for this condition there is no available pore space in the soil matrix at the start of rainfall. Values of DTHETA for the three antecedent soil moisture conditions are shown in Table 2. DTHETA "Dry" should be used for soil that is usually in a state of low soil moisture such as would occur in the desert and rangelands of Maricopa County. DTHETA "Normal" should be used for soil that is usually in a state of moderate soil moisture such as would occur in irrigated lawns, golf courses, parks, and irrigated pastures. DTHETA "Saturated" should be used for soil that is usually in a state of high soil moisture such as irrigated agricultural land.

The hydraulic conductivity (XKSAT) can be affected by several factors besides soil texture. For example, hydraulic conductivity is reduced by soil crusting, it is increased by tillage, and it is increased by the influence of ground cover and canopy cover. The values of XKSAT that have been presented for bare ground as a function of soil texture alone should be adjusted under certain conditions.

Ground cover, such as grass, litter, and rock will generally increase the infiltration rate over that of bare ground conditions. Similarly, canopy cover, such as from trees, brush, and tall grasses can also increase the bare ground infiltration rate. The procedures and data that have been presented are for estimating the Green and Ampt

parameters based solely on soil texture and would be applicable for bare ground conditions. Procedures have been developed (Rawls and others, 1988) for incorporating the effects of ground cover and canopy cover into the estimation of the parameters for the Green and Ampt equation. Past research has shown that the wetting front capillary suction parameter (PSIF) is relatively insensitive in comparison with the hydraulic conductivity parameter (XKSAT); therefore only the hydraulic conductivity parameter is adjusted for the influences of ground cover and canopy cover.

revise

The set of equations that have been developed to adjust the bare soil hydraulic conductivity for the influence of soil ground cover and canopy cover are:

VERY CONFUSING!

$$KE = (CAN)\ (KE_c) + (OP)\ (KE_o) \tag{5}$$

$$KE_c = (K)\ (CF)\left[\left(\frac{BC}{CAN}\right)(CRC) + A\left(1 - \frac{BC}{CAN}\right)\right] \tag{6}$$

WHEN RIGHT PAREN IS ADDED, IS THIS EQ. RIGHT?

$$KE_o = (K)\left[\left(\frac{BO}{CAN}\right)(CRC) + A\left(1 - \frac{BO}{CAN}\right)\right] \tag{7}$$

MIXES FRACTIONS & %'S

$$CF = 1 + 0.96\ CAN \tag{8}$$

$$CRC = \frac{L}{\frac{L - TC}{SC} + \frac{TC}{B}} \tag{9}$$

$$A = e^{[2.82 - 0.099(SA) + 1.94(BD)]} \tag{10}$$

$$B = 0.0099 + 0.0721(TC) + 0.0000068(SA^2) + 0.000021(SA^2)(TC) - 0.000315(SA)(TC) \tag{11}$$

where KE = hydraulic conductivity adjusted for ground cover and canopy cover, and KE is the adjusted value of XKSAT in the Green and Ampt equation,

KE_c = hydraulic conductivity of soil under canopy cover,
KE_o = hydraulic conductivity of soil outside of canopy cover,
K = bare ground hydraulic conductivity, equal to XKSAT,
CF = canopy factor,
CRC = soil crust factor,
A = macroporosity factor,
CAN = ratio of area under canopy cover to total area,
OP = ratio of area outside of canopy cover to total area,
BC = ratio of bare soil (no vegetation, litter, or rock cover) that is under canopy cover to total area,
BO = ratio of bare soil that is outside of canopy cover to total area,
L = wetting front depth (assume 6 cm),
TC = soil crust thickness (assume 0.5 cm),
SC = correction factor for partial saturation of the subcrust soil (see Table 3),
SA = percent sand in the soil,
BD = soil bulk density (see Figure 9).

These equations have been developed for the SI system of units and they should be solved in this system and the resulting hydraulic conductivity (KE) in cm/hr should be converted to XKSAT in inches/hr.

Equations 5 through 7 can be simplified for use in estimating the hydraulic conductivity of turf by the following equation:

$$KE = (K)(A) \qquad (12)$$

where A is defined by Equation 10.

The influence of tillage results in a change in total porosity and therefore a need to modify the three Green and Ampt equation infiltration parameters. The effect of tillage systems on soil porosity and the corresponding changes to hydraulic conductivity, wetting front capillary suction, and water retention is available (Rawls and Brakensiek, 1983). Although this information is available it is not presented in this manual, nor is it recommended that these

adjustments be made to the three infiltration parameters for design purpose use in Maricopa County. This is because for most flood prediction purposes it cannot be assumed that the soil will be in any particular state of tillage at the time of storm occurrence and therefore the base condition infiltration parameters, as presented, should be used for flood prediction purposes. However, appropriate adjustments to the infiltration parameters can be made as necessary for special flood studies such as reconstitution of storm events.

Initial Loss Plus Uniform Loss Rate (IL + ULR)

This is a simplified rainfall loss method that is often used, and generally accepted, for flood hydrology. In using this simplified method it is assumed that the rainfall loss process can be simulated as a two-step procedure, as illustrated in Figure 10. First, all rainfall is lost to runoff until the accumulated rainfall is equal to the initial loss; and second, after the initial loss is satisfied, a portion of all future rainfall is lost at a uniform rate. Two parameters are needed to use this method, the initial loss and the uniform loss rate (STRTL and CNSTL), respectively, according to HEC-1 nomenclature).

The initial loss (STRTL) is the sum of all losses prior to the onset of runoff and is made up of surface retention loss and some amount of infiltration. This is also called initial abstraction. Values of the infiltration part of STRTL for bare ground according to soil texture classification are shown in Columns (3) through (5) in Table 4. These values have been derived from the Green and Ampt infiltration equation and parameter values that are shown in Table 2. The value of STRTL "Dry" should be used for soil that is usually in a state of low soil moisture at or near the wilting point for vegetation. This is a reasonable assumption for most nonirrigated lands in Maricopa County because of the infrequency of rainfall and because of the rapid drainage of these soils after rainfall. The value of STRTL "Normal" should be used for soil that is usually in a state of moderate soil moisture such as occurs for irrigated lawns, turf, and permanent pastures. The value of STRTL "Saturated" should be used for soil that is maintained in a state of high soil moisture such as occurs in

irrigated agricultural lands.

Values of STRTL for bare ground that have been classified according to hydrologic soil group are shown in Table 5. These values within each hydrologic soil group have been derived from the data in Table 4 for the various soil texture classifications.

The values of STRTL from Table 4 and 5 represent that portion of the initial loss that is attributable to infiltration and these should be increased to account for the surface retention loss that is a function of land-use and vegetation. These additive STRTL values are shown in Table 1. The value of STRTL that is used is the sum of the portion due to infiltration (Table 4 or 5) plus the portion that is due to surface retention (Table 1).

The uniform loss rate (CNSTL) represents the long-term, equilibrium infiltration capacity of the soil. The values of CNSTL shown in Column (2) of Table 4 for soils according to soil texture classification are equivalent to the hydraulic conductivity at natural saturation (XKSAT) as determined for the Green and Ampt equation (Table 2). The values of CNSTL for soils classified according to hydrologic soil groups are shown in Table 5. These values within each hydrologic soil group have been selected from inspection of XKSAT values in Table 2 for the various soil texture classifications. These values of CNSTL shown in Table 5 are consistent with general information that is available for estimating CNSTL as shown in Table 6.

Procedure for Estimating Loss Rates

Green and Ampt Method

1. Determine the soil texture classification. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used if adequate documentation on the sampling and laboratory procedure is provided and approved.
2. Estimate the hydraulic conductivity (XKSAT) for bare ground from

Table 2 if general soil texture classification is available or from Figure 2 if adequate soil texture data is available from an approved sampling program.

3. If desired, adjust the value of XKSAT for the influences of ground cover and canopy cover using Equations 5 through 11 or Equation 12 for turf.
4. Estimate the wetting front capillary suction parameter (PSIF) from Table 2 if general soil texture classification is available or from Figure 3 if adequate soil texture data is available from an approved sampling program.
5. Estimate the value of DTHETA from Table 2 if general soil texture classification is available or from either Figure 7 or 8 if adequate soil texture data is available from an approved sampling program. The value of DTHETA must be selected based on the appropriate antecedent soil moisture condition; "Dry" for nonirrigated lands such as desert and rangeland; "Normal" for soil that would be expected to be near soil moisture field capacity such as irrigated lawn, turf, and permanent pasture; and, "Saturated" for irrigated agricultural land.
6. Determine the land-use and/or soil cover for the drainage area and use Table 1 to estimate the surface retention loss (IA).
7. As an alternative to the above procedure, Green and Ampt loss rate parameters can be estimated by reconstitution of recorded rainfall-runoff events on the drainage area or hydrologically similar watersheds, or parameters can be estimated by use of rainfall simulators in field experiments. Plans and procedures for estimating Green and Ampt loss rate parameters by either of these procedures should be approved by the Flood Control District of Maricopa County and the local agency before initiating these procedures.

Initial Loss Plus Uniform Loss Rate Method

1. Determine the soil texture classification and/or the hydrologic soil group. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used to classify the soil if adequate documentation on the sampling and

laboratory procedure is provided and approved.

2. Use values of CNSTL and STRTL from Table 4 if the losses are to be based on soil texture classification.
3. Use values of CNSTL and STRTL from Table 5 if the losses are to be based on hydrologic soil group.
4. Determine the land-use and/or soil cover and use Table 1 to estimate the surface retention loss to be added to STRTL from either Table 4 or 5.

REFERENCES

Brakensiek, D.L., Rawls, W.J., and Stephenson, G.R., 1984, Modifying SCS hydrologic soil groups and Curve Numbers for rangeland soils: Amer. Soc. of Agricultural Engineers, 1984 Annual Meeting, Kennewick, WA.

Eggert, K.G., 1976, Modeling the unsteady infiltration process: unpublished Masters Thesis, Colorado State University, Ft. Collins.

Horton, R.E., 1939, Analysis of runoff-plot experiments with varying infiltration capacity: Trans. of Amer. Geophysical Union, V. 20, pp. 693-711.

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Rawls, W.J., and Brakensiek, D.L., 1983, A procedure to predict Green and Ampt infiltration parameters: Amer. Soc. of Agricultural Engineers, Conference on Advances in Infiltration, Chicago, IL, pp. 102-112.

Rawls, W.J., Brakensiek, D.L., and Miller, N., 1983, Green-Ampt infiltration parameters from soils data: Amer. Soc. of Civil Engineers, Journal of Hydraulic Engineering, V. 109, No. 1, pp. 62-71.

Rawls, W.J., Brakensiek, D.L., and Savabi, M.R., 1988, Infiltration parameters for rangeland soils: draft submitted to the Journal of Range Management.

U.S. Army Corps of Engineers, 1982, Gila River Basin, Phoenix, Arizona and Vicinity, Hydrology Part 2, Design Memorandum No. 2: Los Angeles District, 59 pgs.

TABLE 1

Surface retention loss for various land surfaces in Maricopa County (addition to STRTL for IL+ULR method and IA for Green and Ampt method)

Land-Use and/or Surface Cover	Surface Retention Loss inches
(1)	(2)
Natural	
Desert and rangeland, flat slope	.35
Hillslopes, Sonoran desert	.15
Mountain, brush	.25
Developed (Residential and Commercial)	
Lawn and turf	.20
Desert landscape	.10
Pavement	.05
Agricultural	
Tilled	1.00
Irrigated pasture	.50

TABLE 2

Green and Ampt loss rate parameter values for bare ground

Soil Texture Classification	XKSAT in/hr	PSIF inches	DTHETA[1] Dry	DTHETA[1] Normal	DTHETA[1] Saturated
(1)	(2)	(3)	(4)	(5)	(6)
sand	4.6	1.9	.35	.30	0
loamy sand	1.2	2.4	.35	.30	0
sandy loam	.40	4.3	.35	.25	0
loam	.15	3.5	.35	.25	0
silt loam	.25 .10	6.6 7.5	.40 .33	.25 .14	0
sandy clay loam	.06	8.6	.25	.15	0
clay loam	.04	8.2	.25	.15	0
silty clay loam	.04	10.8	.30	.15	0
sandy clay	.02	9.4	.20	.10	0
silty clay	.02	11.5	.20	.10	0
clay	.01	12.4	.15	.05	0

[1] Selection of DTHETA:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 3

Soil crusting reduction factor for the Green and Ampt infiltration equation hydraulic conductivity parameter.

Soil Texture Classification	Reduction Factor for Subcrust Conductivity SC
(1)	(2)
Sand	0.91
Loamy sand	0.89
Sandy loam	0.86
Loam	0.82
Silt loam	0.81
Sandy clay loam	0.85
Clay loam	0.82
Silty clay loam	0.76
Sandy clay	0.81
Silty clay	0.73
Clay	0.75

TABLE 4

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to soil texture classification

Soil texture Classification	Uniform Loss Rate CNSTL	Initial Loss, STRTL[1] in inches		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
sand	4.6	1.3	1.3	0
loamy sand	1.2	.8	.8	0
sandy loam	.4	.7	.6	0
loam	.15	.6	.5	0
silty loam	.25	.8	.7	0
sandy clay loam	.06	.6	.5	0
clay loam	.04	.5	.4	0
silty clay loam	.04	.6	.5	0
sandy clay	.02	.4	.3	0
silty clay	.02	.4	.3	0
clay	.01	.3	.2	0

[1] Selection of STRTL:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 5

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to hydrologic soil group

Hydrologic Soil Group	Uniform Loss Rate CNSTL	Initial Loss, In inches STRTL[1]		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
A	.40	.6	.5	0
B	.25	.5	.3	0
C	.15	.5	.3	0
D	.05	.4	.2	0

[1] Selection of STRTL:
Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 6

Published values of uniform loss rates

Hydrologic Soil Group	**Uniform Loss Rate,** in inches/hour		
	Musgrave (1955)	USBR (1975)[1]	USBR (1988)[2]
(1)	(2)	(3)	(4)
A	.30 - .45	.40	.30 - .50
B	.15 - .30	.24	.15 - .30
C	.05 - .15	.12	0 - .05

[1] Design of Small Dams, Second Edition, 1975, Appendix A

[2] Design of Small Dams, Third Edition, 1988

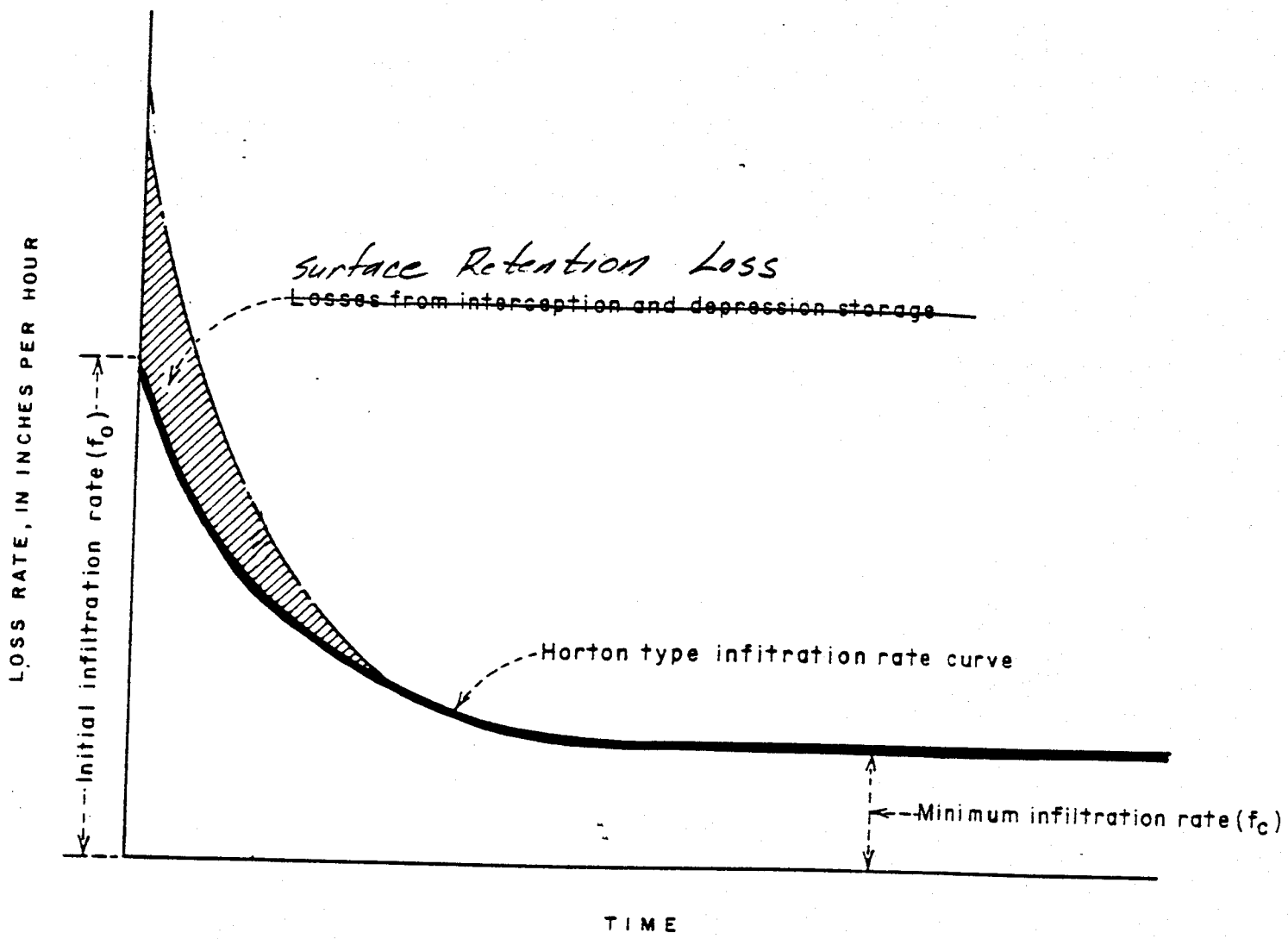
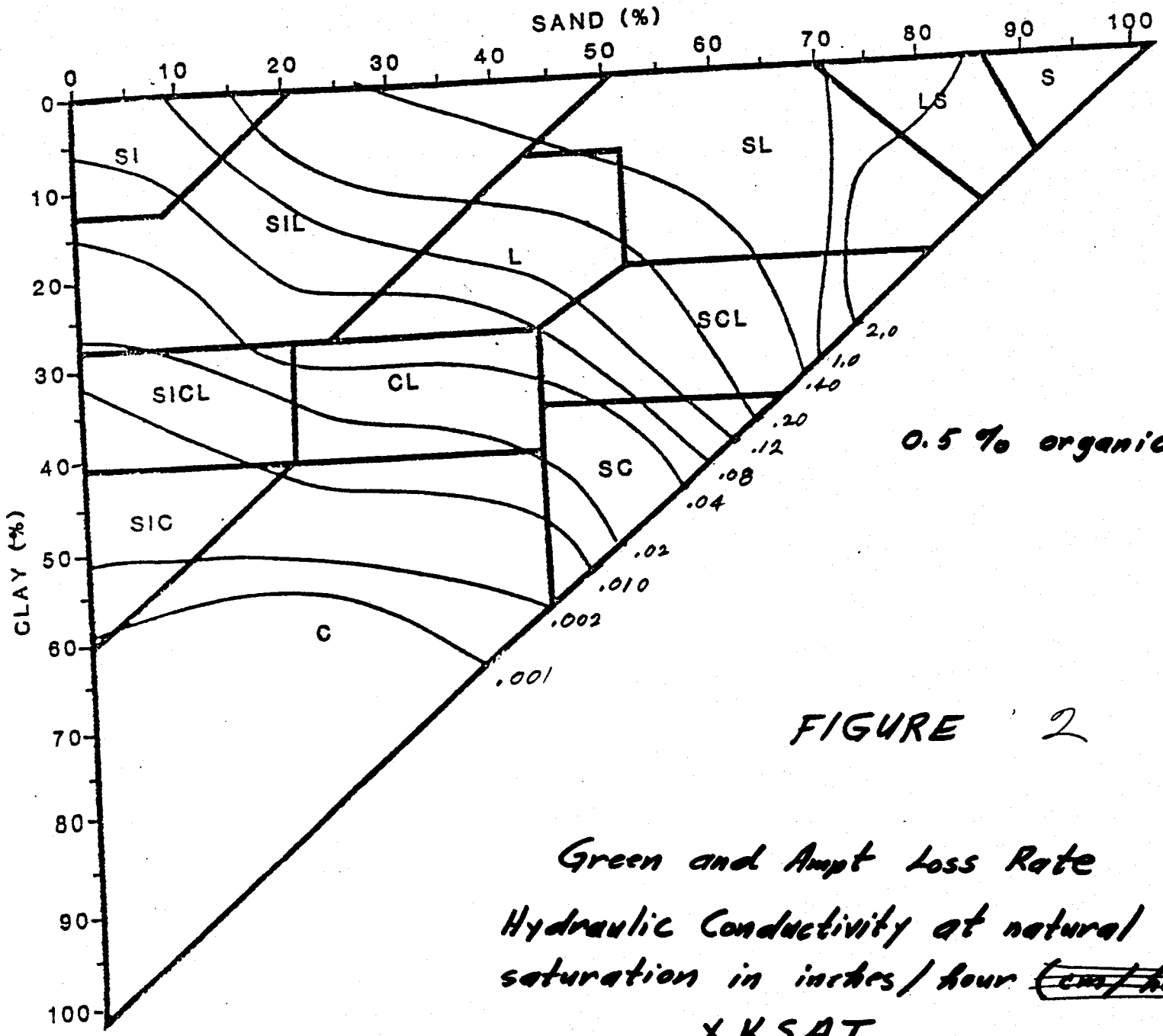


FIGURE 1

Representation of rainfall losses by surface retention and infiltration according to an exponential decay (Horton) type of equation



0.5 % organic matter

FIGURE 2

Green and Ampt Loss Rate

Hydraulic Conductivity at natural saturation in inches/hour ~~(cm/hour)~~

XKSAT

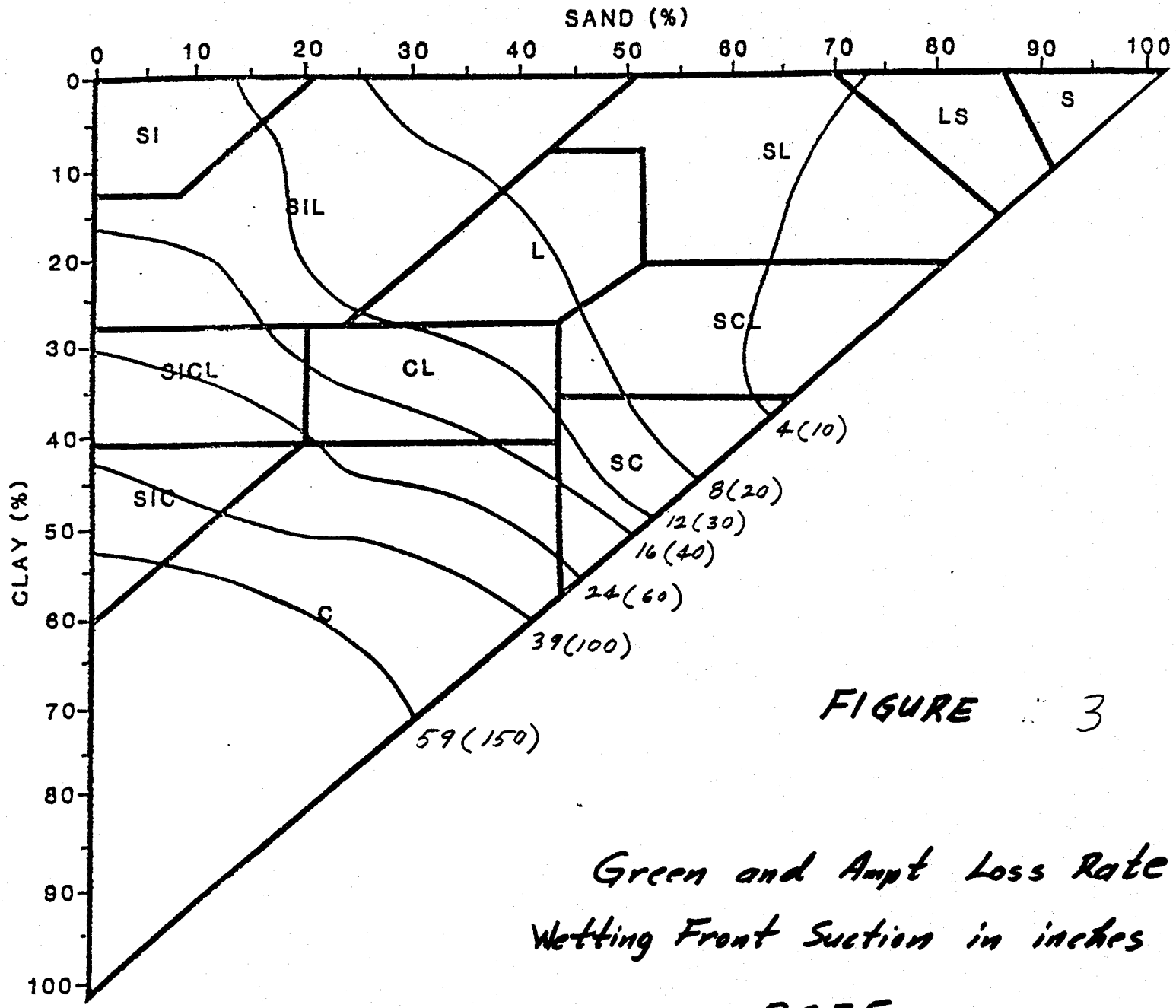


FIGURE 3

Green and Ampt Loss Rate

Wetting Front Suction in inches (cm)

PSIF

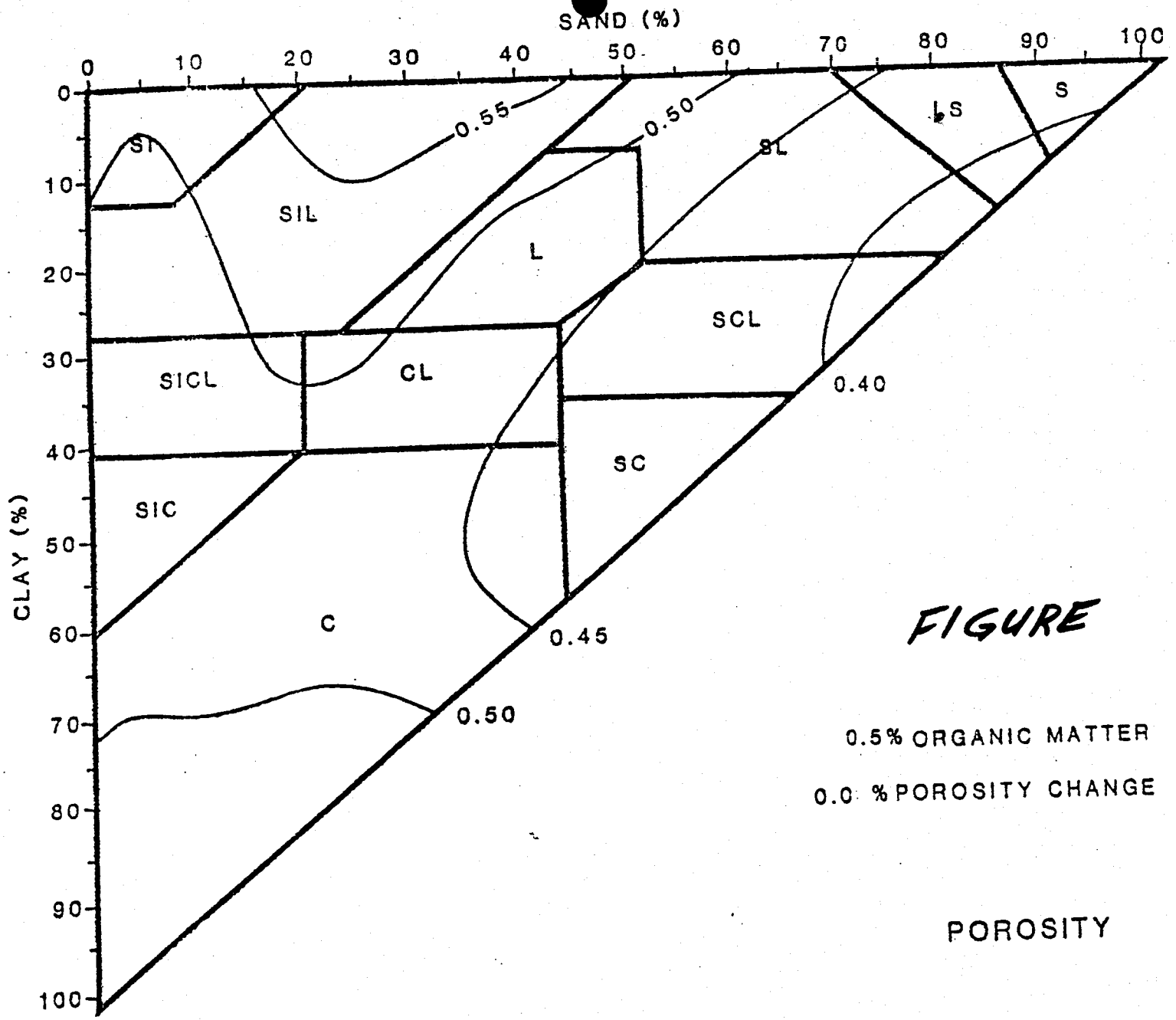


FIGURE 4

0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

POROSITY

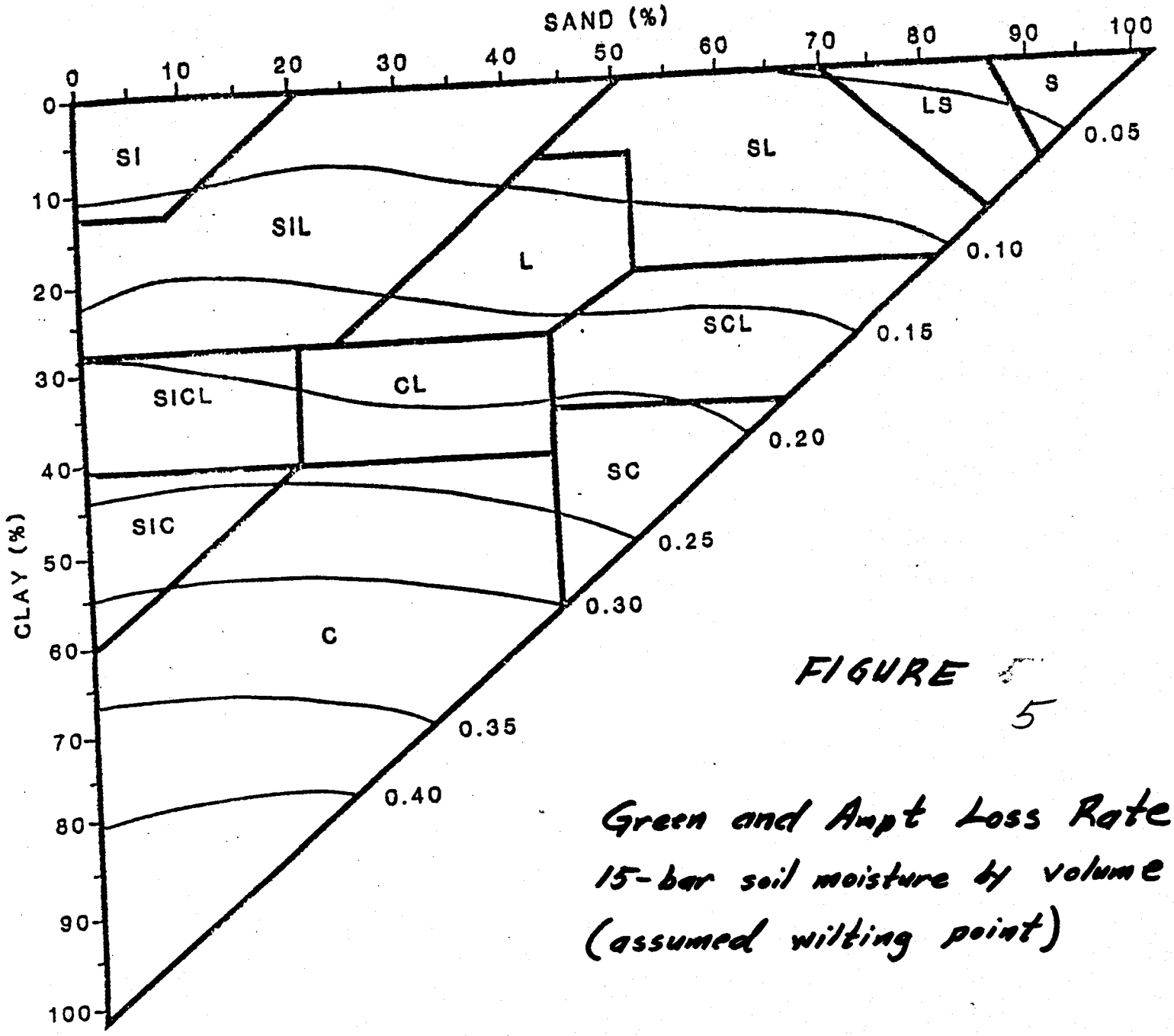


FIGURE 5

Green and Ampt Loss Rate
15-bar soil moisture by volume
(assumed wilting point)

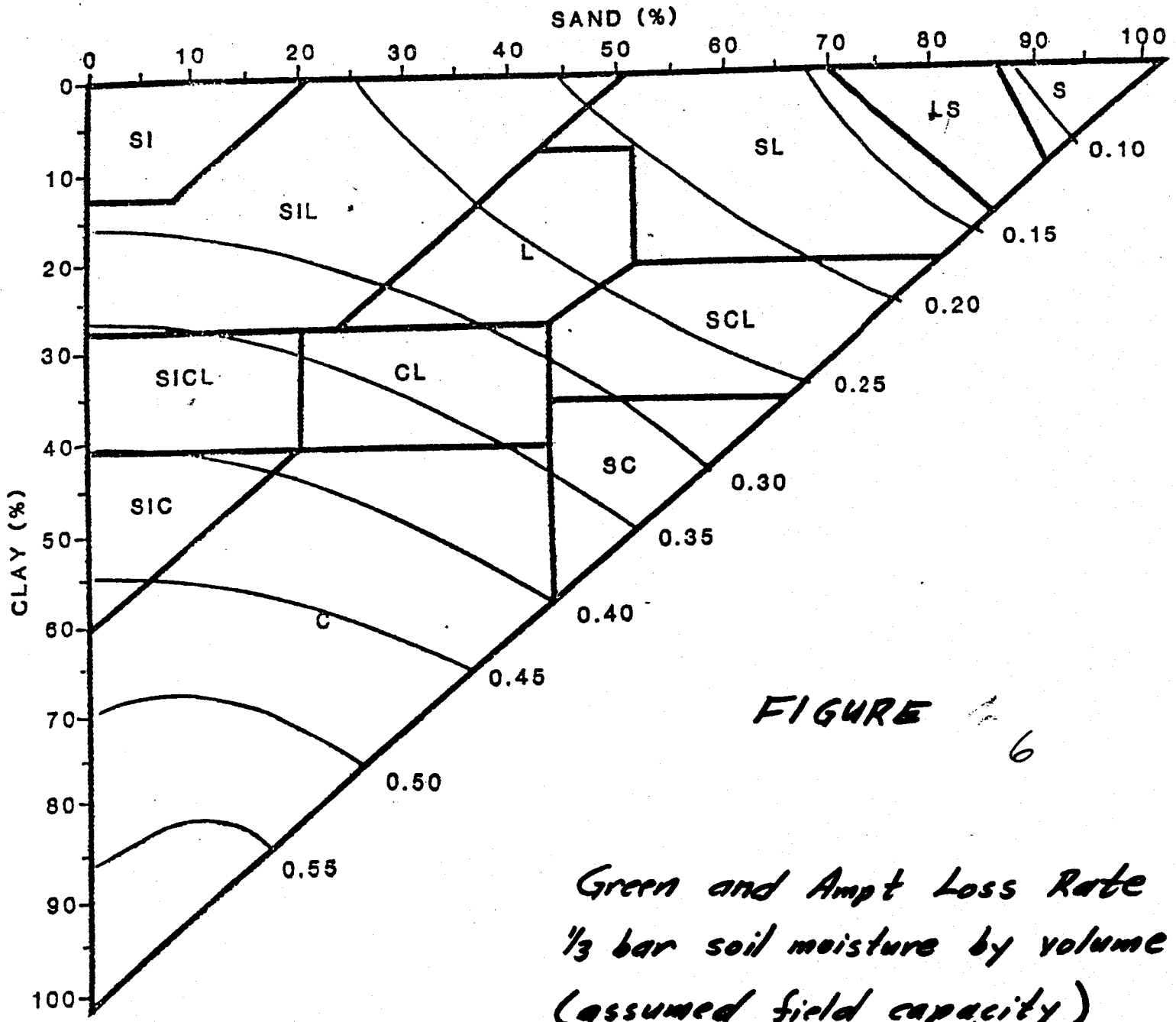


FIGURE 6

Green and Ampt Loss Rate
1/3 bar soil moisture by volume
(assumed field capacity)

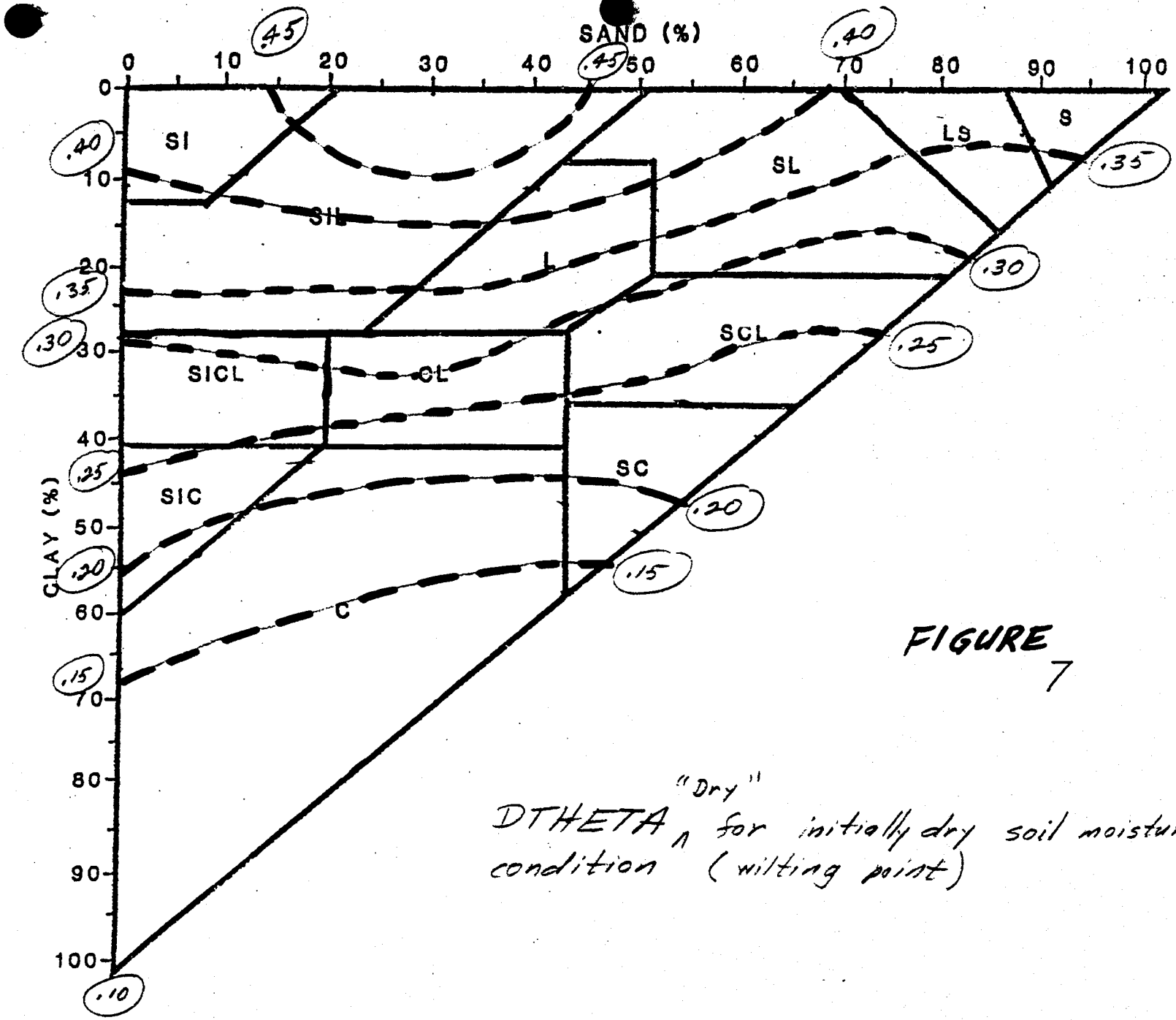


FIGURE 7

DTHETA "Dry" for initially dry soil moisture condition (wilting point)

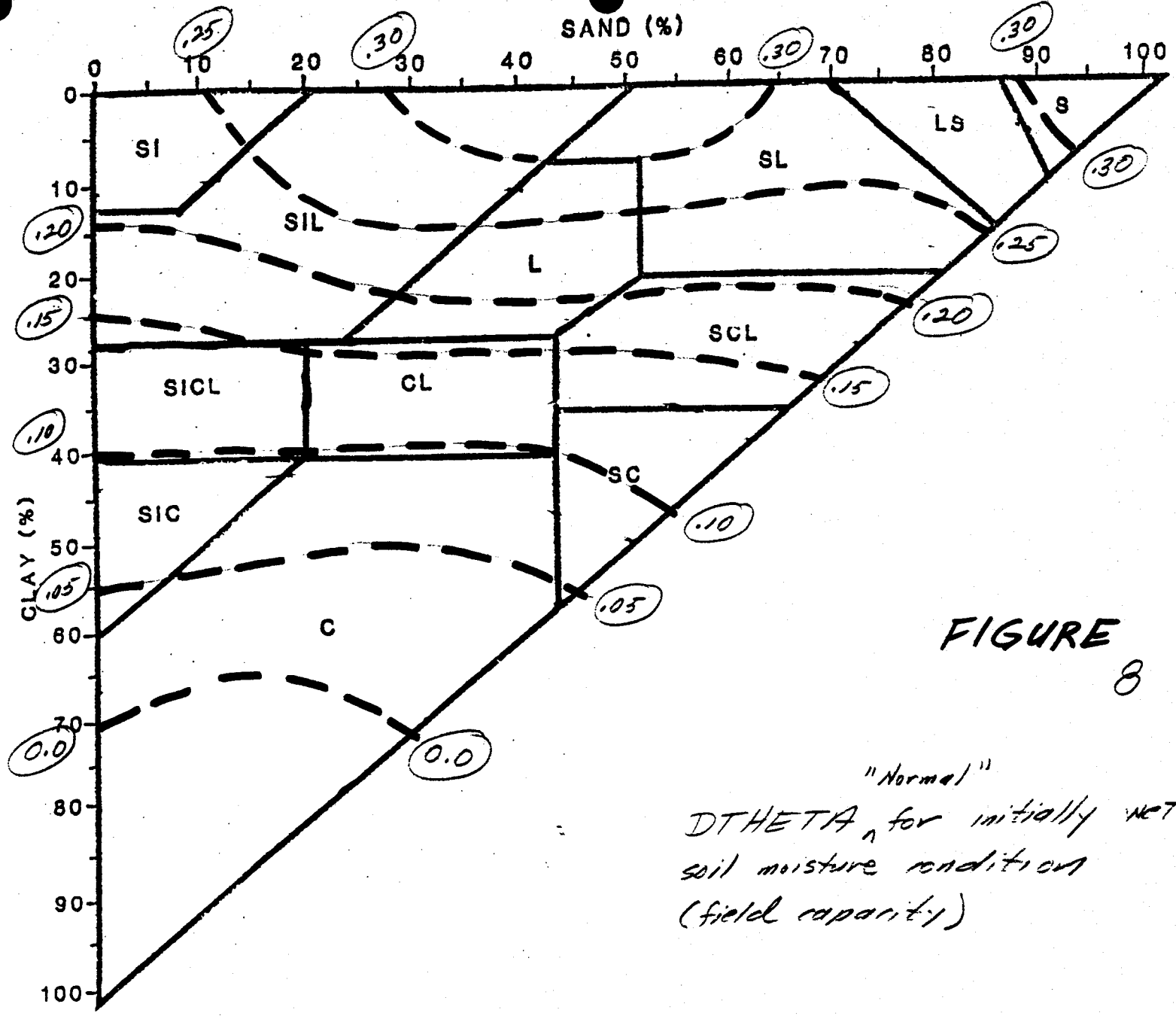


FIGURE 8

"Normal" DTHETA for initially wet soil moisture condition (field capacity)

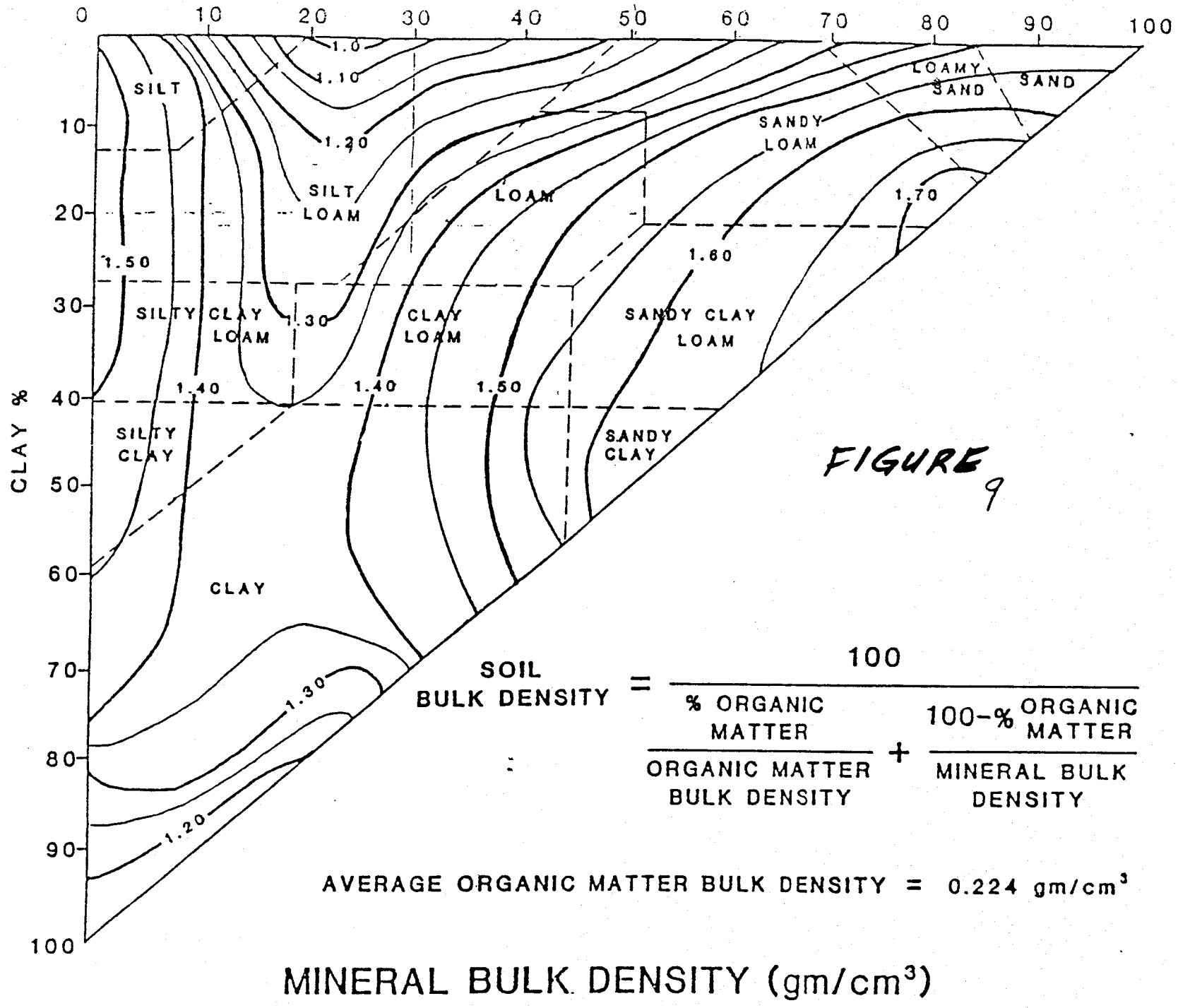


FIGURE 9

$$\text{SOIL BULK DENSITY} = \frac{100}{\dfrac{\%\ \text{ORGANIC MATTER}}{\text{ORGANIC MATTER BULK DENSITY}} + \dfrac{100-\%\ \text{ORGANIC MATTER}}{\text{MINERAL BULK DENSITY}}}$$

AVERAGE ORGANIC MATTER BULK DENSITY = 0.224 gm/cm³

~~Fig. 1. Determination of soil bulk density.~~

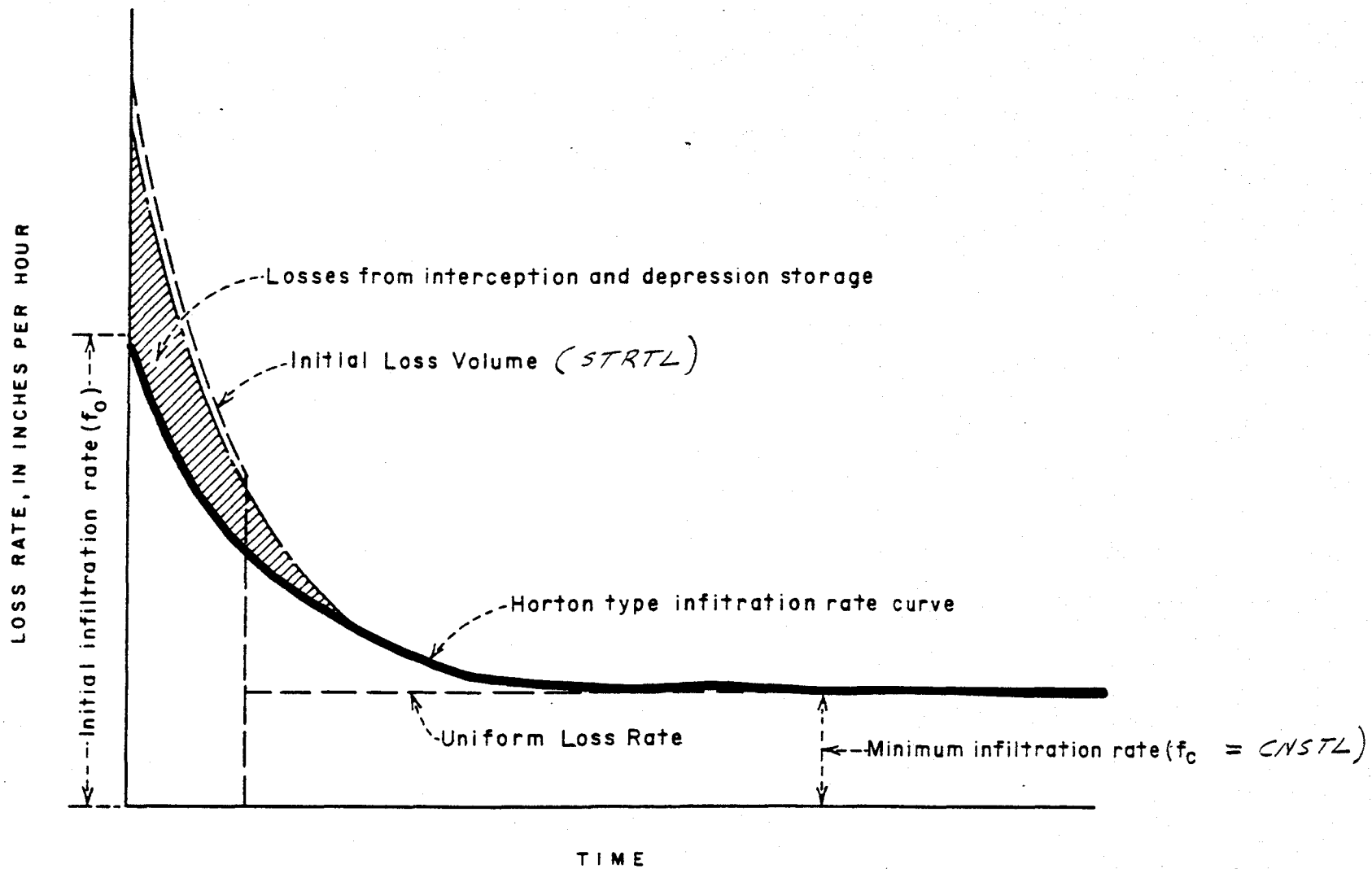


FIGURE 10

SIMULATION OF RAINFALL LOSSES BY THE INITIAL LOSS PLUS UNIFORM LOSS RATE METHOD

2 May 89

Leonard,

I have run the comparative test that you recommended in your review report. The results are enclosed. I would say that the results substantiate that the HEC-1 version of the Green-Ampt equation does account for the infiltration that occurs prior to the time of ponding without input of this loss separately, such as an initial abstraction. Using the HEC-1 version of Green-Ampt, we can input the surface retention loss (as defined in the manual and estimated in Table 1) separately.

I have incorporated your review comments into the draft, and when it is typed I will send the second draft to you. I have completed everything except the modification for canopy and ground covers. I want the comments from you and Tim Ward on the package that I sent last week before I complete this. I would like to use something simple such as the Figure 7A from that package that I sent to you for this modification. I would then delete the equations for modifying hydraulic conductivity for canopy and ground covers.

I have revised the introduction to the Raintall Loss section and I am adding Figures 1 and 2 (enclosed). Figure 2 is to illustrate how losses are calculated by the Green-Ampt method.

Please call me after you have reviewed this. Thanks for your help on this.

Sincerely,

Leo

Enclosures: 1. handwritten sheets on comparison
2. HEC-1 output
3. copy of HEC-1 manual on Green-Ampt
4. copy of new Figures 1 & 2 for manual

Copy w/ enclosures: Joe Rumann, FCDMC

2 May 89

Comparison of HEC-1 Green-Ampt eq'n. results with those by Leonard Lane in his review report

Lane's infiltration parameters for SANDY LOAM

K_s = 11.0 mm/hr — saturated conductivity
N_s = 28.782 mm — effective matric potential
N_e = .41 mm/mm — effective porosity
S_e = 22% — relative saturation (initial)

HEC-1 Green-Ampt parameters

$$XKSAT = \frac{11.0}{25.4} = .4331 \text{ in/hr}$$

$$PSIF = \frac{N_s}{N_e(1-S_e)} = \frac{28.782/25.4}{.41(1-.22)} = 3.5433 \text{ in.}$$

$$DTHETA = N_e(1-S_e) = .41(1-.22) = .3198$$

(Note: These values are very close to those shown in Table 2 of the manual; XKSAT = .4, PSIF = 4.3, DTHETA = .35)

Rainfall

Time, minutes	Accum. Rain, mm	Accum. Rain, inches
0	0	0
5	2.1167	.0833
10	4.2333	.1667
15	8.4667	.3333
20	12.7000	.50
25	12.9117	.5083
30	13.1233	.5167
35	13.3350	.5250
40	13.5467	.5333
45	13.7583	.5417
50	17.9917	.7083
55	22.2250	.8750
60	26.4583	1.0417

Results

Time, minutes	Excess by Lane: Rate, mm/hr	Depth, mm	Depth, in.	by HEC-1: Depth, in.
0	0	0	0	0
5	0	0	0	0
10	0	0	0	0
15	0	0	0	0
20	8.7060	.7255	.0286	.03
25	0	0	0	0
30	0	0	0	0
35	0	0	0	0
40	0	0	0	0
45	0	0	0	0
50	17.7857	1.4821	.0584	.06
55	21.1712	1.7643	.0695	.07
60	23.4561	1.9547	.0770	.08
			.2339	.23

Conclusion:

1. The results by Lane are essentially identical to those from HEC-1.

2. The HEC-1 program accounts for rainfall losses upto the time to ponding, and no adjustment is required to account for infiltration prior to the time of ponding.

```
1*************************************                    *************************************
*                                   *                    *                                   *
*  FLOOD HYDROGRAPH PACKAGE  (HEC-1)  *                    *   U.S. ARMY CORPS OF ENGINEERS    *
*           FEBRUARY 1981           *                    *  THE HYDROLOGIC ENGINEERING CENTER  *
*          REVISED 01 JUN 88        *                    *         609 SECOND STREET         *
*                                   *                    *      DAVIS, CALIFORNIA 95616      *
*  RUN DATE  05/02/1989  TIME  09:38:39 *                *         (916) 551-1748            *
*                                   *                    *                                   *
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X    X  XXXXXXX  XXXXX         X
X    X  X       X    X       XX
X    X  X       X            X
XXXXXXX  XXXX    X      XXXXX  X
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X    X  X       X    X       X
X    X  XXXXXXX  XXXXX       XXX
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THIS PROGRAM REPLACES ALL PREVIOUS VERSIONS OF HEC-1 KNOWN AS HEC1 (JAN 73), HEC1GS, HEC1DB, AND HEC1KW.

THE DEFINITIONS OF VARIABLES -RTIMP- AND -RTIOR- HAVE CHANGED FROM THOSE USED WITH THE 1973-STYLE INPUT STRUCTURE.
THE DEFINITION OF -AMSKK- ON RM-CARD WAS CHANGED WITH REVISIONS DATED 28 SEP 81. THIS IS THE FORTRAN77 VERSION
NEW OPTIONS: DAMBREAK OUTFLOW SUBMERGENCE , SINGLE EVENT DAMAGE CALCULATION, DSS:WRITE STAGE FREQUENCY,
DSS:READ TIME SERIES AT DESIRED CALCULATION INTERVAL LOSS RATE:GREEN AND AMPT INFILTRATION
KINEMATIC WAVE: NEW FINITE DIFFERENCE ALGORITHM

```
1                                        HEC-1 INPUT                                        PAGE  1

        LINE        ID.......1.......2.......3.......4.......5.......6.......7.......8.......9......10

 *** FREE ***
           1        ID    TEST G-A EQN USING L. LANE'S DATA
           2        IT      5                   25
           3        IO

           4        KK   TEST
           5        BA      1
           6        PC      0   .0833   .1666   .3333      .5   .5083   .5167    .525   .5333   .5417
           7        PC   .7083    .875  1.0417
           8        LG      0     .32  3.5433   .4331       0
           9        UC    .25     .25
          10        ZZ
1*************************************                    *************************************
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*
*  FLOOD HYDROGRAPH PACKAGE  (HEC-1)  *
*            FEBRUARY 1981            *
*          REVISED 01 JUN 88          *
*                                     *
*  RUN DATE  05/02/1989  TIME  09:38:39 *
*                                     *
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*    U.S. ARMY CORPS OF ENGINEERS     *
*  THE HYDROLOGIC ENGINEERING CENTER  *
*         609 SECOND STREET           *
*     DAVIS, CALIFORNIA 95616         *
*          (916) 551-1748             *
*                                     *
***************************************
```

```
                    TEST 6-A EQN USING L. LANE'S DATA

 3 IO        OUTPUT CONTROL VARIABLES
                  IPRNT          0  PRINT CONTROL
                  IPLOT          0  PLOT CONTROL
                  QSCAL         0.  HYDROGRAPH PLOT SCALE

   IT        HYDROGRAPH TIME DATA
                  NMIN           5  MINUTES IN COMPUTATION INTERVAL
                  IDATE      1   0  STARTING DATE
                  ITIME       0000  STARTING TIME
                     NQ         25  NUMBER OF HYDROGRAPH ORDINATES
                 NDDATE      1   0  ENDING DATE
                 NDTIME       0200  ENDING TIME
                 ICENT          19  CENTURY MARK

          COMPUTATION INTERVAL     .08 HOURS
               TOTAL TIME BASE    2.00 HOURS

     ENGLISH UNITS
          DRAINAGE AREA           SQUARE MILES
          PRECIPITATION DEPTH     INCHES
          LENGTH, ELEVATION       FEET
          FLOW                    CUBIC FEET PER SECOND
          STORAGE VOLUME          ACRE-FEET
          SURFACE AREA            ACRES
          TEMPERATURE             DEGREES FAHRENHEIT


*** *** *** *** *** *** *** *** *** *** *** *** ***       *** *** *** *** *** *** *** *** *** *** *** *** *** *** *** *** *** ***
```

```
              **************
              *            *
4 KK          *     TEST   *
              *            *
              **************

          SUBBASIN RUNOFF DATA

5 BA        SUBBASIN CHARACTERISTICS
                 TAREA        1.00  SUBBASIN AREA

            PRECIPITATION DATA

5 PB             STORM        1.04  BASIN TOTAL PRECIPITATION

5 PI          INCREMENTAL PRECIPITATION PATTERN
                 .08       .08       .17       .17       .01       .01       .01       .01       .01       .17
                 .17       .17

8 LG        GREEN AND AMPT LOSS RATE
                STRTL         .00  STARTING LOSS
                  DTH         .32  MOISTURE DEFICIT
                 PSIF        3.54  WETTING FRONT SUCTION
                XKSAT         .43  HYDRAULIC CONDUCTIVITY
                RTIMP         .00  PERCENT IMPERVIOUS AREA

9 UC        CLARK UNITGRAPH
                  TC         .25  TIME OF CONCENTRATION
                   R         .25  STORAGE COEFFICIENT

            SYNTHETIC ACCUMULATED-AREA VS. TIME CURVE WILL BE USED

                                          ***

                                   UNIT HYDROGRAPH PARAMETERS
                             CLARK   TC=   .25 HR,      R=   .25 HR
                            SNYDER   TP=   .23 HR,     CP=   .57

                                        UNIT HYDROGRAPH
                                   18 END-OF-PERIOD ORDINATES
          301.     1020.     1534.     1397.      998.      713.      509.      364.      260.      186.
          133.       95.       68.       48.       34.       25.       18.       13.

*****************************************************************************************************************
```

HYDROGRAPH AT STATION TEST

DA	MON	HRMN	ORD	RAIN	LOSS	EXCESS	COMP Q	DA	MON	HRMN	ORD	RAIN	LOSS	EXCESS	COMP Q
1		0000	1	.00	.00	.00	0.	1		0105	14	.00	.00	.00	272.
1		0005	2	.08	.08	.00	0.	1		0110	15	.00	.00	.00	277.
1		0010	3	.08	.08	.00	0.	1		0115	16	.00	.00	.00	221.
1		0015	4	.17	.17	.00	0.	1		0120	17	.00	.00	.00	158.
1		0020	5	.17	.14	.03	9.	1		0125	18	.00	.00	.00	113.
1		0025	6	.01	.01	.00	30.	1		0130	19	.00	.00	.00	81.
1		0030	7	.01	.01	.00	44.	1		0135	20	.00	.00	.00	58.
1		0035	8	.01	.01	.00	40.	1		0140	21	.00	.00	.00	41.
1		0040	9	.01	.01	.00	29.	1		0145	22	.00	.00	.00	29.
1		0045	10	.01	.01	.00	21.	1		0150	23	.00	.00	.00	21.
1		0050	11	.17	.11	.06	32.	1		0155	24	.00	.00	.00	15.
1		0055	12	.17	.10	.07	91.	1		0200	25	.00	.00	.00	11.
1		0100	13	.17	.09	.08	191.								

TOTAL RAINFALL = 1.04, TOTAL LOSS = .81, TOTAL EXCESS = .23

PEAK FLOW	TIME		MAXIMUM AVERAGE FLOW 6-HR	24-HR	72-HR	2.00-HR
+ (CFS)	(HR)					
		(CFS)				
+ 277.	1.17		74.	74.	74.	74.
		(INCHES)	.229	.229	.229	.229
		(AC-FT)	12.	12.	12.	12.

CUMULATIVE AREA = 1.00 SQ MI

1

RUNOFF SUMMARY
FLOW IN CUBIC FEET PER SECOND
TIME IN HOURS, AREA IN SQUARE MILES

OPERATION	STATION	PEAK FLOW	TIME OF PEAK	AVERAGE FLOW FOR MAXIMUM PERIOD 6-HOUR	24-HOUR	72-HOUR	BASIN AREA	MAXIMUM STAGE	TIME OF MAX STAGE
+ HYDROGRAPH AT	TEST	277.	1.17	74.	74.	74.	1.00		

*** NORMAL END OF HEC-1 ***

L. J. Lane
Hydrologist
411 E. Suffolk Dr.
Tucson, AZ 85704
602-575-8009

DATE: Sept. 17, 1989

TO: Dr. George V. Sabol
1351 East 141st Ave.
Brighton, CO 80601
303-457-0989

SUBJECT: 1. Comments on "Rainfall Losses Section"
2. Invoice for June, July, August, and September
3. Suggestions for Additional Research on Infiltration
4. ASCE San Diego Conference

1. Comments on "Rainfall Losses Section"

The document is much improved and will provide the basis for a much improved hydrology manual.

a. General and Surface Retention Loss, pp. 1-5

Good discussion and introduction and Table 1 is a good summary of useful information.

b. Infiltration, pp. 5-15

Again a good discussion and specific recommendations, i.e. the recommendation against sole use of SCS CN procedure, make this a useful section. Table 2~~1~~ gives very useful information. Suggest you cite main reference for material in a footnote so the reader knows source of information. Table 3, footnote. Suggest you change to recently, within 24 hr, irrigated land.

c. Discussion of adjusting hydraulic conductivity pp. 16-19 and Figs. 10 and 11.

The discussion is good, but Fig. 10 is preliminary and should be clearly indicated as such. I am disappointed in our inability to accurately reflect the influence of vegetation canopy cover and all types of ground cover on infiltration (Green-Ampt or any other eq.). We, as a profession, need to address this lack of information. I will discuss a specific proposal in a following section.

In any event, if this is the best we can do at present we should say so in the discussion of Fig. 10.

Figure 11 is a clever way to get around part of the problem.

2. Invoice for June - September, 1989

4.4 days at $350/day = $1540. (See attached detailed invoice)

3. Suggestions for Additional Research on Infiltration

Clearly, as our analyses show, there is an urgent need for research to determine influences of vegetation canopy cover, ground cover, and management practices on Green-Ampt infiltration parameters. Currently reported procedures in the literature can lead to inconsistent results under semiarid, desert, and urban conditions. Some of the reported regression-based procedures for adjusting saturated hydraulic conductivity yield inconsistent results when soil properties used in them deviate from normal ranges for agricultural soils.

Apparently, collecting infiltration data from the literature and analyzing it by regression methods is inadequate because of varying procedures and measuring techniques used in reported experiments. For example, it is not always clear if the infiltrometer data reported in the literature represented steady-state infiltration so that final infiltration rate is a good estimator for hydraulic conductivity.

I suggest that you and the appropriate officials in Maricopa County prepare and publish a White Paper stating the need for information of the above type for desert, semidesert, and urbanizing areas in Arizona. The report should emphasize the need for robust and simple procedures with practical value to the practicing engineer. Moreover, I suggest you distribute this report to research organizations and Universities in Arizona. Because of a possible conflict of interest, I should not participate in development of the White Paper but I could officially respond to it once it was published.

4. ASCE San Diego Conference

It would be a pleasure to participate in the San Diego Conference if we can agree on an appropriate topic and if it does not conflict with previous commitments. Please send me the brochure for the meeting showing dates and sessions and the outline/thoughts you have for your session on alluvial fans.

Thank you very much for the opportunity to participate in the conference and I'm sure we can work something out to our mutual satisfaction.

Sincerely,

Leonard

Leonard J. Lane

attachment

APPENDIX 5-D

Review Comments and Correspondence with Dr. Kenneth Renard

United States Department of Agriculture

Agricultural Research Service

Pacific West Area

USDA-AGRICULTURAL RESEARCH SERVICE
ARIDLAND WATERSHED MANAGEMENT RESEARCH
2000 EAST ALLEN ROAD
TUCSON, ARIZONA 85719
January 26, 1989

George V. Sabol, PhD, PE
Consulting Engineer
1351 East 141st. Avenue
Brighton, CO 80601

Dear George:

Dr. Herman Bouwer sent me a copy of the Rainfall Losses section of the Maricopa County Hydrology Manual and asked if I would make some comments to you.

My comments are few because it is hard to treat a section without seeing more of what you are proposing. For example, the success of using a time-based infiltration model is very much conditioned upon access to hyetograph precipitation or at least to a method for disaggregating daily rainfall. Furthermore, if you are proposing that the manual apply to areas larger than tens of acres in size, then a depth-area method must be applied. Again, if the larger areas are to be simulated, then it is essential to adequately route the flows from individual source areas considering transmission losses in the ephemeral streambeds which dominate hydrologic responses in arid and semiarid areas.

As a final comment, I presume that Dr. W. Rawls and/or D. Brakensiek have or will see this material because of the liberal use of the technology they have developed on the Green-Ampt infiltration model.

Sincerely,

Ken Renard

Kenneth G. Renard, PhD, PE
Research Hydraulic Engineer

Attachment: manual with margin notes

CC: H. Bouwer

Ken Renard

RAINFALL LOSSES 29 Dec 88

PRELIMINARY
For Review Only

Theory

General

Rainfall excess is that portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall losses equals precipitation. When performing a flood analysis using a rainfall-runoff model, the determination of rainfall excess is of utmost importance. Rainfall excess integrated over the entire watershed results in runoff volume, and the temporal distribution of the rainfall excess will, along with the hydraulics of runoff, determine the peak discharge. Therefore, the estimation of the magnitude and time distribution of rainfall losses should be performed with the best practical technology, considering the objective of the analysis, economics of the project, and consequences of inaccurate estimates.

Rainfall losses are generally considered to be the result of interception of rainfall by vegetal cover, depression storage on the land surface (paved or unpaved), evaporation of water from the land surface, and infiltration of water into the soil matrix. For the purposes of this Hydrology Manual rainfall losses are classified as either surface retention loss or infiltration. Losses are also often separated into accumulated losses prior to the initiation of surface runoff (initial abstraction), and losses during surface runoff; however, initial abstraction is not identical to surface retention loss because initial abstraction includes some amount of infiltration losses prior to the start of surface runoff.

Surface Retention Loss

Surface retention loss, as used herein, is the summation of all rainfall losses other than infiltration. The major component of this loss is depression storage consisting of rainfall that is captured in puddles, small surface depressions, road gutters, ditches, roofs, and other non-draining surface features. A relatively minor contribution by interception is also considered as a part of the total surface

retention loss. Estimates of surface retention loss are difficult to obtain and are a function of the physiography and land-use of the area. Estimates of surface retention loss contained in this manual have been obtained from the analysis of rainfall-runoff data, results of rainfall simulator studies conducted on rangelands and turf, and published estimates for such losses.

Infiltration

Infiltration is the movement of water from the land surface into the soil. Infiltration is distinguished from percolation in that percolation is the movement of water through the soil subsequent to infiltration. Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, the extent by which percolation can restrict infiltration of rainfall should be carefully evaluated before percolation can be assumed to restrict infiltration for the design rainfalls that are being considered in Maricopa County. For example, hydrologic soil group D has been defined by SCS soil scientists as:

> "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."

This definition indicates that soils in hydrologic soil groups A, B, or C could be classified as D if they are underlain by an impervious strata of clay, caliche, or rock. When these soils are considered in regard to long-duration rainfalls that are the design events for many parts of the United States this definition may be valid. However, when considered for short-duration and relatively small design rainfall depths in Maricopa County this definition could result in under estimation of the rainfall losses for these storms. This is because even a relatively shallow horizon of soil overlaying an impervious layer still has the ability to store a significant amount of infiltrated rainfall. For example, consider the situation where only 4 inches of soil covers an impervious layer. If the effective

porosity is 0.30 then 1.2 inches (4 inches times 0.30) of water can be infiltrated and stored in the shallow soil horizon. For a design rainfall of 6 hours and a rainfall depth of about 4 inches this represents a significant storage volume for infiltrated rainfall. Therefore, for drainage studies in Maricopa County that contain major areas of soil that are classified as hydrologic soil group D, the reason for the soil survey classification as D should be determined. Hydrologic soil group D should be retained for clay soils, soils with a permanent high water table, and rock outcrop. Hydrologic soil group D should probably not be retained in all situations where the classification is based on shallow soils over nearly impervious layers, and site specific studies and sensitivity analyses should be performed to estimate the loss rates that should be used for such soils.

Infiltration of water into the soil is generally believed to follow an exponential decay function as proposed by Horton (1939):

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where f is the infiltration rate at time t,

f_c is the minimum (equilibrium) infiltration rate,

f_o is the initial infiltration rate,

t is the time from start of rainfall,

k is a constant that is dependent upon the soil-vegetation complex, and

e is the base of the Naperian logarithms.

This infiltration function is illustrated in Figure 1. In Figure 1, the infiltration rate is shown to be a continually decreasing function of time and the surface retention loss is shown to be a loss that is independent of and separate from the infiltration of rainfall into the soil. This represents the physical process that is to be simulated in modeling rainfall loss.

The driving force for infiltration is gravity and capillary forces drawing water into and through the pore spaces of the soil matrix.

Infiltration is controlled by soil properties, vegetation influences on the soil structure, surface cover by rock and vegetation, and by tillage practices.

Methods for Estimating Rainfall Losses

Numerous methods have been developed for estimating rainfall losses. Five methods are available as options in the HEC-1 Flood Hydrology Package:

1. SCS CN loss rate,
2. Initial loss plus uniform loss rate,
3. Exponential loss rate,
4. Holtan infiltration equation, and
5. Green and Ampt infiltration equation.

The Holtan infiltration equation is similar to the Horton equation in that it is an exponential decay type of equation for which the rainfall loss rate asymptotically diminishes to the minimum infiltration rate, f_c. The Holtan equation is not extensively used and data and procedures to estimate the parameters for use in Maricopa County are not available. The Holtan equation is not recommended for general use in Maricopa County.

The Exponential loss rate method is a four parameter method that is not extensively used, but it is a preferred method of the U.S. Army Corps of Engineers. Data and procedures are not available to estimate the parameters for this loss rate method for all physiographic areas in Maricopa County, but Exponential loss rate parameters have been developed from the reconstitution of flood events for a flood hydrology study in a portion of Maricopa County (U.S. Army Corps of Engineers, 1982). However, adequate data is not available to estimate the necessary parameters and this method is not recommended for general use in Maricopa County.

The SCS CN method is the most extensively used rainfall loss rate method in Maricopa County and it has wide acceptance among many

agencies, consulting engineering firms, and individuals throughout the community. However, the method is limited because of both theoretical and practical deficiencies of the method. Several of the deficiencies of the SCS CN method are:

1. Rainfall losses are independent of the duration of rainfall. That is, for a given depth of rainfall the same rainfall loss results regardless of the duration of rainfall, and the same rainfall excess would be estimated for a given rainfall depth occurring in, for example, either 1 hour or 24 hours.
2. The estimated rainfall loss rate is a function of rainfall intensity. Short periods of high intensity rainfall would often result in large estimates of rainfall losses. This is contrary to the Horton type infiltration relation as illustrated in Figure 1.
3. The infiltration rate approaches zero rather than a minimum infiltration rate, f_c.
4. The initial abstraction of 0.2S is not justified nor is it based on data for hydrologic conditions that are representative of Maricopa County.
5. The selection of CN is too subjective and is based more on traditional acceptance of CN values rather than scientifically substantiated findings.
6. At low rainfalls (less than 4 inches), the estimate of rainfall loss is very sensitive to the selection of CN.

For these reasons the SCS CN method is not recommended for general use in Maricopa County.

Two methods are recommended for use in Maricopa County; these are the initial loss plus uniform loss rate (IL+ULR), and the Green and Ampt infiltration equation. Other methods should be used only if there is technical justification for a variance from this recommendation and if adequate information is available to estimate the necessary parameter values. Use of rainfall loss methods other than those recommended should not be undertaken unless previously approved by the Flood Control District and the local regulatory agency.

Green and Ampt Infiltration Equation

This model, first developed in 1911 by W.H. Green and G.A. Ampt, has since 1973 received increased interest for estimating rainfall infiltration losses. The model has the form:

$$f = K\left(1 + \frac{a}{F}\right)$$
$$a = \psi\phi\,(S_f - S_i) \qquad (2)$$

where
- f = infiltration rate,
- K = hydraulic conductivity in the wetted zone (the ultimate steady state rate),
- ψ = average capillary suction in the wetted zone,
- S_f = final soil saturation (volumetric),
- S_i = initial soil saturation (volumetric),
- ϕ = soil porosity, and
- F = depth of rainfall that has infiltrated into the soil since the beginning of rainfall.

It is important to note that as rain continues, F increases and f approaches K, and therefore, f is inversely related to time. Equation 2 is implicit with respect to f which causes computational difficulties. Eggert (1976) simplified Equation 1 by expanding the equation in a power series and truncating all but the first two terms of the expansion. The simplified solution (Li and others, 1976) is:

$$\Delta F = -.5(2F-K\Delta t)+.5((2F-K\Delta t)^2 + 8K\Delta t(a + F))^{1/2} \qquad (3)$$

where t is the computation interval and F is accumulated depth of infiltration at the start of t. The average infiltration rate is:

$$\Delta f = \frac{\Delta F}{\Delta t} \qquad (4)$$

Use of the Green and Ampt equation as coded in HEC-1 involves the simulation of rainfall loss as a two phase process. The first phase is the simulation of the surface retention loss as previously described, and this loss is called the initial loss (IA) in HEC-1.

During this first phase all rainfall is lost (zero rainfall excess generated) during the period from the start of rainfall up to the time that the accumulated rainfall equals the value of IA. It is assumed for modeling purposes, that no infiltration of rainfall occurs during this first phase. Initial loss (IA) is primarily a function of land-use and surface cover, and recommended values of IA for use with the Green and Ampt equation are presented in Table 1. For example, as shown in Table 1 about 0.35 inches of rainfall will be lost to runoff due to surface retention for desert and rangelands on relatively flat slopes in Maricopa County.

The second phase of the rainfall loss process is the infiltration of rainfall into the soil matrix. For modeling purposes, the infiltration begins immediately after the surface retention loss (IA) is completely satisfied. The three Green and Ampt equation infiltration parameters as coded in HEC-1 are hydraulic conductivity at natural saturation (XKSAT), wetting front capillary suction (PSIF), and volumetric soil moisture deficit at the start of rainfall (DTHETA). The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture), organic matter, and bulk density. The primary soil surface characteristics are vegetation cover, rock cover, and soil crusting. The land management practices are identified as various tillages as they result in changes to soil porosity.

Values of Green and Ampt equation parameters as a function of soil characteristics alone (bare ground condition) have been obtained from published reports (Rawls and others, 1983; Rawls and Brakensiek, 1983). Average values of XKSAT and PSIF for each of the soil texture classes are shown in Columns (2) and (3) of Table 2 (Rawls and others, 1983). Values of XKSAT and PSIF as a function of percent of sand and percent of clay for soil with 0.5 percent organic matter and base value (unaltered) soil porosity are shown in Figures 2 and 3, respectively (Rawls and Brakensiek, 1983). The values of XKSAT and PSIF from Table 2 should be used if general soil texture classification of the drainage area is available. The values of XKSAT

and PSIF from Figures 2 and 3 can be used if more specific soil texture classification is available from a detailed soil survey for which the percentage of sand and clay has been determined by an appropriate field soil survey. The use of the information in Figures 2 and 3 will require an extensive study of the soil for the drainage area and for most drainage studies only general soil texture classification will be known and the values from Table 2 should be used.

The soil moisture deficit (DTHETA) is a volumetric measure of the soil moisture storage capacity that is available at the start of the rainfall. DTHETA is a function of the effective porosity of the soil. If the soil is saturated at the start of rainfall then DTHETA equals 0.0. If the soil is devoid of moisture at the start of rainfall the DTHETA equals the effective porosity of the soil. Therefore the range of DTHETA is 0.0 to the effective porosity. The porosity of soil as a function of soil texture (percent of sand and percent of clay) is shown in Figure 4 (Brakensiek and others, 1984).

Under natural conditions, soil seldom reaches a state of soil moisture less than the wilting point of vegetation, and a graph of volumetric soil moisture at wilting point as a function of soil texture is shown in Figure 5. Due to the rapid drainage capacity of most soils in Maricopa County the soil would not be expected to be in a state of soil moisture greater than the field capacity at the start of a design storm. A graph of volumetric soil moisture at field capacity as a function of soil texture is shown in Figure 6. However, Maricopa County also has a large segment of its land area under irrigated agriculture and it is reasonable to assume that the design frequency storm could occur during or shortly after certain lands had been irrigated. Therefore, for irrigated lands it would be reasonable to assume that soil moisture could be at or near effective saturation during the start of the design rainfall.

Three conditions for DTHETA have been defined for use in Maricopa County based on the antecedent soil moisture condition that could be expected to exist at the start of the design rainfall. These three

conditions are "Dry" for antecedent soil moisture near the vegetation wilting point; "Normal" for antecedent soil moisture condition near field capacity due to previous rainfall or irrigation applications on nonagricultural lands; and "Saturated" for antecedent soil moisture near effective saturation due to recent irrigation of agricultural lands. Values of DTHETA have been estimated by subtracting the initial volumetric soil moisture for each of the three conditions from the soil porosity. The value of DTHETA "Dry" as a function of soil texture is shown in Figure 7. This figure was prepared by subtracting the wilting point soil moisture on Figure 5 from the soil porosity on Figure 4. The value of DTHETA "Normal" as a function of soil texture is shown in Figure 8. This figure was prepared by subtracting the field capacity soil moisture on Figure 6 from the soil porosity on Figure 4. The value of DTHETA "Saturated" is always equal to 0.0 because for this condition there is no available pore space in the soil matrix at the start of rainfall. Values of DTHETA for the three antecedent soil moisture conditions are shown in Table 2. DTHETA "Dry" should be used for soil that is usually in a state of low soil moisture such as would occur in the desert and rangelands of Maricopa County. DTHETA "Normal" should be used for soil that is usually in a state of moderate soil moisture such as would occur in irrigated lawns, golf courses, parks, and irrigated pastures. DTHETA "Saturated" should be used for soil that is usually in a state of high soil moisture such as irrigated agricultural land.

The hydraulic conductivity (XKSAT) can be affected by several factors besides soil texture. For example, hydraulic conductivity is reduced by soil crusting, it is increased by tillage, and it is increased by the influence of ground cover and canopy cover. The values of XKSAT that have been presented for bare ground as a function of soil texture alone should be adjusted under certain conditions. - How do they do this? Adjusting

Ground cover, such as grass, litter, and rock will generally increase the infiltration rate over that of bare ground conditions. Similarly, canopy cover, such as from trees, brush, and tall grasses can also increase the bare ground infiltration rate. The procedures and data that have been presented are for estimating the Green and Ampt

parameters based solely on soil texture and would be applicable for bare ground conditions. Procedures have been developed (Rawls and others, 1988) for incorporating the effects of ground cover and canopy cover into the estimation of the parameters for the Green and Ampt equation. Past research has shown that the wetting front capillary suction parameter (PSIF) is relatively insensitive in comparison with the hydraulic conductivity parameter (XKSAT); therefore only the hydraulic conductivity parameter is adjusted for the influences of ground cover and canopy cover.

The set of equations that have been developed to adjust the bare soil hydraulic conductivity for the influence of soil ground cover and canopy cover are:

$$KE = (CAN)\ (KE_c) + (OP)\ (KE_o) \tag{5}$$

$$KE_c = (K)\ (CF)\left[\left(\frac{BC}{CAN}\right)(CRC) + A\left(1 - \frac{BC}{CAN}\right)\right] \tag{6}$$

$$KE_o = (K)\left[\left(\frac{BO}{CAN}\right)(CRC) + A\left(1 - \frac{BO}{CAN}\right)\right] \tag{7}$$

$$CF = 1 + 0.96\ CAN \tag{8}$$

$$CRC = \frac{L}{\frac{L - TC}{SC} + \frac{TC}{B}} \tag{9}$$

$$A = e^{\left[2.82 - 0.099(SA) + 1.94(BD)\right]} \tag{10}$$

$$B = 0.0099 + 0.0721(TC) + 0.0000068(SA^2) + 0.000021(SA^2)(TC) - 0.000315(SA)(TC) \tag{11}$$

where KE = hydraulic conductivity adjusted for ground cover and canopy cover, and KE is the adjusted value of XKSAT in the Green and Ampt equation,

KE_c = hydraulic conductivity of soil under canopy cover,

KE_o = hydraulic conductivity of soil outside of canopy cover,

K = bare ground hydraulic conductivity, equal to XKSAT,

CF = canopy factor,

CRC = soil crust factor,

A = macroporosity factor,

CAN = ratio of area under canopy cover to total area,

OP = ratio of area outside of canopy cover to total area,

BC = ratio of bare soil (no vegetation, litter, or rock cover) that is under canopy cover to total area,

BO = ratio of bare soil that is outside of canopy cover to total area,

L = wetting front depth (assume 6 cm),

TC = soil crust thickness (assume 0.5 cm),

SC = correction factor for partial saturation of the subcrust soil (see Table 3),

SA = percent sand in the soil,

BD = soil bulk density (see Figure 9).

These equations have been developed for the SI system of units and they should be solved in this system and the resulting hydraulic conductivity (KE) in cm/hr should be converted to XKSAT in inches/hr.

Equations 5 through 7 can be simplified for use in estimating the hydraulic conductivity of turf by the following equation:

$$KE = (K)(A) \tag{12}$$

where A is defined by Equation 10.

The influence of tillage results in a change in total porosity and therefore a need to modify the three Green and Ampt equation infiltration parameters. The effect of tillage systems on soil porosity and the corresponding changes to hydraulic conductivity, wetting front capillary suction, and water retention is available (Rawls and Brakensiek, 1983). Although this information is available it is not presented in this manual, nor is it recommended that these

adjustments be made to the three infiltration parameters for design purpose use in Maricopa County. This is because for most flood prediction purposes it cannot be assumed that the soil will be in any particular state of tillage at the time of storm occurrence and therefore the base condition infiltration parameters, as presented, should be used for flood prediction purposes. However, appropriate adjustments to the infiltration parameters can be made as necessary for special flood studies such as reconstitution of storm events.

Initial Loss Plus Uniform Loss Rate (IL + ULR)

This is a simplified rainfall loss method that is often used, and generally accepted, for flood hydrology. In using this simplified method it is assumed that the rainfall loss process can be simulated as a two-step procedure, as illustrated in Figure 10. First, all rainfall is lost to runoff until the accumulated rainfall is equal to the initial loss; and second, after the initial loss is satisfied, a portion of all future rainfall is lost at a uniform rate. Two parameters are needed to use this method, the initial loss and the uniform loss rate (STRTL and CNSTL), respectively, according to HEC-1 nomenclature).

The initial loss (STRTL) is the sum of all losses prior to the onset of runoff and is made up of surface retention loss and some amount of infiltration. This is also called initial abstraction. Values of the infiltration part of STRTL for bare ground according to soil texture classification are shown in Columns (3) through (5) in Table 4. These values have been derived from the Green and Ampt infiltration equation and parameter values that are shown in Table 2. The value of STRTL "Dry" should be used for soil that is usually in a state of low soil moisture at or near the wilting point for vegetation. This is a reasonable assumption for most nonirrigated lands in Maricopa County because of the infrequency of rainfall and because of the rapid drainage of these soils after rainfall. The value of STRTL "Normal" should be used for soil that is usually in a state of moderate soil moisture such as occurs for irrigated lawns, turf, and permanent pastures. The value of STRTL "Saturated" should be used for soil that is maintained in a state of high soil moisture such as occurs in

irrigated agricultural lands.

the USDA-SCS

Values of STRTL for bare ground that have been classified according to hydrologic soil group are shown in Table 5. These values within each hydrologic soil group have been derived from the data in Table 4 for the various soil texture classifications.

The values of STRTL from Table 4 and 5 represent that portion of the initial loss that is attributable to infiltration and these should be increased to account for the surface retention loss that is a function of land-use and vegetation. These additive STRTL values are shown in Table 1. The value of STRTL that is used is the sum of the portion due to infiltration (Table 4 or 5) plus the portion that is due to surface retention (Table 1).

The uniform loss rate (CNSTL) represents the long-term, equilibrium infiltration capacity of the soil. The values of CNSTL shown in Column (2) of Table 4 for soils according to soil texture classification are equivalent to the hydraulic conductivity at natural saturation (XKSAT) as determined for the Green and Ampt equation (Table 2). The values of CNSTL for soils classified according to hydrologic soil groups are shown in Table 5. These values within each hydrologic soil group have been selected from inspection of XKSAT values in Table 2 for the various soil texture classifications. These values of CNSTL shown in Table 5 are consistent with general information that is available for estimating CNSTL as shown in Table 6.

Procedure for Estimating Loss Rates

Green and Ampt Method

1. Determine the soil texture classification. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used if adequate documentation on the sampling and laboratory procedure is provided and approved.
2. Estimate the hydraulic conductivity (XKSAT) for bare ground from

Table 2 if general soil texture classification is available or from Figure 2 if adequate soil texture data is available from an approved sampling program.

3. If desired, adjust the value of XKSAT for the influences of ground cover and canopy cover using Equations 5 through 11 or Equation 12 for turf.
4. Estimate the wetting front capillary suction parameter (PSIF) from Table 2 if general soil texture classification is available or from Figure 3 if adequate soil texture data is available from an approved sampling program.
5. Estimate the value of DTHETA from Table 2 if general soil texture classification is available or from either Figure 7 or 8 if adequate soil texture data is available from an approved sampling program. The value of DTHETA must be selected based on the appropriate antecedent soil moisture condition; "Dry" for nonirrigated lands such as desert and rangeland; "Normal" for soil that would be expected to be near soil moisture field capacity such as irrigated lawn, turf, and permanent pasture; and, "Saturated" for irrigated agricultural land.
6. Determine the land-use and/or soil cover for the drainage area and use Table 1 to estimate the surface retention loss (IA).
7. As an alternative to the above procedure, Green and Ampt loss rate parameters can be estimated by reconstitution of recorded rainfall-runoff events on the drainage area or hydrologically similar watersheds, or parameters can be estimated by use of rainfall simulators in field experiments. Plans and procedures for estimating Green and Ampt loss rate parameters by either of these procedures should be approved by the Flood Control District of Maricopa County and the local agency before initiating these procedures.

Initial Loss Plus Uniform Loss Rate Method

1. Determine the soil texture classification and/or the hydrologic soil group. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used to classify the soil if adequate documentation on the sampling and

laboratory procedure is provided and approved.

2. Use values of CNSTL and STRTL from Table 4 if the losses are to be based on soil texture classification.
3. Use values of CNSTL and STRTL from Table 5 if the losses are to be based on hydrologic soil group.
4. Determine the land-use and/or soil cover and use Table 1 to estimate the surface retention loss to be added to STRTL from either Table 4 or 5.

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TABLE 1

Surface retention loss for various land surfaces in Maricopa County (addition to STRTL for IL+ULR method and IA for Green and Ampt method)

Land-Use and/or Surface Cover	Surface Retention Loss inches
(1)	(2)
Natural	
Desert and rangeland, flat slope	.35
Hillslopes, Sonoran desert	.15
Mountain, brush	.25
Developed (Residential and Commercial)	
Lawn and turf	.20
Desert landscape	.10
Pavement	.05
Agricultural	
Tilled	1.00
Irrigated pasture	.50

Do you have some references on these values?

TABLE 2

Green and Ampt loss rate parameter values for bare ground

Soil Texture Classification	XKSAT in/hr	PSIF inches	DTHETA[1] Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)	(6)
sand	4.6	1.9	.35	.30	0
loamy sand	1.2	2.4	.35	.30	0
sandy loam	.40	4.3	.35	.25	0
loam	.15	3.5	.35	.25	0
silty loam	.25	6.6	.40	.25	0
sandy clay loam	.06	8.6	.25	.15	0
clay loam	.04	8.2	.25	.15	0
silty clay loam	.04	10.8	.30	.15	0
sandy clay	.02	9.4	.20	.10	0
silty clay	.02	11.5	.20	.10	0
clay	.01	12.4	.15	.05	0

[1] Selection of DTHETA:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 3

Soil crusting reduction factor for the Green and Ampt infiltration equation hydraulic conductivity parameter.

Soil Texture Classification	Reduction Factor for Subcrust Conductivity SC
(1)	(2)
Sand	0.91
Loamy sand	0.89
Sandy loam	0.86
Loam	0.82
Silt loam	0.81
Sandy clay loam	0.85
Clay loam	0.82
Silty clay loam	0.76
Sandy clay	0.81
Silty clay	0.73
Clay	0.75

TABLE 4

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to USDA soil texture classification

USDA Soil texture Classification	Uniform Loss Rate CNSTL (inch/hr)	Initial Loss, in inches STRTL[1]		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
sand	4.6	1.3	1.3	0
loamy sand	1.2	.8	.8	0
sandy loam	.4	.7	.6	0
loam	.15	.6	.5	0
silty loam	.25	.8	.7	0
sandy clay loam	.06	.6	.5	0
clay loam	.04	.5	.4	0
silty clay loam	.04	.6	.5	0
sandy clay	.02	.4	.3	0
silty clay	.02	.4	.3	0
clay	.01	.3	.2	0

[1] Selection of STRTL:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 5

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to hydrologic soil group

Hydrologic Soil Group	Uniform Loss Rate CNSTL	Initial Loss, in inches STRTL[1]		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
A	.40	.6	.5	0
B	.25	.5	.3	0
C	.15	.5	.3	0
D	.05	.4	.2	0

[1] Selection of STRTL:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 6

Published values of uniform loss rates

Hydrologic Soil Group	Uniform Loss Rate, in inches/hour		
	Musgrave (1955)	USBR (1975)[1]	USBR (1988)[2]
(1)	(2)	(3)	(4)
A	.30 - .45	.40	.30 - .50
B	.15 - .30	.24	.15 - .30
C	.05 - .15	.12	0 - .05

[1] Design of Small Dams, Second Edition, 1975, Appendix A

[2] Design of Small Dams, Third Edition, 1988

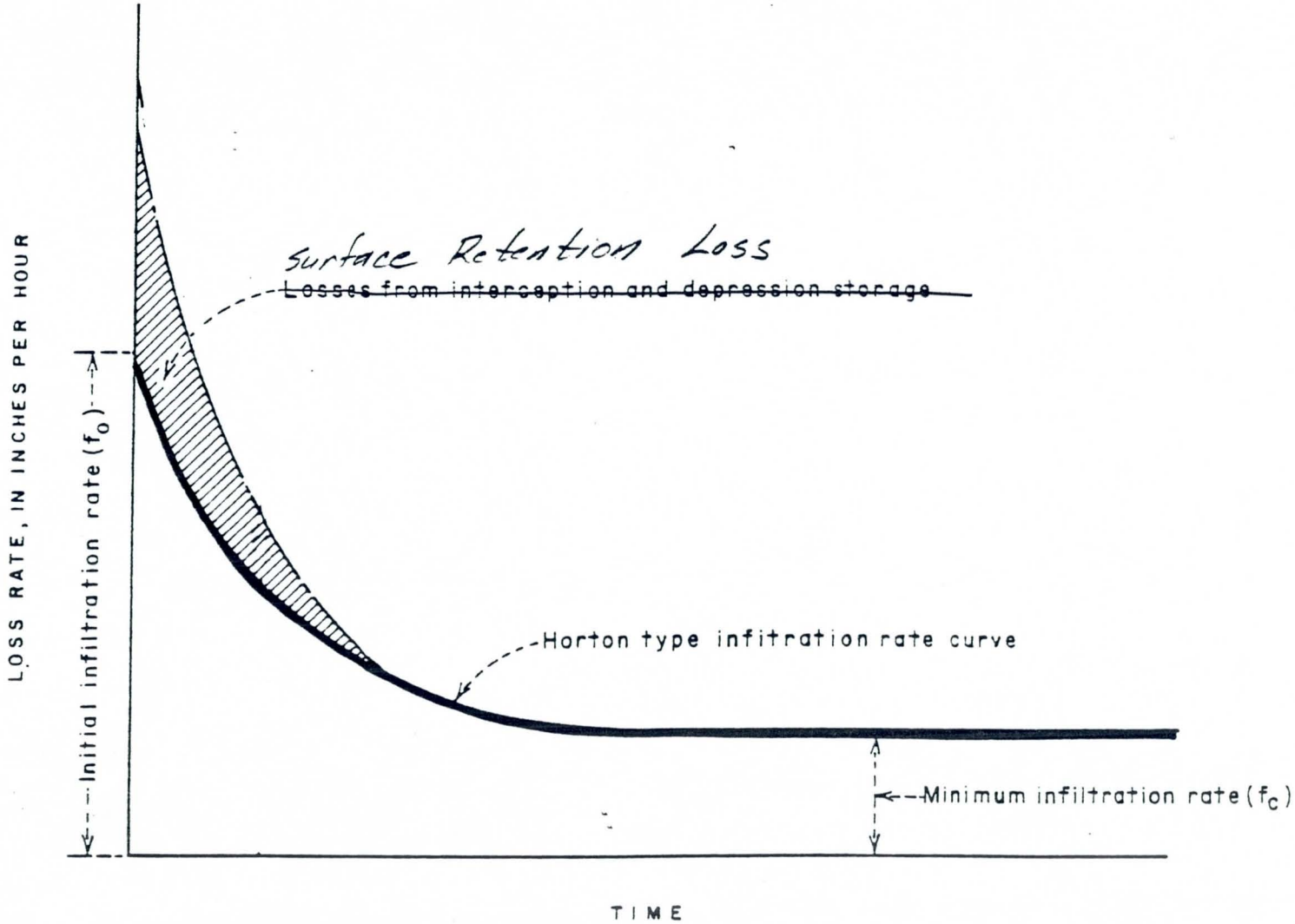
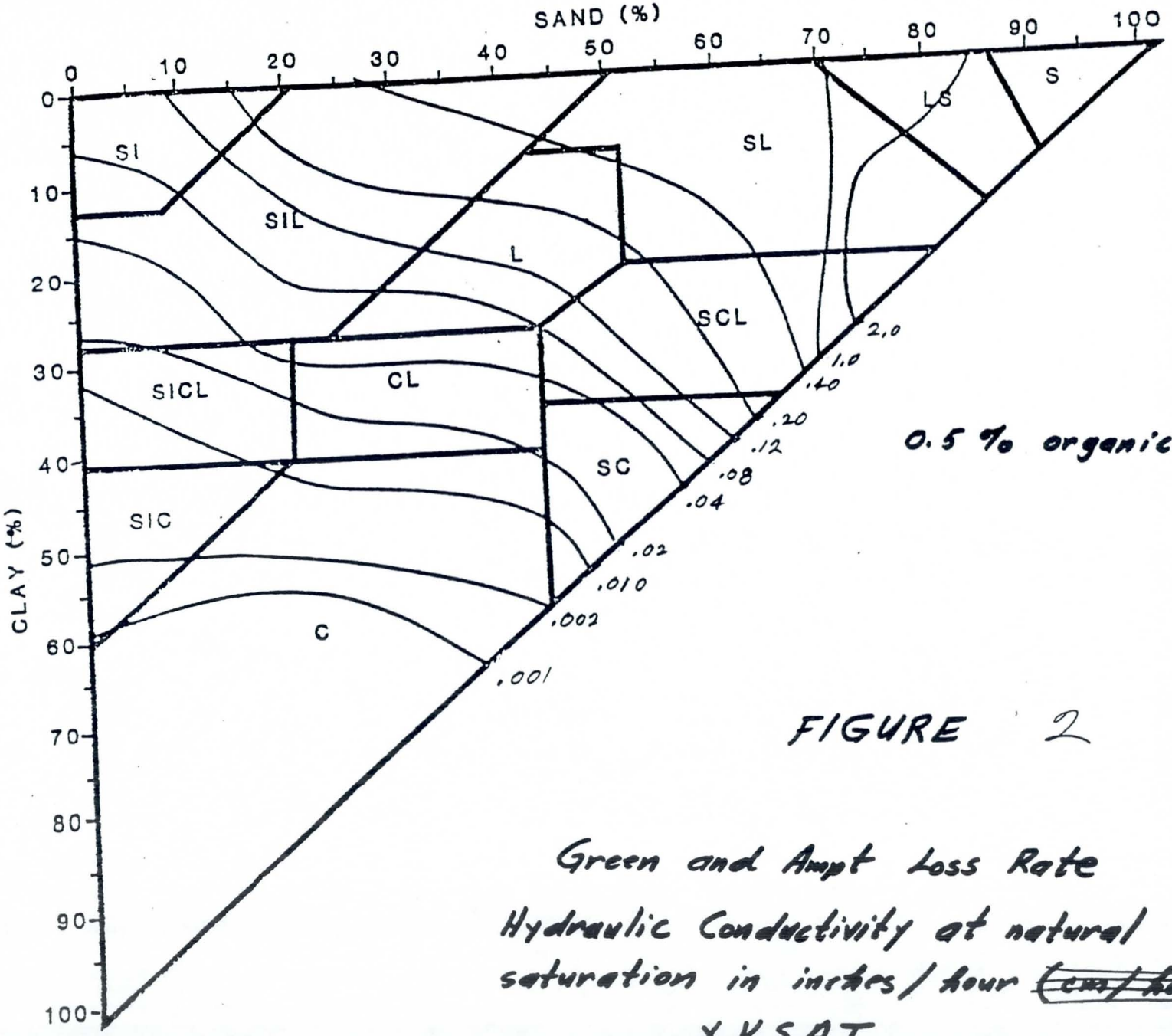


FIGURE 1

Representation of rainfall losses by surface retention and infiltration according to an exponential decay (Horton) type of equation



0.5 % organic matter

FIGURE 2

Green and Ampt Loss Rate

Hydraulic Conductivity at natural saturation in inches/hour ~~(cm/hour)~~

XKSAT

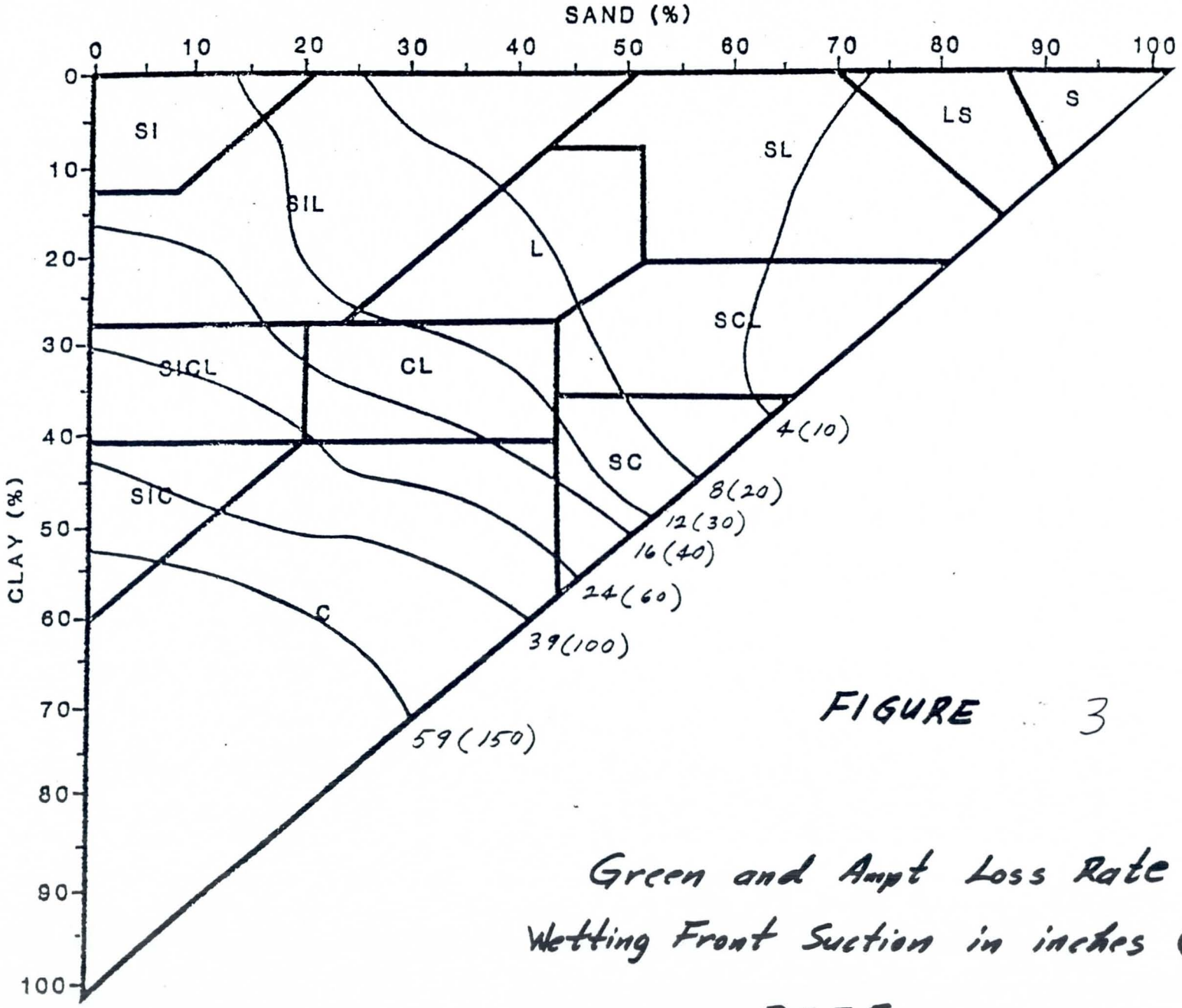


FIGURE 3

Green and Ampt Loss Rate

Wetting Front Suction in inches (cm)

PSIF

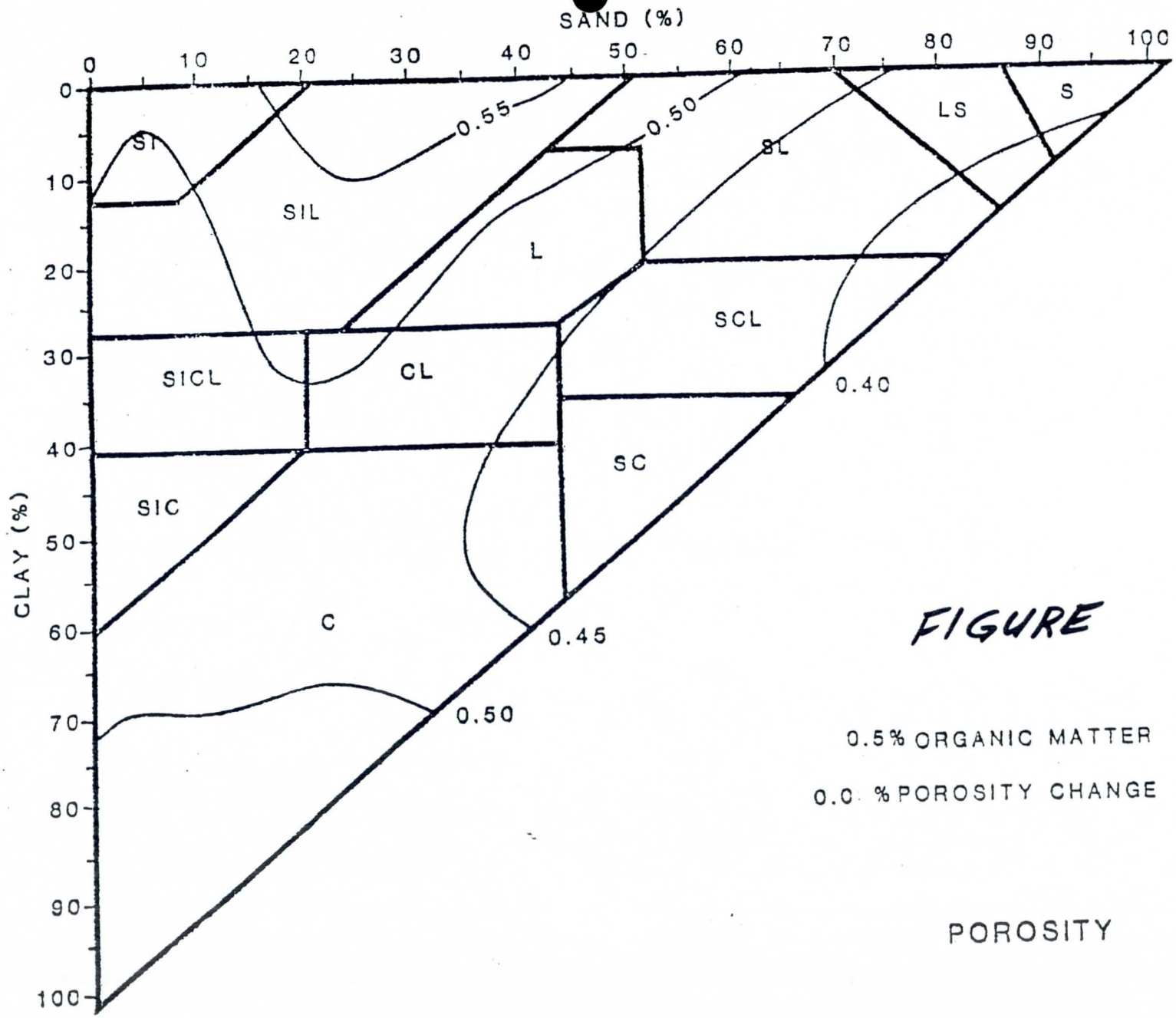


FIGURE 4

0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

POROSITY

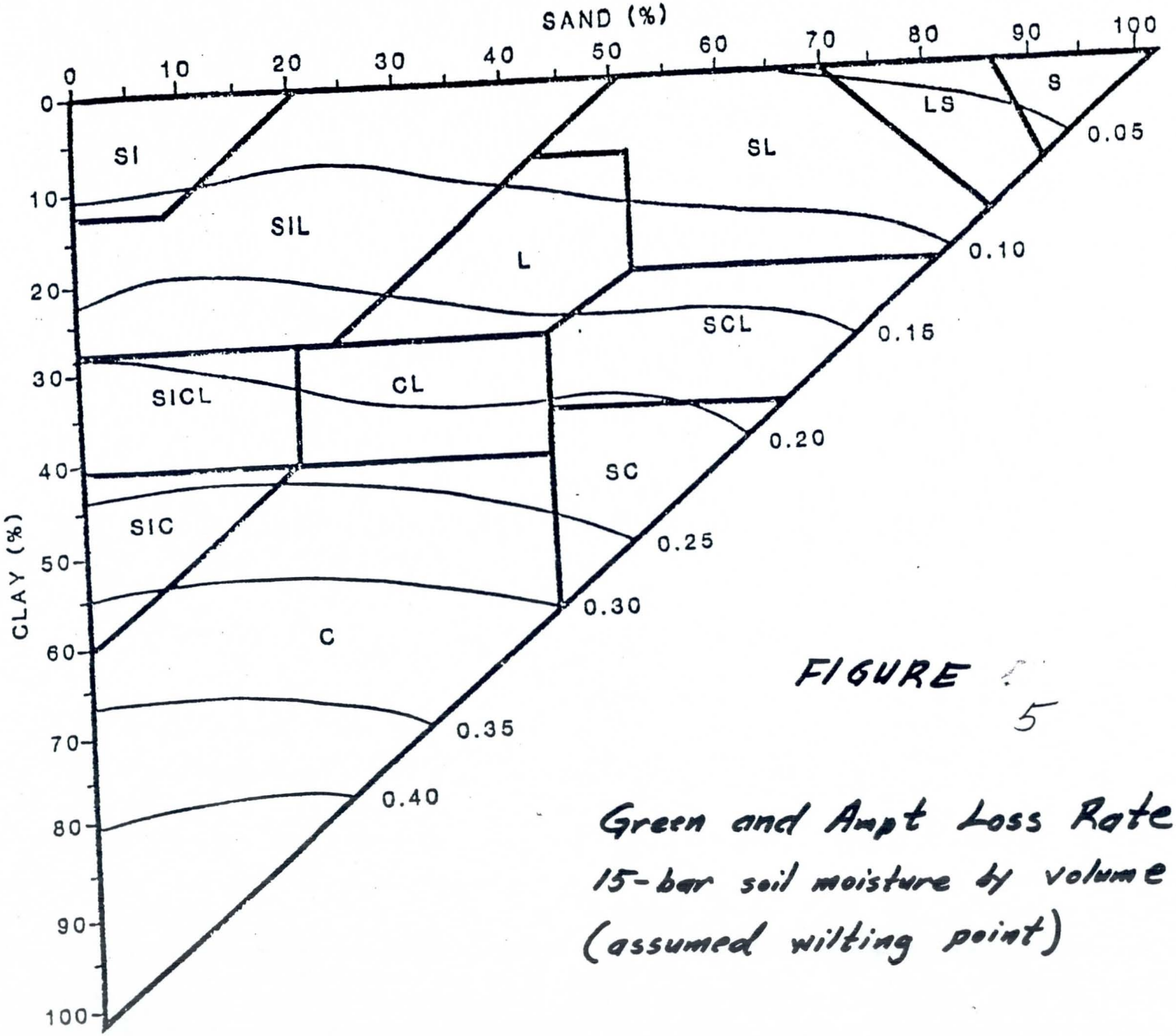


FIGURE 5

Green and Ampt Loss Rate
15-bar soil moisture by volume
(assumed wilting point)

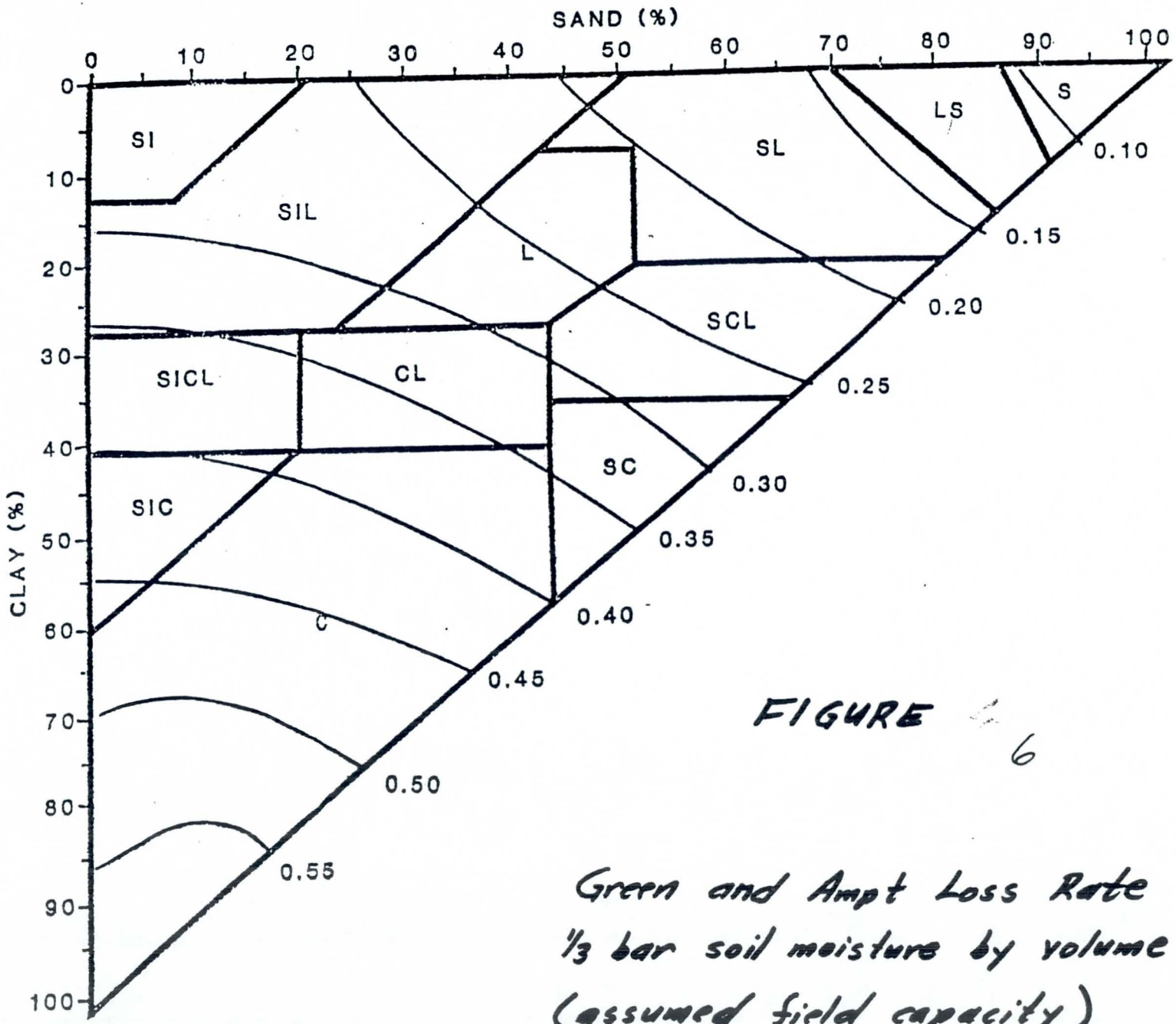


FIGURE 6

Green and Ampt Loss Rate
1/3 bar soil moisture by volume
(assumed field capacity)

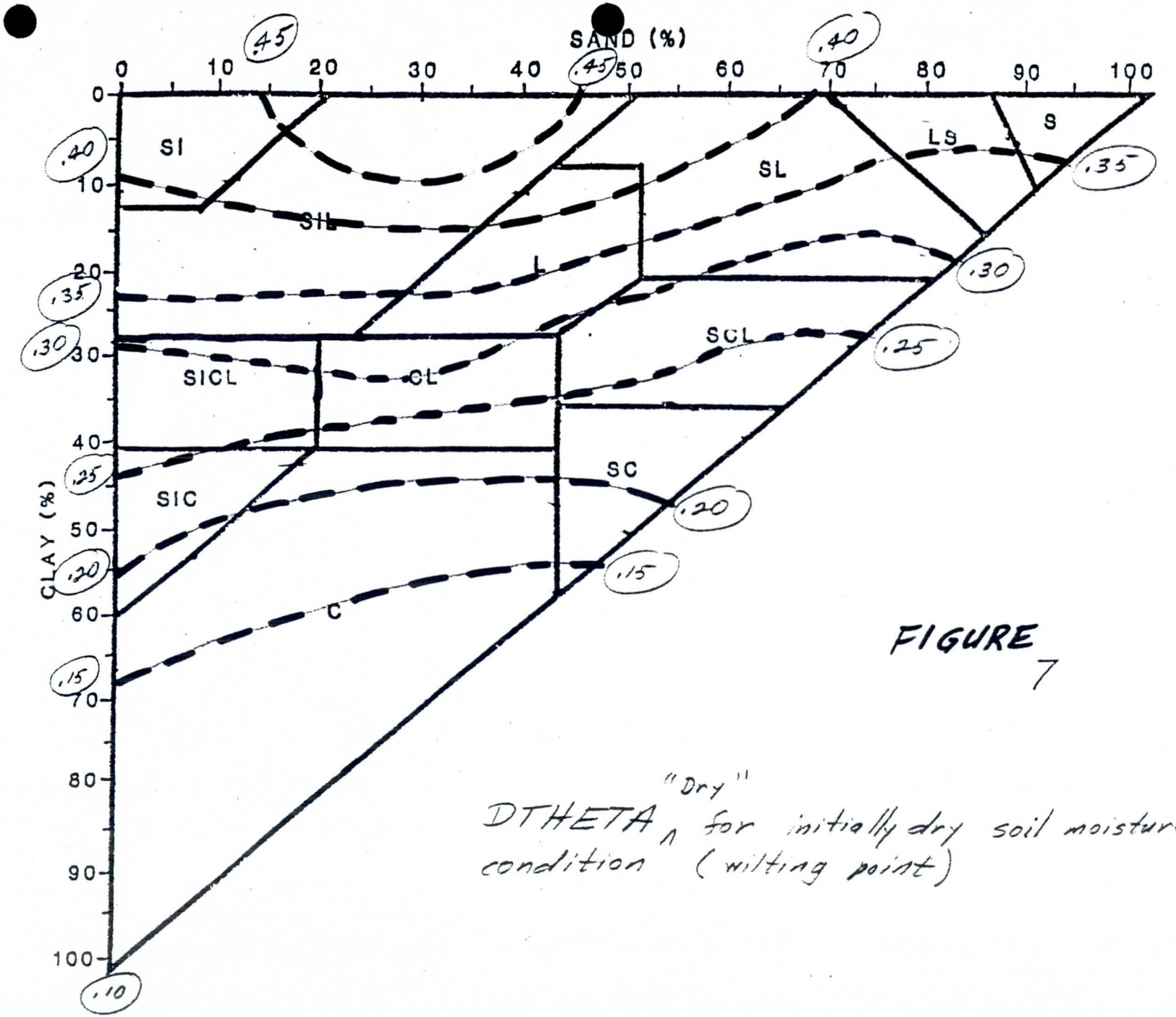


FIGURE 7

DTHETA "Dry" for initially dry soil moisture condition (wilting point)

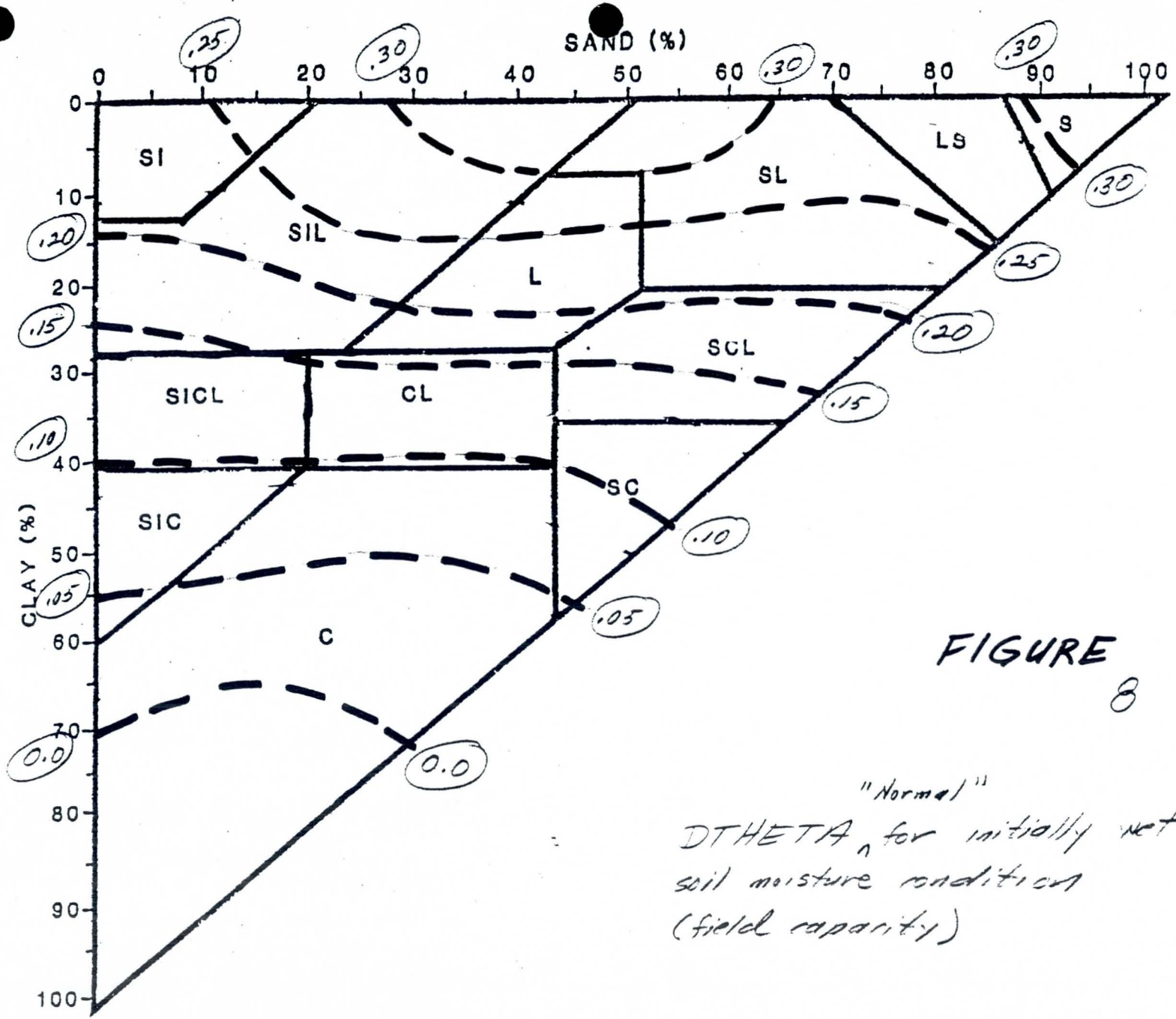


FIGURE 8

"Normal" DTHETA for initially wet soil moisture condition (field capacity)

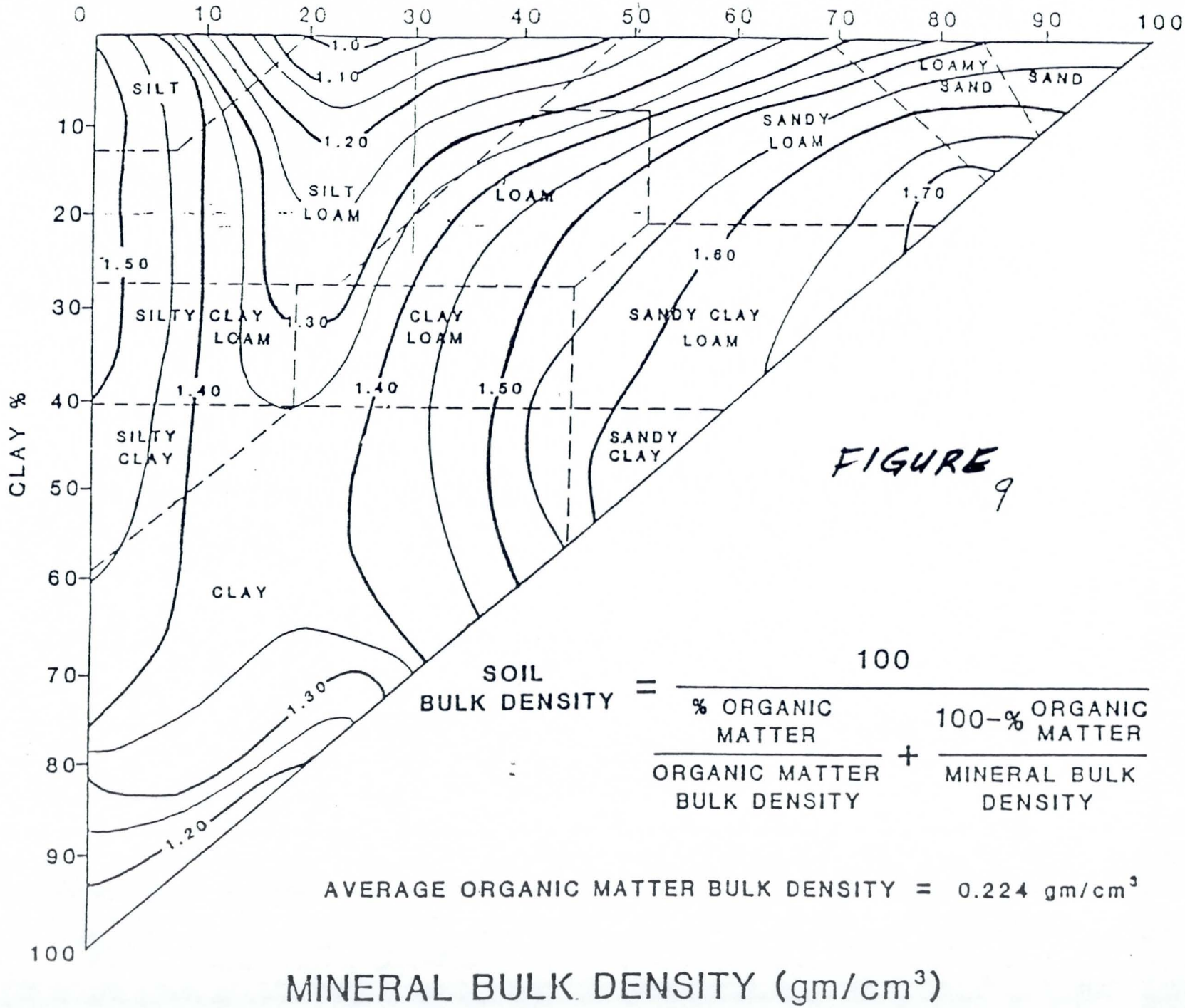


FIGURE 9

$$\text{SOIL BULK DENSITY} = \frac{100}{\dfrac{\%\ \text{ORGANIC MATTER}}{\text{ORGANIC MATTER BULK DENSITY}} + \dfrac{100-\%\ \text{ORGANIC MATTER}}{\text{MINERAL BULK DENSITY}}}$$

AVERAGE ORGANIC MATTER BULK DENSITY = 0.224 gm/cm³

~~Fig. 1. Determination of soil bulk density.~~

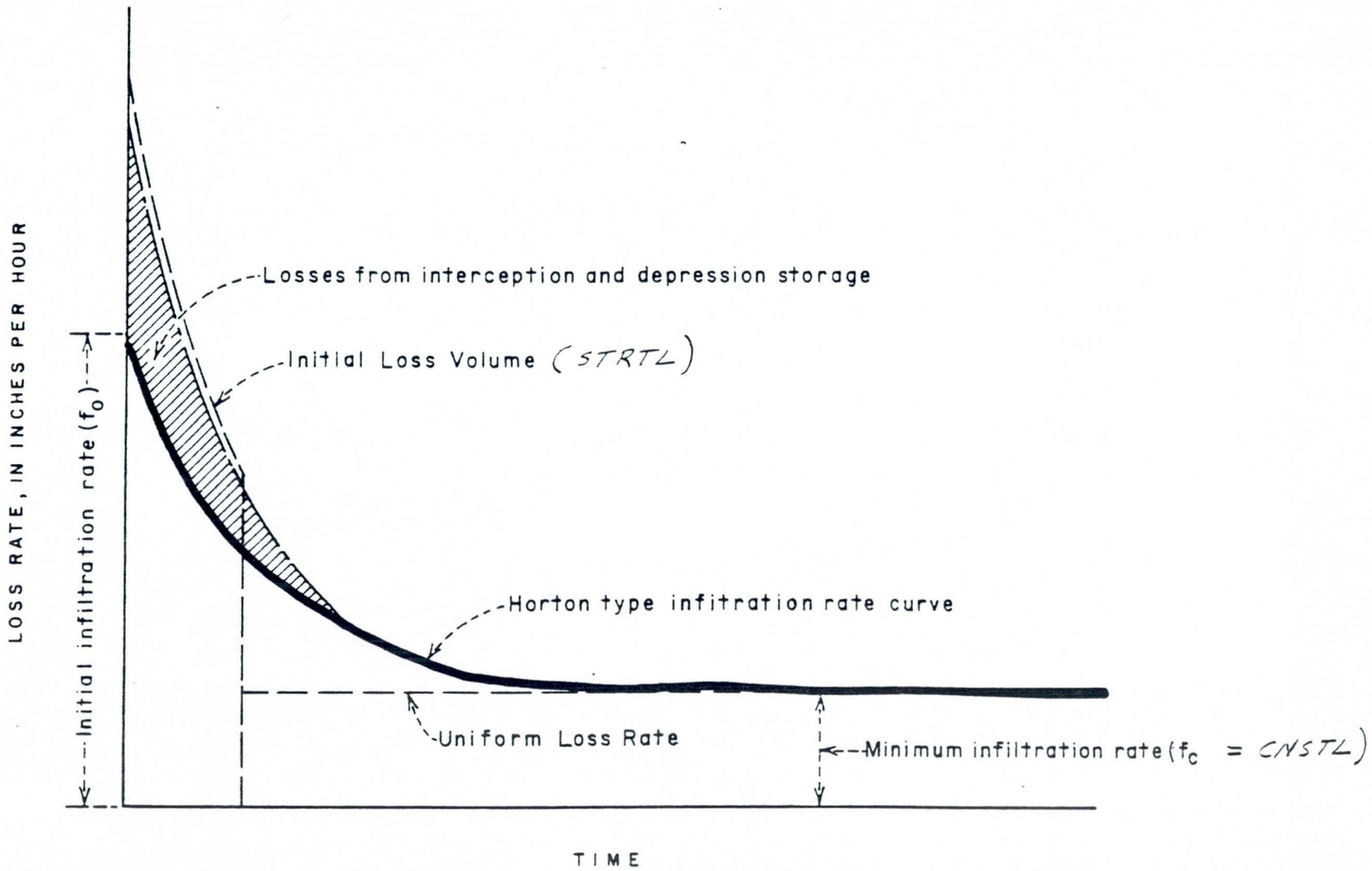


FIGURE 10

SIMULATION OF RAINFALL LOSSES BY THE INITIAL LOSS PLUS UNIFORM LOSS RATE METHOD

APPENDIX 5-E

Review Comments and Correspondence with Mr. Harry Millsaps

United States
Department of
Agriculture

Soil
Conservation
Service

201 E. Indianola Ave
Suite 200
Phoenix, AZ 85012

March 3, 1989

Mr. George V. Sabol, PhD, P.E.
Consulting Engineer
1351 East 141st Avenue
Brighton, CO 80601

Dear Mr. Sabol:

Enclosed is a marked-up copy of the preliminary draft of the Hydrology Manual which you prepared for Maricopa County, Arizona. This copy was furnished to Mr. Robin McArthur on our staff for his review. Robin did review the draft, but unfortunately prior to his returning his comments he became sick, and has not been back to work. His comments are provided in the margin of the report. Please recognize the comments are somewhat informal, but we hope they will be of benefit to you. Should you have questions concerning the comments, it is hopeful that Mr. McArthur will be back to answer them. If not, please feel free to call me at (602) 241-2547.

Sincerely,

Harry C. Millsaps

Harry C. Millsaps
Hydraulic Engineer

(1) No discussion of different frequency series - partial duration vs annual
(2) Alteration of NOAA Atlas interpolation equations for no apparent reason
(3) Short Storm Duration (6 Hrs) for 540 M²
(4) Poor map for Precip; need areas adjacent to County line
(5) No explanation for varying 6 Hr storm distribution with area
(6) Storm distribution for 2 Hr, 6 Hr & 24 Hr not sufficiently steep to give proper short duration intensities.

2.1 GENERAL

Precipitation in Maricopa County is strongly influenced by variation in climate, changing from a warm and arid desert environment to a cool and moderately humid mountainous area. Mean annual precipitation changes from about 7 inches in the Phoenix vicinity to more than 30 inches in the mountain regions of northern Maricopa County. The precipitation is typically divided into two seasons, summer season (June through ~~September~~ October) and winter (December through March), and is divided equally ? in depth. The storm patterns are generally categorized into three types, though any combination of the storm types is possible.

2.1.1 General Winter Storms. This type of storm normally moves in from the north Pacific Ocean, which will produce light to moderate precipitation over relatively large areas. These storms occur between late October and May, producing the heaviest precipitation from December to early March. A pattern could last over several days with slight breaks in-between storms. They generally represent orographic effects, and as a result the mountain areas receive a higher precipitation as compared to low elevation desert areas. These storms are characterized by low intensity, long duration events over a large areal extend which can contribute to substantial runoff volumes and peak discharge on major river systems.

2.1.2 General Summer Storms. General summer storms are the result of warm and moist tropical air from the southeast or the southern region. As these systems move into Arizona they turn into tropical storms or hurricanes. They can occur any time from late June to mid-October, producing the most amount of rainfall during late July to early October. The storm pattern consists of local heavy cells, and a light to moderate rainfall which could last one to three days. They are similar to general winter storms in that they also reflect orographic influence, with higher elevations receiving most of the rainfall. These storms are characterized by high intensity, short duration events with an areal extend smaller than the winter storms. The generated peak discharge and volume from these storms are smaller than the winter storms, producing higher infiltration rates for large river systems. The period of late September through October may have storm patterns which are similar to both the winter and summer general storms.

Not for smaller areas.. peaks usually higher. Agree SCW

2.1.3 Local Storms. These storms are mostly heavy downpours of rain over small areas of up to about 300 square miles for a time period of about 6 hours. They are typically associated with lightening and thunder, and are referred to as "thunderstorms" or "cloudbursts." While they can occur any time during the year, they are more frequent during summer months (July to September) when tropical moisture enters the area on a frequent basis from the southeast or the southern region. These storms turn into longer duration events in late summer and may be associated with general summer storms. A local storm generally produces a high peak event, affecting smaller areas. It can result in flash floods, and sometimes loss of life and property damage.

2.2 DEPTH-DURATION-FREQUENCY ANALYSIS

The commonly required precipitation parameters used in hydrologic modeling are depth, intensity, duration, spatial distribution and frequency of rainfall. The selection of a design frequency is often an administrative or economic decision rather than a hydrologic one. The duration of the design storm is usually a function of the topography of the watershed, though it too can be administratively selected. In general, one should insure that the design storm is of sufficient duration to allow the entire watershed to be contributing to the flow at the point of interest.

Spatial and temporal variation of precipitation, and lack of long term data in Maricopa County requires a procedure for rainfall input, for design purposes. Regardless of ~~weather~~ whether the desired output is a peak discharge for sizing a conveyance structure, or a volume for sizing a basin, or the overland flow from a natural watershed, the designer needs to know the total depth of the design precipitation event and how it is structured both in time and space. However, selection of the appropriate event is constraint~~t~~ed by availability and quality of data.

2.2.1 Source of Data. The only comprehensive, available source of data for depth-duration-frequency analysis is Precipitation-Frequency Atlas for Arizona referred to as NOAA Atlas~~s~~ 2, published by the United States Depatment of Commerce, in 1973. The climatological data utilized in the NOAA Atlas was the source available through 1969. Until a more up to date data base becomes available, NOAA Atlas is to be used for all design purposes within Maricopa County.

2.3 DEPTH-AREA RELATION

The problem of spatial variability of rainfall is quite difficult to handle due to limited network of raingauge coverage. Work in the southwest by the United States Deparment of Agriculture ~~and~~ Agricultural Research Service indicates that high intensity storms do not have large areal extents, usually less than one square mile.

The above argument would support development of areal reduction curves which reflect the nature of the thunderstorms in the southwest. However, drainage facilities such as storm drains, channels, and culverts should be sized to handle the peak discharge resulting from the design storm critically centered above them so as to create the worst case discharge. Only retention/detention facilities serving as an outfall for a large contributing area would appear to justify areal reduction of the depth. Then areal reduction seems appropriate for runoff calculations of contributing areas larger than 10 square miles.

2.3.1 Procedure For Depth-Area Adjustments. The Depth-Area Reduction Curves in HYDRO-40 are to be used. These curves originally developed by Osborn, Lane, and Myers (1980) are based on data from Walnut Gulch, Arizona and were selected to be appropriate for use in Maricopa County. Figures *** to *** along with the following procedure are for the areal reduction curves:

a. Justify that areal reduction is necessary.

b. Indicate the size of the contributing drainage area.

c. Select the appropriate design storm (SECTION 2.4). CALCULATE AVERAGE DEPTH. If the storm duration is greater than 6-hour, use the 6-hour curve.

d. Select reduction coefficient from the appropriate curve.

e. Multiply reduction coefficient by the rainfall depth.

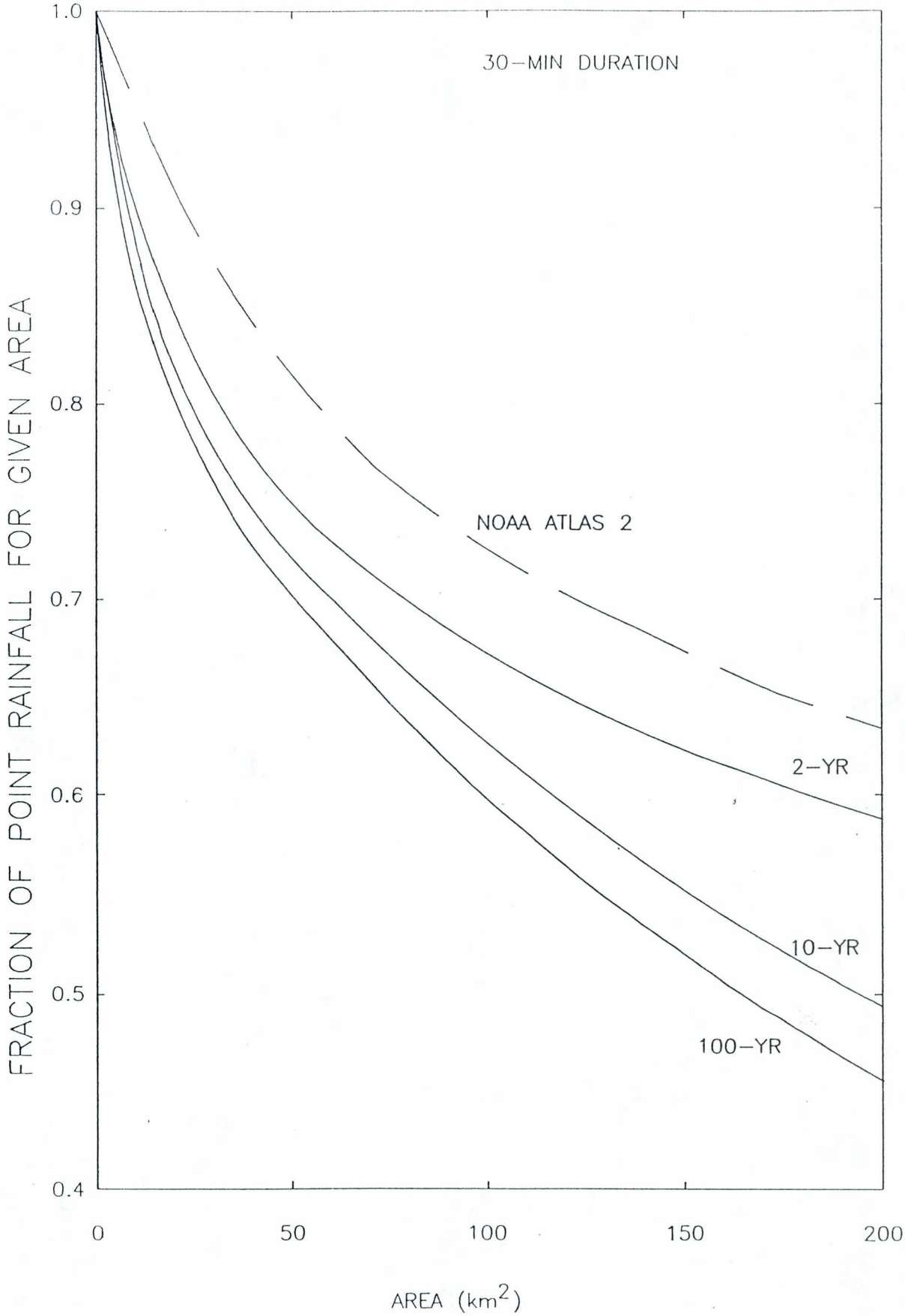


FIGURE Point-to-area conversion rations for 30-min duration rainfalls for selected frequencies.

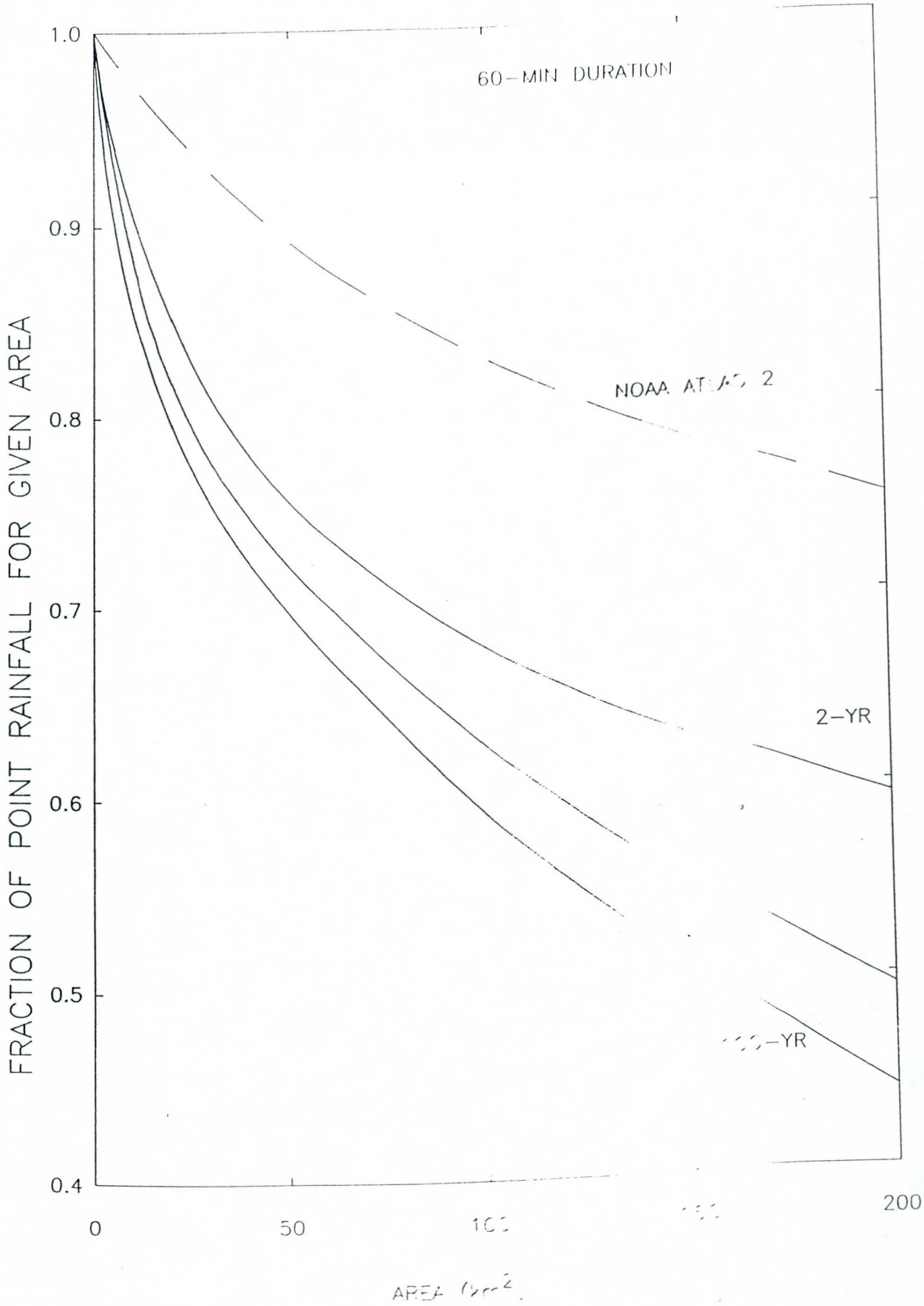


FIGURE Point-to-area conversion ratios for [illegible] duration rainfalls for selected frequencies.

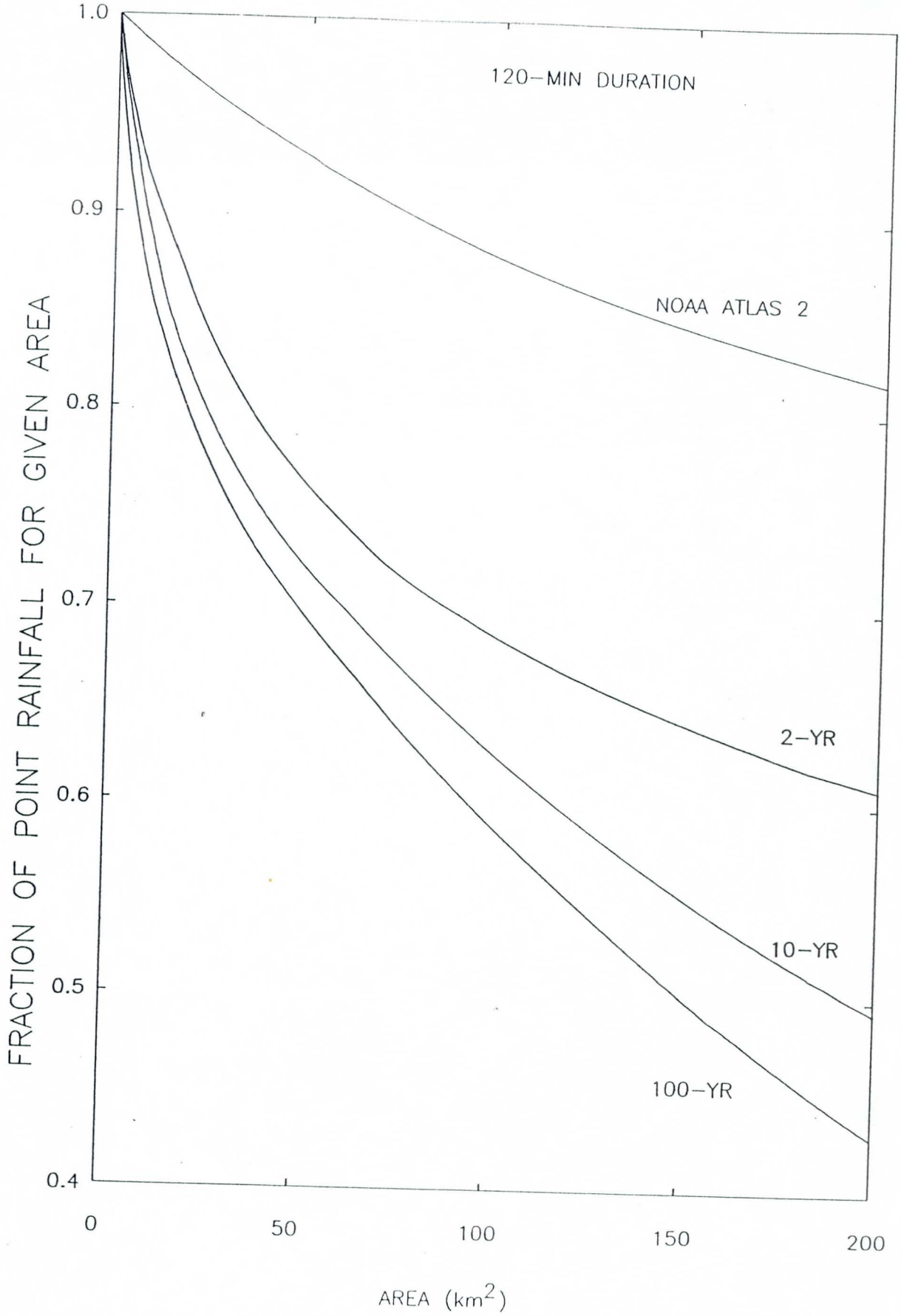


FIGURE Point-to-area conversion ratios for 2-h duration rainfalls for selected frequencies.

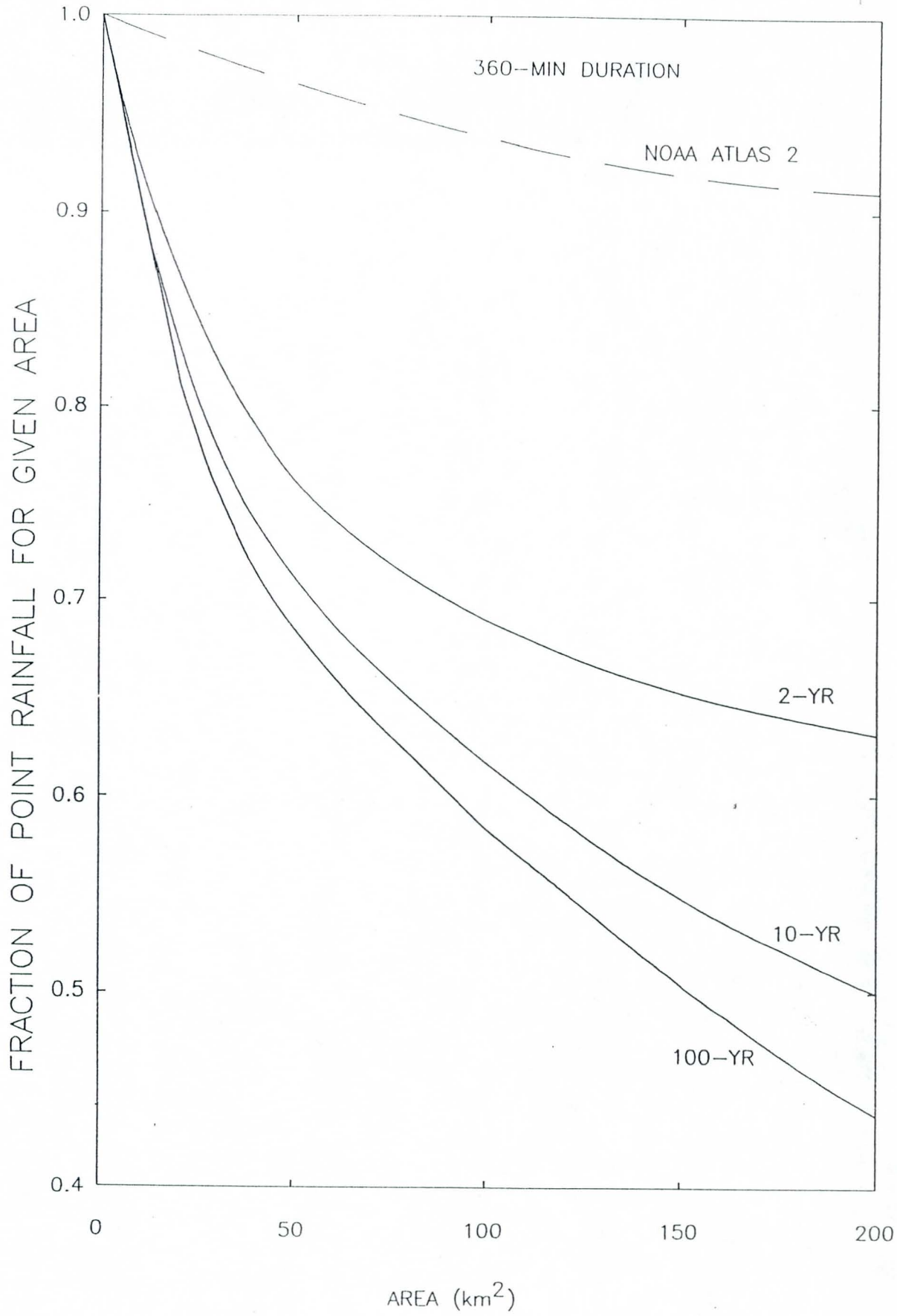


FIGURE Point-to-area conversion ratios for 6-h duration rainfalls for selected frequencies.

4 2.4 SELECTION OF APPROPRIATE DESIGN STORM

The design hydrologist must specify the appropriate rainfall frequency, duration, depth and the corresponding time distribution for any design purposes which require calculation of runoff volume and peak discharge. The only exception to the above statement is with the application of the Rational Formula since a time distribution is not required. For the purposes of the Hydrology Manual the following guidelines are to be used for developing a design storm:

Show example

1) Using Plates 1-12, read rainfall depths for 2-, 5-, 10-, 25-, 50, and 100-year return periods, 6- and 24-hour durations, employing linear interpolation between isolines when required. The numbers on the isolines represent tenths of inches of rainfall (i.e, 23=2.3 inches).

2) Using Figure ***, verify the selected rainfall depths. As indicated in NOAA Atlas (page 16) the obtained rainfall depths are to be verified by plotting them on the return-period diagram, because of the possibility of error that may have occurred during printing or obtaining of the values. After positioning the data points on Figure ***, fit a straight line to the 6-hour data and another one to the 24-hour data. Check for any deviations from the lines, then pick the corrected values located on the line.

3) At this time the data should include 6-hour and 24-hour durations for all frequencies with the exception of 1-year values. If for any reason there is a need for the 1-year distribution then use:

What about use of annual series vs partial duration series?

$$P_1 = P_2 - .16(P_{100} - P_2)$$

where P_2 and P_{100} are the 100-year and the 2-year frequencies, respectively.

4) A particular design may require a duration different from 24-hour or 6-hour. For example retention design requires a 100-year frequency, 2-hour duration design storm. In such cases the following procedure should be used. Let X1, X2,...,X24 be the estimated precipitation for durations of 1, 2, ...24 hour, respectively.

A. Compute $X_{12} = X_{24} - .51(X_{24} - X_6)$

B. Compute $X_1 = 2X_6 - X_{24}$

$$\begin{cases} Y_2 = -0.011 + 0.942\left[(X_6)(X_1/X_2)\right] \\ Y_{100} = 0.494 + 0.755\left[(X_3)(X_6/X_3)\right] \end{cases}$$

I fail to follow these relationships from those in NOAA Atlas

C. Check to see that $(X_6 - X_1) = (X_{24} - X_6)$

D. Compute $X_3 = X_6 - .55(X_6 - X_1)$

E. Compute $X_2 = X_6 - .77(X_6 - X_1)$

F. Check to see that $(X_3 - X_2) = .22(X_6 - X_1)$

G. Compute $X_{30\ minutes} = .79X_1$

H. Compute $X_{15\ minutes} = .57X_1$

why not use NOAA Atlas?

In the above procedure, if the designer needs the rainfall depth for a 2-hour duration, there is no need to continue beyond that point.

2.5 DEVELOPMENT OF DESIGN STORM DISTRIBUTIONS

The design storms for use in Maricopa County will be a 2-hour, 6-hour, or a 24-hour distribution. The 2-hour storm is to be used for retention design purposes. The 6-hour storm is for all hydrologic analysis for areas of up to 540 square miles. The 24-hour storm should be used for very large, natural watersheds (> 540 square miles).

seems too short for 540 M²

? Basis?

$\frac{l}{540} = 4$

$l/w = 4$

$(w = 540 M^2$

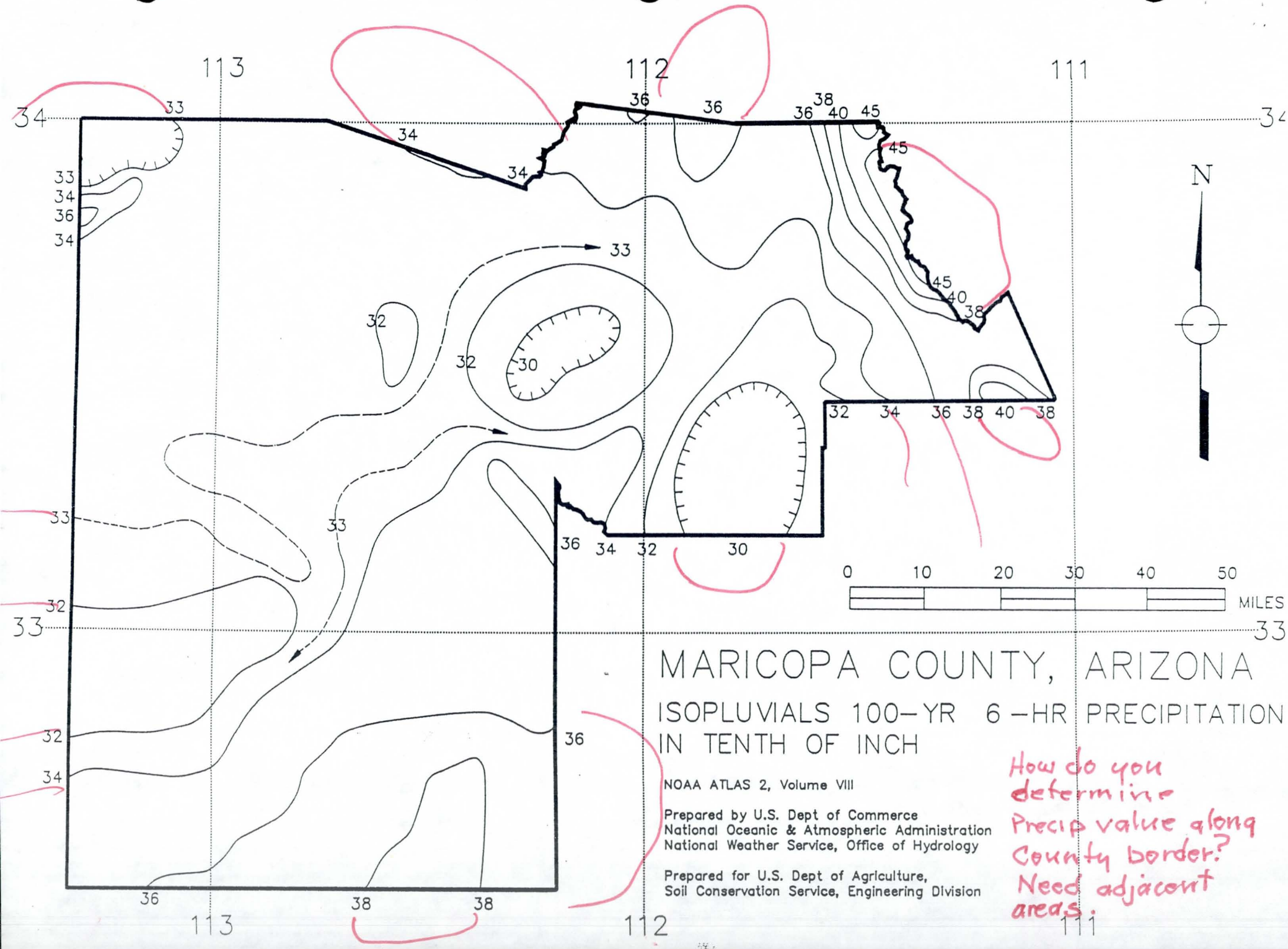
$w = \frac{540}{l}$

$l = 209\, a^{0.6}$ experimental watersheds a (acres) l (feet) 540 M² 83 Miles 83 m/6 hr = 13 mph = 8.9 kts

The following isopluvial maps of Maricopa County (from NOAA Atlas 2, Volume VIII, Arizona) are to be included in the manual:

2-yr, 6-hr
2-yr, 24-hr
5-yr, 6-hr
5-yr, 24-hr
10-yr, 6-hr
10-yr, 24-hr
25-yr, 6-hr
25-yr, 24-hr
50-yr, 6-hr
50-yr, 24-hr
* 100-yr, 6-hr
100-yr, 24-hr

* This figure is shown in the review draft as an example of all the isopluvial maps that are to be contained.



MARICOPA COUNTY, ARIZONA

ISOPLUVIALS 100-YR 6-HR PRECIPITATION IN TENTH OF INCH

NOAA ATLAS 2, Volume VIII

Prepared by U.S. Dept of Commerce
National Oceanic & Atmospheric Administration
National Weather Service, Office of Hydrology

Prepared for U.S. Dept of Agriculture,
Soil Conservation Service, Engineering Division

How do you determine Precip value along County border? Need adjacent areas.

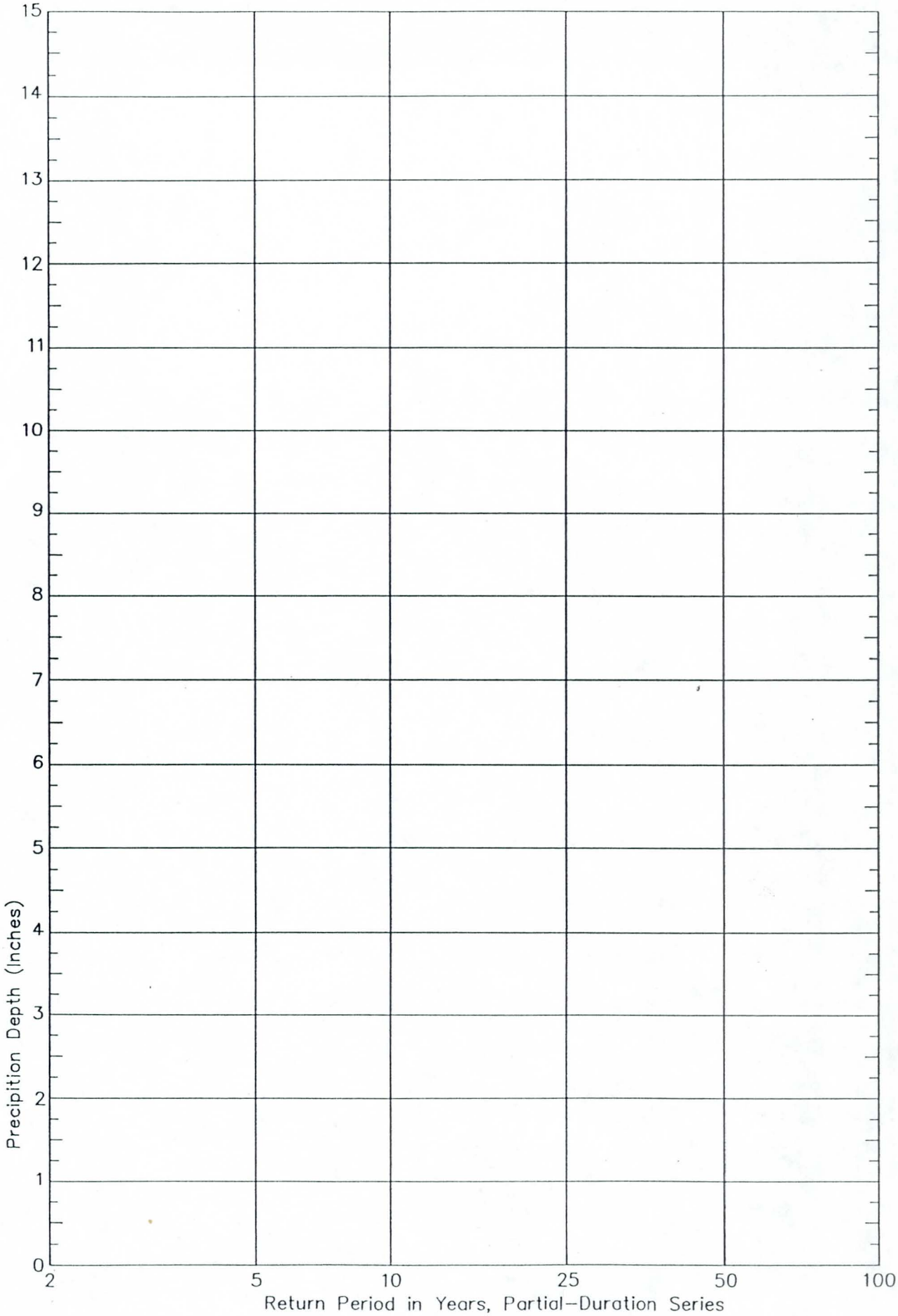


Figure Precipitation depth versus return period for partial-duration series

2.5.1 2-hour Storm distribution. If the Rational Method is to be used, there is no need for a time distribution. The selected depth should be used based on the procedures in Chapter 3 of this manual. If a time distribution is required, i.e., rainfall input for the HEC-1 model, the dimensionless 2-hour cumulative rainfall distribution of Table *** should be used. These values then would be direct input into HEC-1, assuming a 15-minute intensity as the rainfall time step. A graphical representation of this distribution is also shown on Figure ***.

2.5.2 6-hour Storm Distribution. The 6-hour rainfall distribution is a function of drainage area size. For this purpose 5 dimensionless rainfall distributions were developed. These distributions are a function of drainage area size of up to 540 square miles. A dimensionless rainfall pattern can be selected from Table *** for direct input into HEC-1, once the size of the drainage area is determined. In this case also the 15-minute intensity is to be used for the rainfall time step. Figure *** illustrates graphical representations of the dimensionless rainfall patterns.

BASIS?

2.5.3 24-hour Storm Distribution. The 24-hour storm distribution in Table *** can be used for large, natural watershed areas (> 540 square miles). The rainfall intensity would be of 15-minute for rainfall time step computations. If the designer would prefer another method, i.e., SCS TYPEII, which can better reflect the local conditions, then it should be used. Figure *** shows the graphical representation of the 24-hour dimensionless rainfall distribution.

Time Elapsed (minutes)	% Rainfall Depth
0	.0
15	4.2
30	11.7
45	25.7
60	51.2
75	77.6
90	88.9
105	95.6
120	100.0

Does Not give sufficient short duration intensities

Table. 2-hour storm distribution for retention design.

Form a 6-hour duration design storm the following pattern # versus drainage area FIG. #1 should be used in Table. .

For drainage area of up to 10 square miles use pattern #1.

For drainage area of up to 35 square miles use pattern #2.

For drainage area of up to 110 square miles use pattern #3.

For drainage area of up to 270 square miles use pattern #4.

For drainage area of up to 540 square miles use pattern #5.

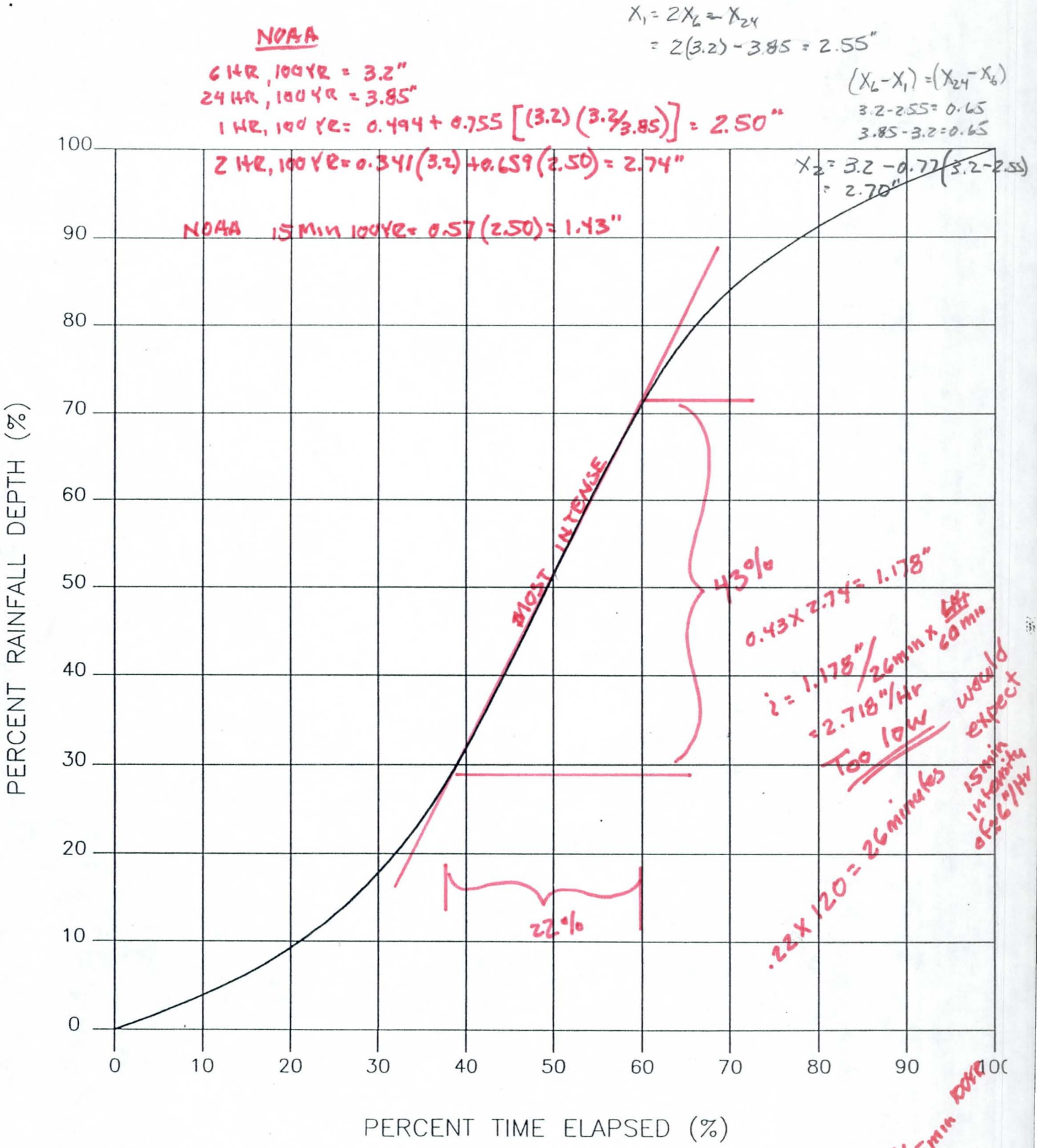


FIGURE 2—HOUR MASS CURVE FOR RETENTION DESIGN MARICOPA COUNTY

is this correct.

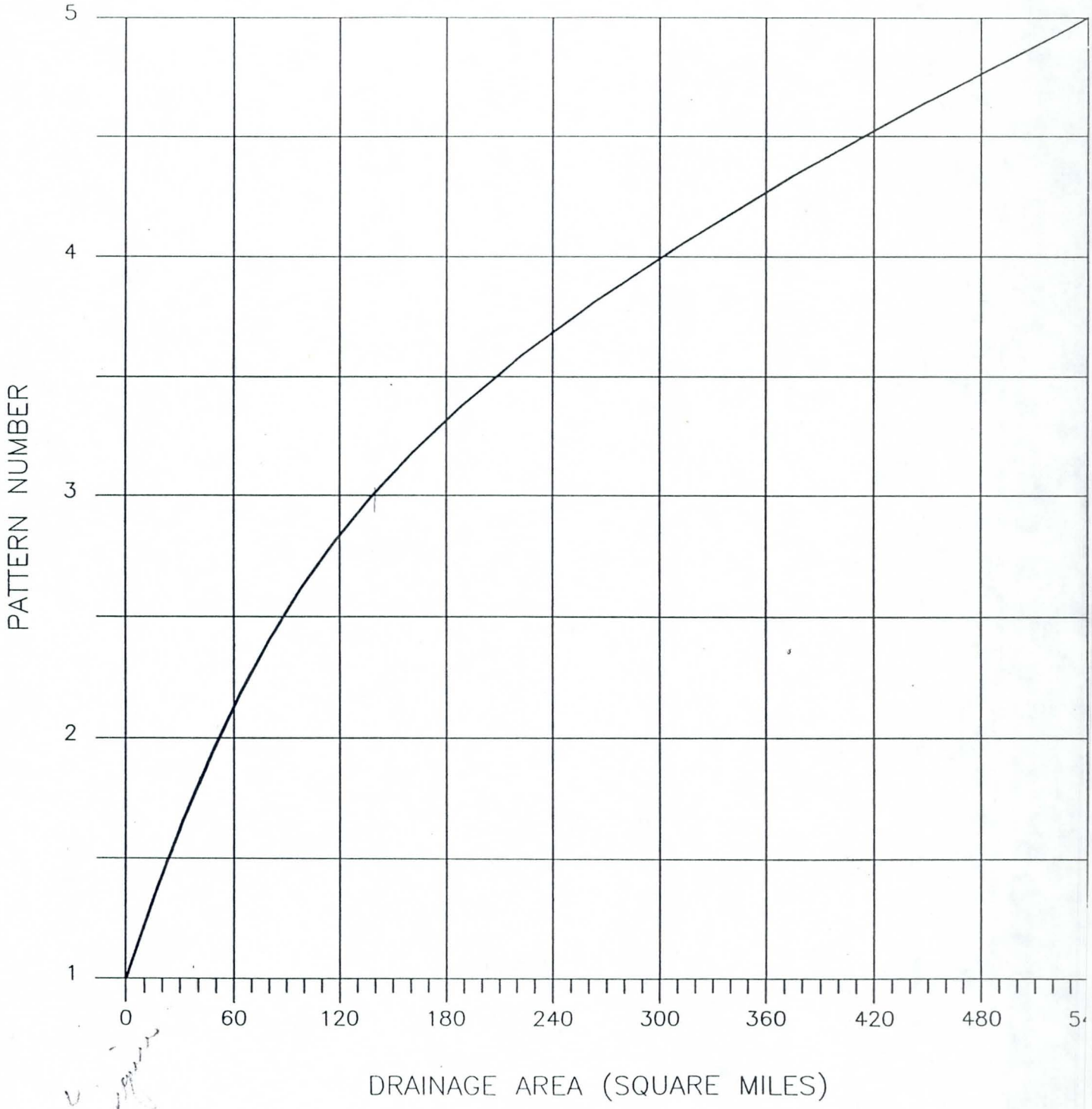


FIGURE AREA VERSUS PATTERN NUMBER FOR MARICOPA COUNTY

Time Elapsed (min)		Pattern #1	Pattern #2	Pattern #3	Pattern #4	Pattern #5
0		.0	.0	.0	.0	.0
15	0.042	.6	.6	1.5	2.1	2.4
30	0.083	1.2	1.2	2.0	3.5	4.3
45	0.125	1.7	2.0	3.0	5.1	5.9
60	0.167	2.7	3.1	4.8	7.1	7.8
75	0.208	3.7	3.9	6.3	8.7	9.8
90	0.25	4.7	4.9	7.6	10.5	11.9
105	0.292	5.6	5.7	9.0	12.5	14.1
120	0.333	6.7	6.7	10.5	14.3	16.2
135	0.375	7.5	7.6	11.9	16.0	18.6
150	0.417	8.7	8.7	13.5	17.9	21.2
165	0.458	9.9	10.0	15.2	20.1	23.9
180	0.50	11.1	12.0	17.5	23.2	27.1
195	0.542	12.3	16.3	22.2	28.1	32.1
210	0.583	20.8	25.2	30.4	36.4	40.8
225	0.625	38.5	45.1	47.2	50.0	51.5
240	0.667	84.8	69.4	67.0	65.8	62.7
255	0.708	93.3	83.7	79.6	77.3	73.5
270	0.75	94.6	90.0	86.8	84.1	81.4
285	0.792	95.8	93.8	91.2	88.8	86.4
300	0.833	96.9	96.7	94.6	92.7	90.7
315	0.875	98.1	98.5	97.4	95.8	94.5
330	0.917	98.5	99.0	98.0	96.5	95.5
345	0.958	99.0	99.0	98.7	97.6	96.9
360	1.000	100.0	100.0	100.0	100.0	100.0

Table. 6-hour distributions. Pattern # represents %rainfall depth.

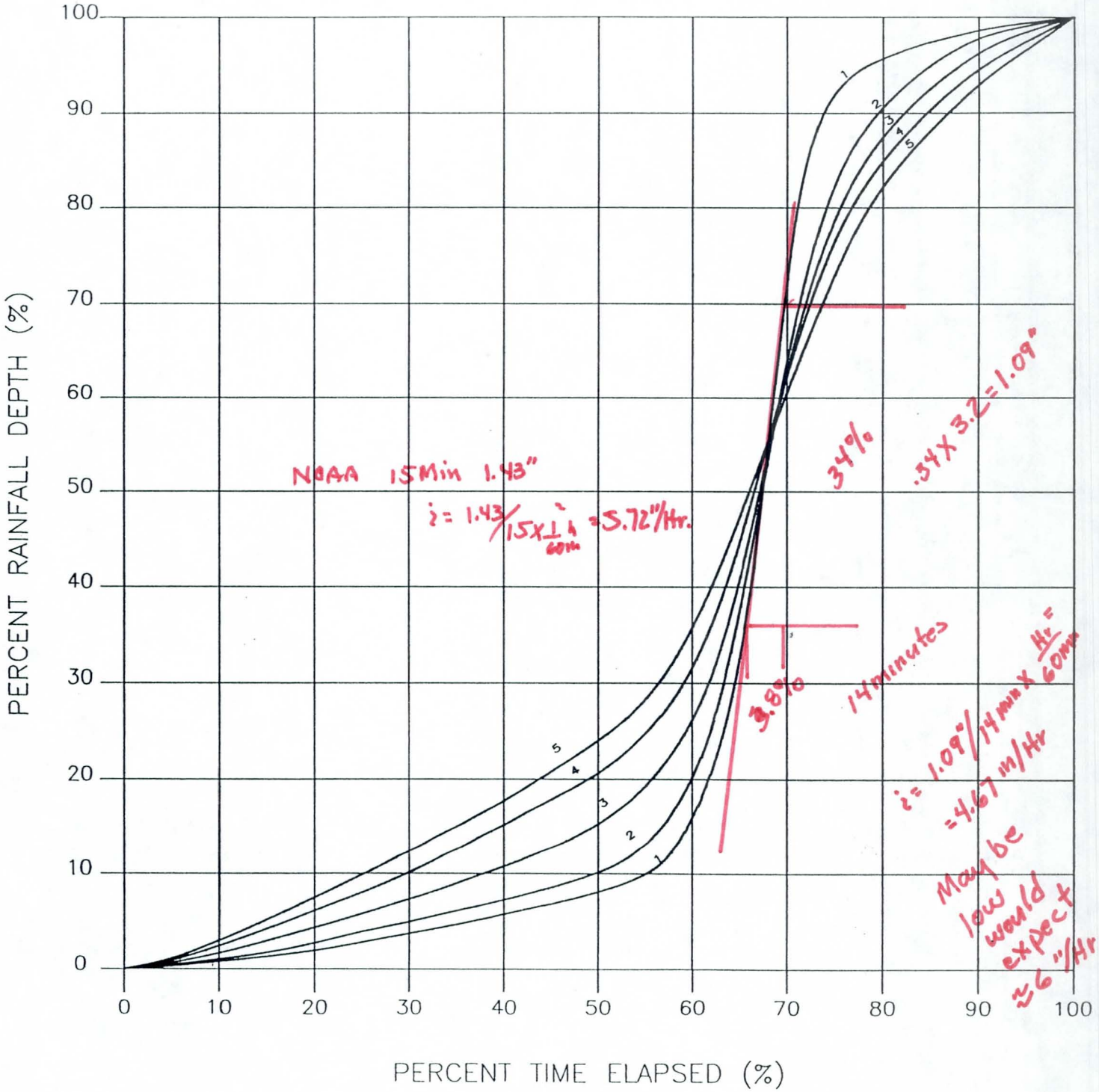


FIGURE 6-HOUR MASS CURVES FOR MARICOPA COUNTY

NO WAY

Max 100yr
i=0.4"/Hr
No!

Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth
0	.0	375	12.4	735	28.4	1095	82.7
15	.6	390	13.0	750	29.6	1110	84.0
30	1.2	405	13.6	765	30.8	1125	85.3
45	1.8	420	14.1	780	31.3	1140	86.4
60	2.4	435	14.6	795	34.3	1155	87.5
75	2.8	450	15.2	810	36.4	1170	88.6
90	3.4	465	15.6	825	38.6	1185	89.8
105	3.8	480	16.3	840	40.8	1200	90.7
120	4.4	495	16.8	855	43.5	1215	91.6
135	4.7	510	17.4	870	46.2	1230	92.5
150	5.1	525	18.0	885	48.8	1245	93.6
165	5.5	540	18.6	900	51.5	1260	94.5
180	5.9	555	19.2	915	54.3	1275	94.8
195	6.4	570	20.0	930	57.1	1290	95.0
210	6.8	585	20.6	945	59.9	1305	95.2
225	7.3	600	21.2	960	62.7	1320	95.5
240	7.8	615	21.9	975	65.4	1335	95.8
255	8.3	630	22.5	990	68.1	1350	96.2
270	8.8	645	23.2	1005	70.8	1365	96.6
285	9.3	660	23.9	1020	73.5	1380	96.9
300	9.8	675	24.7	1035	75.5	1395	97.6
315	10.3	690	25.5	1050	77.4	1410	98.4
330	10.9	705	26.3	1065	79.4	1425	99.2
345	11.4	720	27.1	1080	81.4	1440	100.0
360	11.9						

Table . 24-hour design storm distribution.

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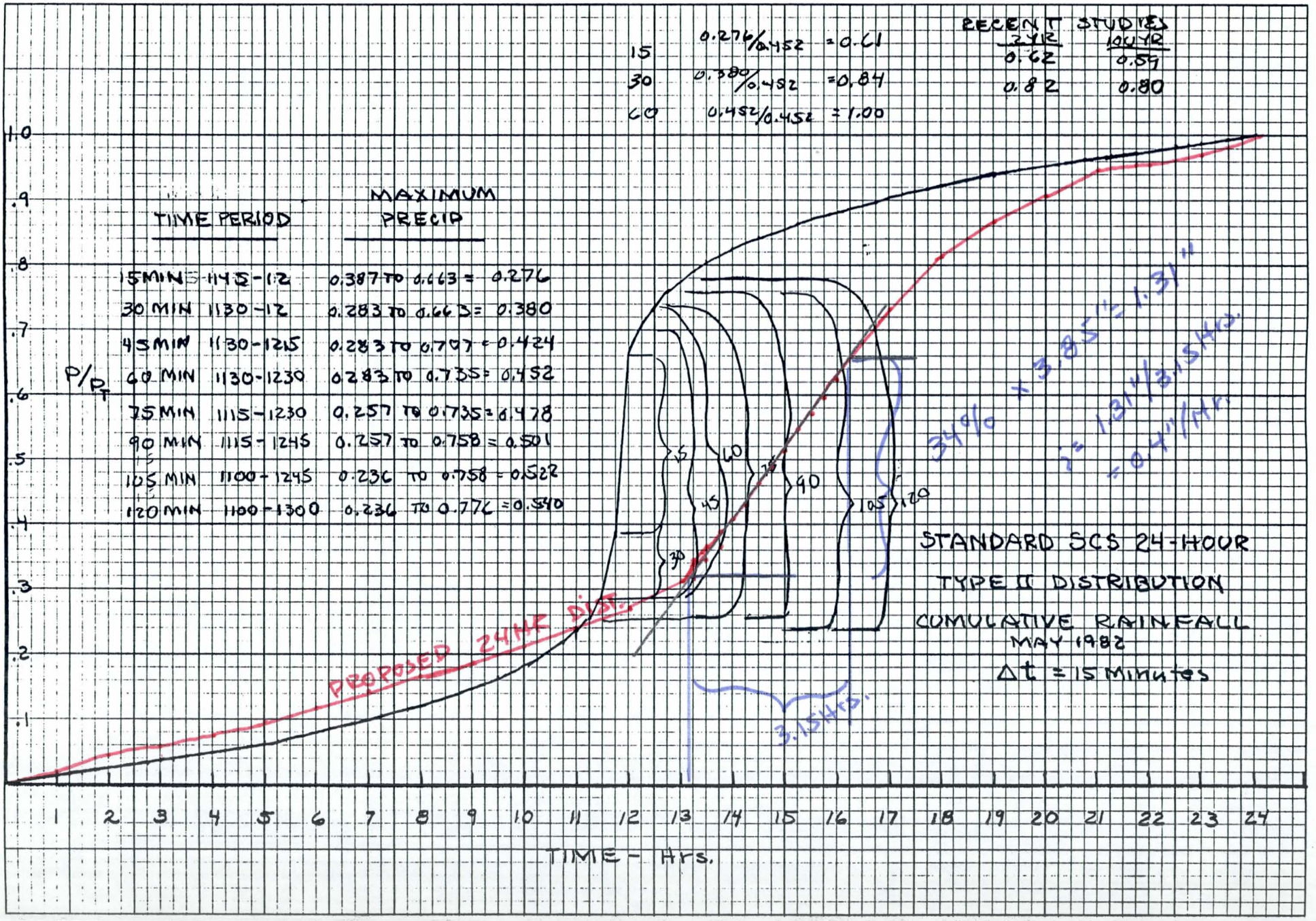

~~Doesn't~~

I have serious reservations about the use of the Green & Ampt Equation.

(1) The number of parameters to estimate
(2) Availability of the soil parameters
(3) Areal variation of soil parameters.
(4) Computation variations with different users selection of parameters

RAINFALL LOSSES 29 Dec 88

PRELIMINARY
For Review Only

General Theory

Rainfall excess is that portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall losses equals precipitation. When performing a flood analysis using a rainfall-runoff model, the determination of rainfall excess is of utmost importance. Rainfall excess integrated over the entire watershed results in runoff volume, and the temporal distribution of the rainfall excess will, along with the hydraulics of runoff, determine the peak discharge. Therefore, the estimation of the magnitude and time distribution of rainfall losses should be performed with the best practical technology, considering the objective of the analysis, economics of the project, and consequences of inaccurate estimates.

Rainfall losses are generally considered to be the result of interception of rainfall by vegetal cover, depression storage on the land surface (paved or unpaved), evaporation of water from the land surface, and infiltration of water into the soil matrix. For the purposes of this Hydrology Manual rainfall losses are classified as either surface retention loss or infiltration. Losses are also often separated into accumulated losses prior to the initiation of surface runoff (initial abstraction), and losses during surface runoff; however, initial abstraction is not identical to surface retention loss because initial abstraction includes some amount of infiltration losses prior to the start of surface runoff.

Surface Retention Loss

Surface retention loss, as used herein, is the summation of all rainfall losses other than infiltration. The major component of this loss is depression storage consisting of rainfall that is captured in puddles, small surface depressions, road gutters, ditches, roofs, and other non-draining surface features. A relatively minor contribution by interception is also considered as a part of the total surface

retention loss. Estimates of surface retention loss are difficult to obtain and are a function of the physiography and land-use of the area. Estimates of surface retention loss contained in this manual have been obtained from the analysis of rainfall-runoff data, results of rainfall simulator studies conducted on rangelands and turf, and published estimates for such losses.

Infiltration

Infiltration is the movement of water from the land surface into the soil. Infiltration is distinguished from percolation in that percolation is the movement of water through the soil subsequent to infiltration. Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, the extent by which percolation can restrict infiltration of rainfall should be carefully evaluated before percolation can be assumed to restrict infiltration for the design rainfalls that are being considered in Maricopa County. For example, hydrologic soil group D has been defined by SCS soil scientists as:

> "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."

This definition indicates that soils in hydrologic soil groups A, B, or C could be classified as D if they are underlain by an impervious strata of clay, caliche, or rock. When these soils are considered in regard to long-duration rainfalls that are the design events for many parts of the United States this definition may be valid. However, when considered for short-duration and relatively small design rainfall depths in Maricopa County this definition could result in under estimation of the rainfall losses for these storms. This is because even a relatively shallow horizon of soil overlaying an impervious layer still has the ability to store a significant amount of infiltrated rainfall. For example, consider the situation where only 4 inches of soil covers an impervious layer. If the effective

porosity is 0.30 then 1.2 inches (4 inches times 0.30) of water can be infiltrated and stored in the shallow soil horizon. For a design rainfall of 6 hours and a rainfall depth of about 4 inches this represents a significant storage volume for infiltrated rainfall. Therefore, for drainage studies in Maricopa County that contain major areas of soil that are classified as hydrologic soil group D, the reason for the soil survey classification as D should be determined. Hydrologic soil group D should be retained for clay soils, soils with a permanent high water table, and rock outcrop. Hydrologic soil group D should probably not be retained in all situations where the classification is based on shallow soils over nearly impervious layers, and site specific studies and sensitivity analyses should be performed to estimate the loss rates that should be used for such soils.

Infiltration of water into the soil is generally believed to follow an exponential decay function as proposed by Horton (1939):

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where f is the infiltration rate at time t,

f_c is the minimum (equilibrium) infiltration rate,

f_o is the initial infiltration rate,

t is the time from start of rainfall,

k is a constant that is dependent upon the soil-vegetation complex, and

e is the base of the Naperian logarithms.

This infiltration function is illustrated in Figure 1. In Figure 1, the infiltration rate is shown to be a continually decreasing function of time and the surface retention loss is shown to be a loss that is independent of and separate from the infiltration of rainfall into the soil. This represents the physical process that is to be simulated in modeling rainfall loss.

The driving force for infiltration is gravity and capillary forces drawing water into and through the pore spaces of the soil matrix.

Infiltration is controlled by soil properties, vegetation influences on the soil structure, surface cover by rock and vegetation, and by tillage practices.

Methods for Estimating Rainfall Losses

Numerous methods have been developed for estimating rainfall losses. Five methods are available as options in the HEC-1 Flood Hydrology Package:

1. SCS CN loss rate,
2. Initial loss plus uniform loss rate,
3. Exponential loss rate,
4. Holtan infiltration equation, and
5. Green and Ampt infiltration equation.

The Holtan infiltration equation is similar to the Horton equation in that it is an exponential decay type of equation for which the rainfall loss rate asymptotically diminishes to the minimum infiltration rate, f_c. The Holtan equation is not extensively used and data and procedures to estimate the parameters for use in Maricopa County are not available. The Holtan equation is not recommended for general use in Maricopa County.

The Exponential loss rate method is a four parameter method that is not extensively used, but it is a preferred method of the U.S. Army Corps of Engineers. Data and procedures are not available to estimate the parameters for this loss rate method for all physiographic areas in Maricopa County, but Exponential loss rate parameters have been developed from the reconstitution of flood events for a flood hydrology study in a portion of Maricopa County (U.S. Army Corps of Engineers, 1982). However, adequate data is not available to estimate the necessary parameters and this method is not recommended for general use in Maricopa County.

The SCS CN method is the most extensively used rainfall loss rate method in Maricopa County and it has wide acceptance among many

agencies, consulting engineering firms, and individuals throughout the community. However, the method is limited because of both theoretical and practical deficiencies of the method. Several of the deficiencies of the SCS CN method are:

1. Rainfall losses are independent of the duration of rainfall. That is, for a given depth of rainfall the same rainfall loss results regardless of the duration of rainfall, and the same rainfall excess would be estimated for a given rainfall depth occurring in, for example, either 1 hour or 24 hours.
2. The estimated rainfall loss rate is a function of rainfall intensity. Short periods of high intensity rainfall would often result in large estimates of rainfall losses. This is contrary to the Horton type infiltration relation as illustrated in Figure 1.
3. The infiltration rate approaches zero rather than a minimum infiltration rate, f_c.
4. The initial abstraction of 0.2S is not justified nor is it based on data for hydrologic conditions that are representative of Maricopa County.
5. The selection of CN is too subjective and is based more on traditional acceptance of CN values rather than scientifically substantiated findings.
6. At low rainfalls (less than 4 inches), the estimate of rainfall loss is very sensitive to the selection of CN.

For these reasons the SCS CN method is not recommended for general use in Maricopa County.

Two methods are recommended for use in Maricopa County; these are the initial loss plus uniform loss rate (IL+ULR), and the Green and Ampt infiltration equation. Other methods should be used only if there is technical justification for a variance from this recommendation and if adequate information is available to estimate the necessary parameter values. Use of rainfall loss methods other than those recommended should not be undertaken unless previously approved by the Flood Control District and the local regulatory agency.

Green and Ampt Infiltration Equation

This model, first developed in 1911 by W.H. Green and G.A. Ampt, has since 1973 received increased interest for estimating rainfall infiltration losses. The model has the form:

$$f = K\left(1 + \frac{a}{F}\right)$$
$$a = \psi\phi(S_f - S_i) \qquad (2)$$

where f = infiltration rate,

K = hydraulic conductivity in the wetted zone (the ultimate steady state rate),

ψ = average capillary suction in the wetted zone,

S = final soil saturation (volumetric),

S = initial soil saturation (volumetric),

ϕ = soil porosity, and

F = depth of rainfall that has infiltrated into the soil since the beginning of rainfall.

It is important to note that as rain continues, F increases and f approaches K, and therefore, f is inversely related to time. Equation 2 is implicit with respect to f which causes computational difficulties. Eggert (1976) simplified Equation 1 by expanding the equation in a power series and truncating all but the first two terms of the expansion. The simplified solution (Li and others, 1976) is:

$$\Delta F = -.5(2F-K\Delta t)+.5((2F-K\Delta t)^2 + 8K\Delta t(a + F))^{1/2} \qquad (3)$$

where t is the computation interval and F is accumulated depth of infiltration at the start of t. The average infiltration rate is:

$$\Delta f = \frac{\Delta F}{\Delta t} \qquad (4)$$

Use of the Green and Ampt equation as coded in HEC-1 involves the simulation of rainfall loss as a two phase process. The first phase is the simulation of the surface retention loss as previously described, and this loss is called the initial loss (IA) in HEC-1.

During this first phase all rainfall is lost (zero rainfall excess generated) during the period from the start of rainfall up to the time that the accumulated rainfall equals the value of IA. It is assumed for modeling purposes, that no infiltration of rainfall occurs during this first phase. Initial loss (IA) is primarily a function of land-use and surface cover, and recommended values of IA for use with the Green and Ampt equation are presented in Table 1. For example, as shown in Table 1 about 0.35 inches of rainfall will be lost to runoff due to surface retention for desert and rangelands on relatively flat slopes in Maricopa County.

BASIS?

The second phase of the rainfall loss process is the infiltration of rainfall into the soil matrix. For modeling purposes, the infiltration begins immediately after the surface retention loss (IA) is completely satisfied. The three Green and Ampt equation infiltration parameters as coded in HEC-1 are hydraulic conductivity at natural saturation (XKSAT), wetting front capillary suction (PSIF), and volumetric soil moisture deficit at the start of rainfall (DTHETA). The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture), organic matter, and bulk density. The primary soil surface characteristics are vegetation cover, rock cover, and soil crusting. The land management practices are identified as various tillages as they result in changes to soil porosity.

infiltration is taken place during retention

Values of Green and Ampt equation parameters as a function of soil characteristics alone (bare ground condition) have been obtained from published reports (Rawls and others, 1983; Rawls and Brakensiek, 1983). Average values of XKSAT and PSIF for each of the soil texture classes are shown in Columns (2) and (3) of Table 2 (Rawls and others, 1983). Values of XKSAT and PSIF as a function of percent of sand and percent of clay for soil with 0.5 percent organic matter and base value (unaltered) soil porosity are shown in Figures 2 and 3, respectively (Rawls and Brakensiek, 1983). The values of XKSAT and PSIF from Table 2 should be used if general soil texture classification of the drainage area is available. The values of XKSAT

and PSIF from Figures 2 and 3 can be used if more specific soil texture classification is available from a detailed soil survey for which the percentage of sand and clay has been determined by an appropriate field soil survey. The use of the information in Figures 2 and 3 will require an extensive study of the soil for the drainage area and for most drainage studies only general soil texture classification will be known and the values from Table 2 should be used.

The soil moisture deficit (DTHETA) is a volumetric measure of the soil moisture storage capacity that is available at the start of the rainfall. DTHETA is a function of the effective porosity of the soil. If the soil is saturated at the start of rainfall then DTHETA equals 0.0. If the soil is devoid of moisture at the start of rainfall the DTHETA equals the effective porosity of the soil. Therefore the range of DTHETA is 0.0 to the effective porosity. The porosity of soil as a function of soil texture (percent of sand and percent of clay) is shown in Figure 4 (Brakensiek and others, 1984).

Under natural conditions, soil seldom reaches a state of soil moisture less than the wilting point of vegetation, and a graph of volumetric soil moisture at wilting point as a function of soil texture is shown in Figure 5. Due to the rapid drainage capacity of most soils in Maricopa County the soil would not be expected to be in a state of soil moisture greater than the field capacity at the start of a design storm. A graph of volumetric soil moisture at field capacity as a function of soil texture is shown in Figure 6. However, Maricopa County also has a large segment of its land area under irrigated agriculture and it is reasonable to assume that the design frequency storm could occur during or shortly after certain lands had been irrigated. Therefore, for irrigated lands it would be reasonable to assume that soil moisture could be at or near effective saturation during the start of the design rainfall.

Three conditions for DTHETA have been defined for use in Maricopa County based on the antecedent soil moisture condition that could be expected to exist at the start of the design rainfall. These three

conditions are "Dry" for antecedent soil moisture near the vegetation wilting point; "Normal" for antecedent soil moisture condition near field capacity due to previous rainfall or irrigation applications on nonagricultural lands; and "Saturated" for antecedent soil moisture near effective saturation due to recent irrigation of agricultural lands. Values of DTHETA have been estimated by subtracting the initial volumetric soil moisture for each of the three conditions from the soil porosity. The value of DTHETA "Dry" as a function of soil texture is shown in Figure 7. This figure was prepared by subtracting the wilting point soil moisture on Figure 5 from the soil porosity on Figure 4. The value of DTHETA "Normal" as a function of soil texture is shown in Figure 8. This figure was prepared by subtracting the field capacity soil moisture on Figure 6 from the soil porosity on Figure 4. The value of DTHETA "Saturated" is always equal to 0.0 because for this condition there is no available pore space in the soil matrix at the start of rainfall. Values of DTHETA for the three antecedent soil moisture conditions are shown in Table 2. DTHETA "Dry" should be used for soil that is usually in a state of low soil moisture such as would occur in the desert and rangelands of Maricopa County. DTHETA "Normal" should be used for soil that is usually in a state of moderate soil moisture such as would occur in irrigated lawns, golf courses, parks, and irrigated pastures. DTHETA "Saturated" should be used for soil that is usually in a state of high soil moisture such as irrigated agricultural land.

The hydraulic conductivity (XKSAT) can be affected by several factors besides soil texture. For example, hydraulic conductivity is reduced by soil crusting, it is increased by tillage, and it is increased by the influence of ground cover and canopy cover. The values of XKSAT that have been presented for bare ground as a function of soil texture alone should be adjusted under certain conditions.

Ground cover, such as grass, litter, and rock will generally increase the infiltration rate over that of bare ground conditions. Similarly, canopy cover, such as from trees, brush, and tall grasses can also increase the bare ground infiltration rate. The procedures and data that have been presented are for estimating the Green and Ampt

parameters based solely on soil texture and would be applicable for bare ground conditions. Procedures have been developed (Rawls and others, 1988) for incorporating the effects of ground cover and canopy cover into the estimation of the parameters for the Green and Ampt equation. Past research has shown that the wetting front capillary suction parameter (PSIF) is relatively insensitive in comparison with the hydraulic conductivity parameter (XKSAT); therefore only the hydraulic conductivity parameter is adjusted for the influences of ground cover and canopy cover.

The set of equations that have been developed to adjust the bare soil hydraulic conductivity for the influence of soil ground cover and canopy cover are:

$$KE = (CAN)\ (KE_c) + (OP)\ (KE_o) \tag{5}$$

$$KE_c = (K)\ (CF)\left[\left(\frac{BC}{CAN}\right)(CRC) + A\left(1 - \frac{BC}{CAN}\right)\right] \tag{6}$$

$$KE_o = (K)\left[\left(\frac{BO}{CAN}\right)(CRC) + A\left(1 - \frac{BO}{CAN}\right)\right] \tag{7}$$

$$CF = 1 + 0.96\ CAN \tag{8}$$

$$CRC = \frac{L}{\frac{L - TC}{SC} + \frac{TC}{B}} \tag{9}$$

$$A = e^{\left[2.82 - 0.099(SA) + 1.94(BD)\right]} \tag{10}$$

$$B = 0.0099 + 0.0721(TC) + 0.0000068(SA^2) + 0.000021(SA^2)(TC) - 0.000315(SA)(TC) \tag{11}$$

where KE = hydraulic conductivity adjusted for ground cover and canopy cover, and KE is the adjusted value of XKSAT in the Green and Ampt equation,

KE_c = hydraulic conductivity of soil under canopy cover,

KE_o = hydraulic conductivity of soil outside of canopy cover,

K = bare ground hydraulic conductivity, equal to XKSAT,

CF = canopy factor,

CRC = soil crust factor,

A = macroporosity factor,

CAN = ratio of area under canopy cover to total area,

OP = ratio of area outside of canopy cover to total area,

BC = ratio of bare soil (no vegetation, litter, or rock cover) that is under canopy cover to total area,

BO = ratio of bare soil that is outside of canopy cover to total area,

L = wetting front depth (assume 6 cm),

TC = soil crust thickness (assume 0.5 cm),

SC = correction factor for partial saturation of the subcrust soil (see Table 3),

SA = percent sand in the soil,

BD = soil bulk density (see Figure 9).

These equations have been developed for the SI system of units and they should be solved in this system and the resulting hydraulic conductivity (KE) in cm/hr should be converted to XKSAT in inches/hr.

Equations 5 through 7 can be simplified for use in estimating the hydraulic conductivity of turf by the following equation:

$$KE = (K)(A) \qquad (12)$$

where A is defined by Equation 10.

The influence of tillage results in a change in total porosity and therefore a need to modify the three Green and Ampt equation infiltration parameters. The effect of tillage systems on soil porosity and the corresponding changes to hydraulic conductivity, wetting front capillary suction, and water retention is available (Rawls and Brakensiek, 1983). Although this information is available it is not presented in this manual, nor is it recommended that these

adjustments be made to the three infiltration parameters for design purpose use in Maricopa County. This is because for most flood prediction purposes it cannot be assumed that the soil will be in any particular state of tillage at the time of storm occurrence and therefore the base condition infiltration parameters, as presented, should be used for flood prediction purposes. However, appropriate adjustments to the infiltration parameters can be made as necessary for special flood studies such as reconstitution of storm events.

Initial Loss Plus Uniform Loss Rate (IL + ULR)

This is a simplified rainfall loss method that is often used, and generally accepted, for flood hydrology. In using this simplified method it is assumed that the rainfall loss process can be simulated as a two-step procedure, as illustrated in Figure 10. First, all rainfall is lost to runoff until the accumulated rainfall is equal to the initial loss; and second, after the initial loss is satisfied, a portion of all future rainfall is lost at a uniform rate. Two parameters are needed to use this method, the initial loss and the uniform loss rate (STRTL and CNSTL), respectively, according to HEC-1 nomenclature).

The initial loss (STRTL) is the sum of all losses prior to the onset of runoff and is made up of surface retention loss and some amount of infiltration. This is also called initial abstraction. Values of the infiltration part of STRTL for bare ground according to soil texture classification are shown in Columns (3) through (5) in Table 4. These values have been derived from the Green and Ampt infiltration equation and parameter values that are shown in Table 2. The value of STRTL "Dry" should be used for soil that is usually in a state of low soil moisture at or near the wilting point for vegetation. This is a reasonable assumption for most nonirrigated lands in Maricopa County because of the infrequency of rainfall and because of the rapid drainage of these soils after rainfall. The value of STRTL "Normal" should be used for soil that is usually in a state of moderate soil moisture such as occurs for irrigated lawns, turf, and permanent pastures. The value of STRTL "Saturated" should be used for soil that is maintained in a state of high soil moisture such as occurs in

irrigated agricultural lands.

Values of STRTL for bare ground that have been classified according to hydrologic soil group are shown in Table 5. These values within each hydrologic soil group have been derived from the data in Table 4 for the various soil texture classifications.

The values of STRTL from Table 4 and 5 represent that portion of the initial loss that is attributable to infiltration and these should be increased to account for the surface retention loss that is a function of land-use and vegetation. These additive STRTL values are shown in Table 1. The value of STRTL that is used is the sum of the portion due to infiltration (Table 4 or 5) plus the portion that is due to surface retention (Table 1).

The uniform loss rate (CNSTL) represents the long-term, equilibrium infiltration capacity of the soil. The values of CNSTL shown in Column (2) of Table 4 for soils according to soil texture classification are equivalent to the hydraulic conductivity at natural saturation (XKSAT) as determined for the Green and Ampt equation (Table 2). The values of CNSTL for soils classified according to hydrologic soil groups are shown in Table 5. These values within each hydrologic soil group have been selected from inspection of XKSAT values in Table 2 for the various soil texture classifications. These values of CNSTL shown in Table 5 are consistent with general information that is available for estimating CNSTL as shown in Table 6.

Procedure for Estimating Loss Rates

Green and Ampt Method

1. Determine the soil texture classification. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used if adequate documentation on the sampling and laboratory procedure is provided and approved.
2. Estimate the hydraulic conductivity (XKSAT) for bare ground from

Table 2 if general soil texture classification is available or from Figure 2 if adequate soil texture data is available from an approved sampling program.

3. If desired, adjust the value of XKSAT for the influences of ground cover and canopy cover using Equations 5 through 11 or Equation 12 for turf.
4. Estimate the wetting front capillary suction parameter (PSIF) from Table 2 if general soil texture classification is available or from Figure 3 if adequate soil texture data is available from an approved sampling program.
5. Estimate the value of DTHETA from Table 2 if general soil texture classification is available or from either Figure 7 or 8 if adequate soil texture data is available from an approved sampling program. The value of DTHETA must be selected based on the appropriate antecedent soil moisture condition; "Dry" for nonirrigated lands such as desert and rangeland; "Normal" for soil that would be expected to be near soil moisture field capacity such as irrigated lawn, turf, and permanent pasture; and, "Saturated" for irrigated agricultural land.
6. Determine the land-use and/or soil cover for the drainage area and use Table 1 to estimate the surface retention loss (IA).
7. As an alternative to the above procedure, Green and Ampt loss rate parameters can be estimated by reconstitution of recorded rainfall-runoff events on the drainage area or hydrologically similar watersheds, or parameters can be estimated by use of rainfall simulators in field experiments. Plans and procedures for estimating Green and Ampt loss rate parameters by either of these procedures should be approved by the Flood Control District of Maricopa County and the local agency before initiating these procedures.

Initial Loss Plus Uniform Loss Rate Method

1. Determine the soil texture classification and/or the hydrologic soil group. Soils reports such as those of the Soil Conservation Service can be used if available, or laboratory analysis of appropriate soil samples from the drainage area can be used to classify the soil if adequate documentation on the sampling and

laboratory procedure is provided and approved.

2. Use values of CNSTL and STRTL from Table 4 if the losses are to be based on soil texture classification.
3. Use values of CNSTL and STRTL from Table 5 if the losses are to be based on hydrologic soil group.
4. Determine the land-use and/or soil cover and use Table 1 to estimate the surface retention loss to be added to STRTL from either Table 4 or 5.

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TABLE 1

Surface retention loss for various land surfaces in Maricopa County (addition to STRTL for IL+ULR method and IA for Green and Ampt method)

Land-Use and/or Surface Cover	Surface Retention Loss inches
(1)	(2)
Natural	
Desert and rangeland, flat slope	.35
Hillslopes, Sonoran desert	.15
Mountain, brush	.25
Developed (Residential and Commercial)	
Lawn and turf	.20
Desert landscape	.10
Pavement	.05
Agricultural	
Tilled	1.00
Irrigated pasture	.50

TABLE 2

Green and Ampt loss rate parameter values for bare ground

Soil Texture Classification	XKSAT in/hr	PSIF inches	DTHETA[1] Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)	(6)
sand	4.6	1.9	.35	.30	0
loamy sand	1.2	2.4	.35	.30	0
sandy loam	.40	4.3	.35	.25	0
loam	.15	3.5	.35	.25	0
silty loam	.25	6.6	.40	.25	0
sandy clay loam	.06	8.6	.25	.15	0
clay loam	.04	8.2	.25	.15	0
silty clay loam	.04	10.8	.30	.15	0
sandy clay	.02	9.4	.20	.10	0
silty clay	.02	11.5	.20	.10	0
clay	.01	12.4	.15	.05	0

[1] Selection of DTHETA:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 3

Soil crusting reduction factor for the Green and Ampt infiltration equation hydraulic conductivity parameter.

Soil Texture Classification	Reduction Factor for Subcrust Conductivity SC
(1)	(2)
Sand	0.91
Loamy sand	0.89
Sandy loam	0.86
Loam	0.82
Silt loam	0.81
Sandy clay loam	0.85
Clay loam	0.82
Silty clay loam	0.76
Sandy clay	0.81
Silty clay	0.73
Clay	0.75

TABLE 4

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to soil texture classification

Soil texture Classification	Uniform Loss Rate CNSTL	Initial Loss, in inches STRTL[1]		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
sand	4.6	1.3	1.3	0
loamy sand	1.2	.8	.8	0
sandy loam	.4	.7	.6	0
loam	.15	.6	.5	0
silty loam	.25	.8	.7	0
sandy clay loam	.06	.6	.5	0
clay loam	.04	.5	.4	0
silty clay loam	.04	.6	.5	0
sandy clay	.02	.4	.3	0
silty clay	.02	.4	.3	0
clay	.01	.3	.2	0

[1] Selection of STRTL:
Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 5

Initial Loss plus Uniform Loss Rate parameter values for bare ground according to hydrologic soil group

Hydrologic Soil Group	Uniform Loss Rate CNSTL	Initial Loss, in inches STRTL[1]		
		Dry	Normal	Saturated
(1)	(2)	(3)	(4)	(5)
A	.40	.6	.5	0
B	.25	.5	.3	0
C	.15	.5	.3	0
D	.05	.4	.2	0

[1] Selection of STRTL:

Dry - for nonirrigated lands such as desert and rangeland
Normal - for irrigated lawn, turf, and permanent pasture
Saturated - for irrigated agricultural land

TABLE 6

Published values of uniform loss rates

Hydrologic Soil Group	Uniform Loss Rate, in inches/hour		
	Musgrave (1955)	USBR (1975)[1]	USBR (1988)[2]
(1)	(2)	(3)	(4)
A	.30 - .45	.40	.30 - .50
B	.15 - .30	.24	.15 - .30
C	.05 - .15	.12	0 - .05

[1] Design of Small Dams, Second Edition, 1975, Appendix A

[2] Design of Small Dams, Third Edition, 1988

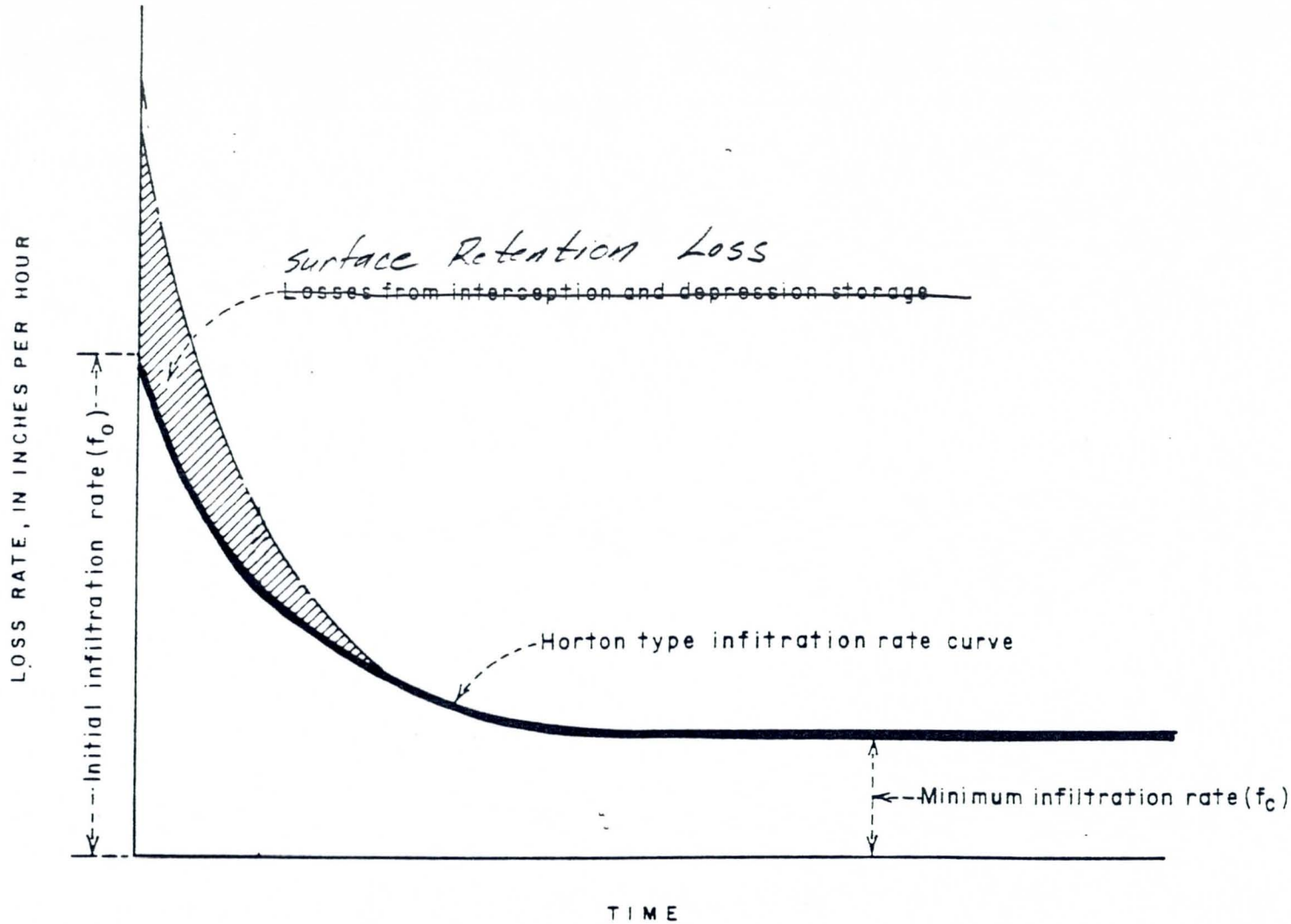
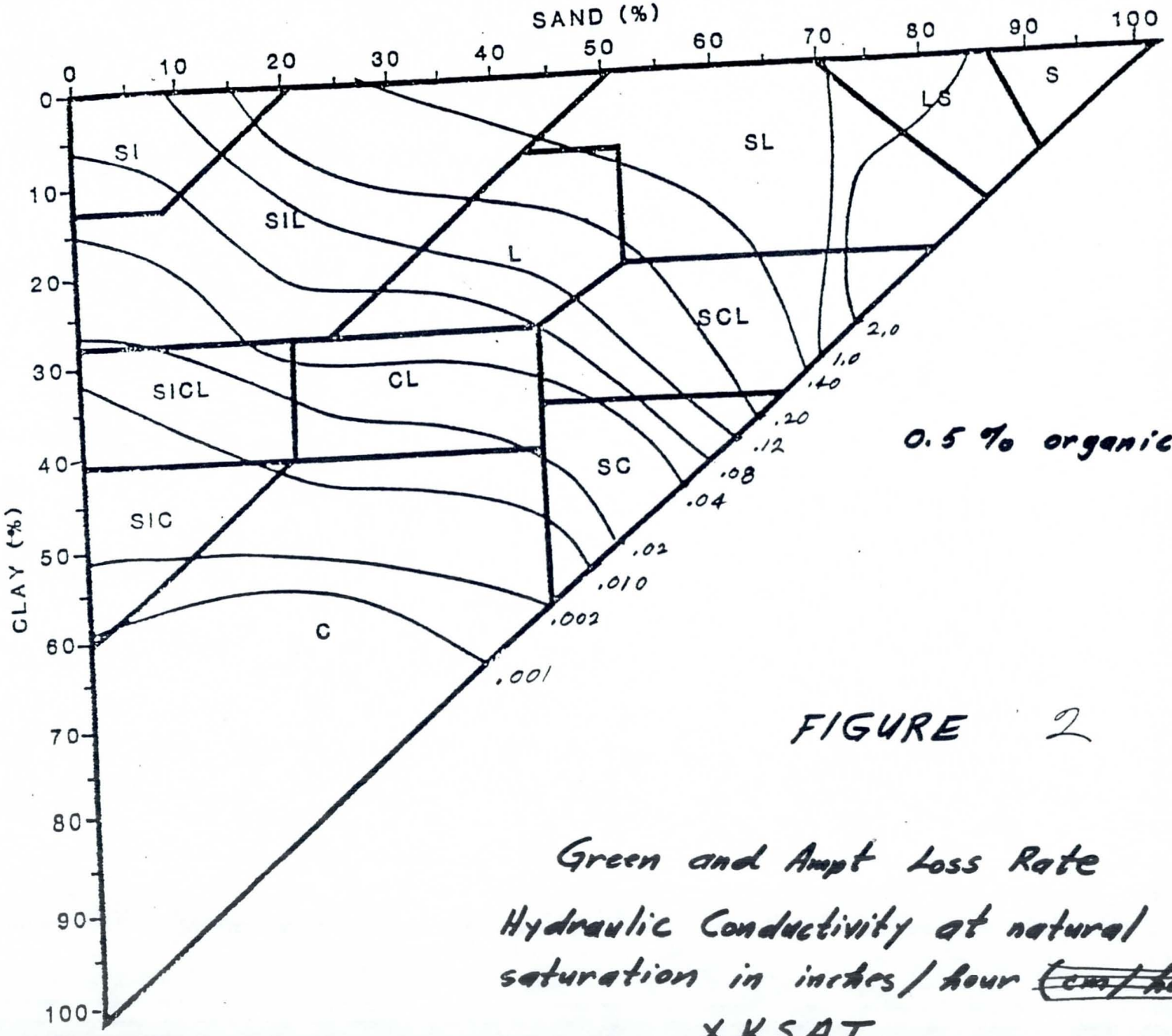


FIGURE 1

Representation of rainfall losses by surface retention and infiltration according to an exponential decay (Horton) type of equation



0.5 % organic matter

FIGURE 2

Green and Ampt Loss Rate

Hydraulic Conductivity at natural saturation in inches/hour ~~(cm/hour)~~

XKSAT

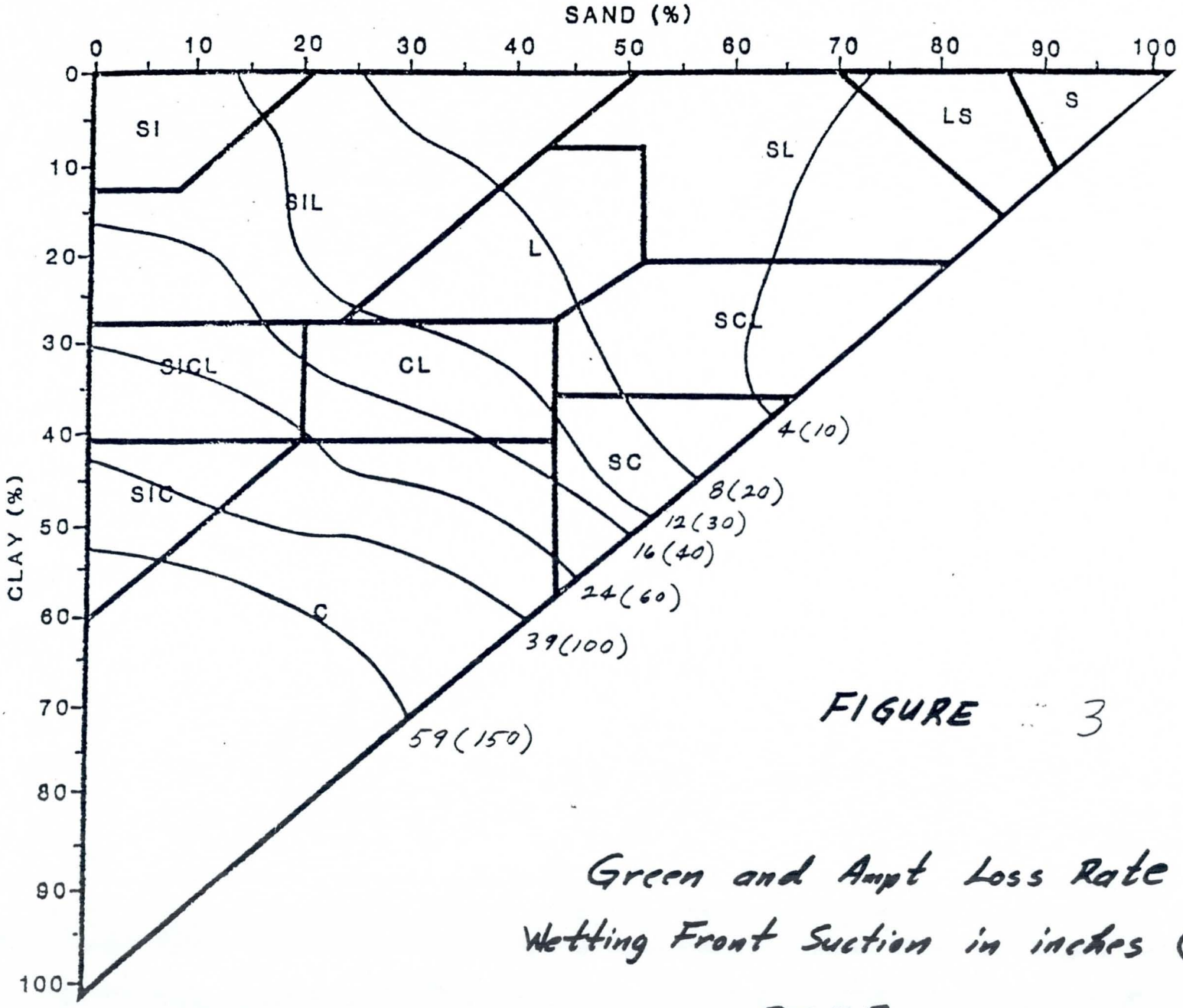


FIGURE 3

Green and Ampt Loss Rate

Wetting Front Suction in inches (cm)

PSIF

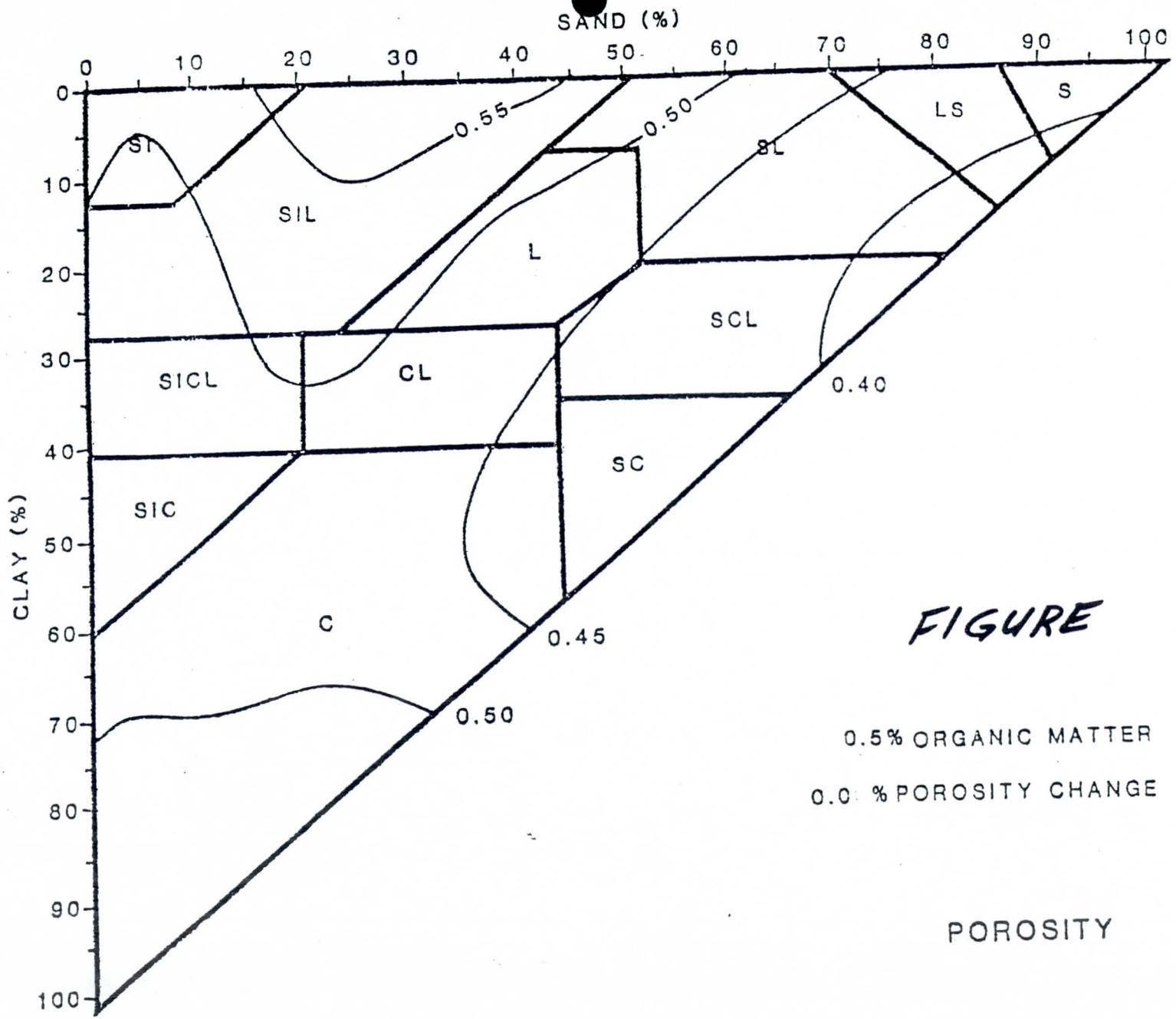


FIGURE 4

0.5% ORGANIC MATTER

0.0 % POROSITY CHANGE

POROSITY

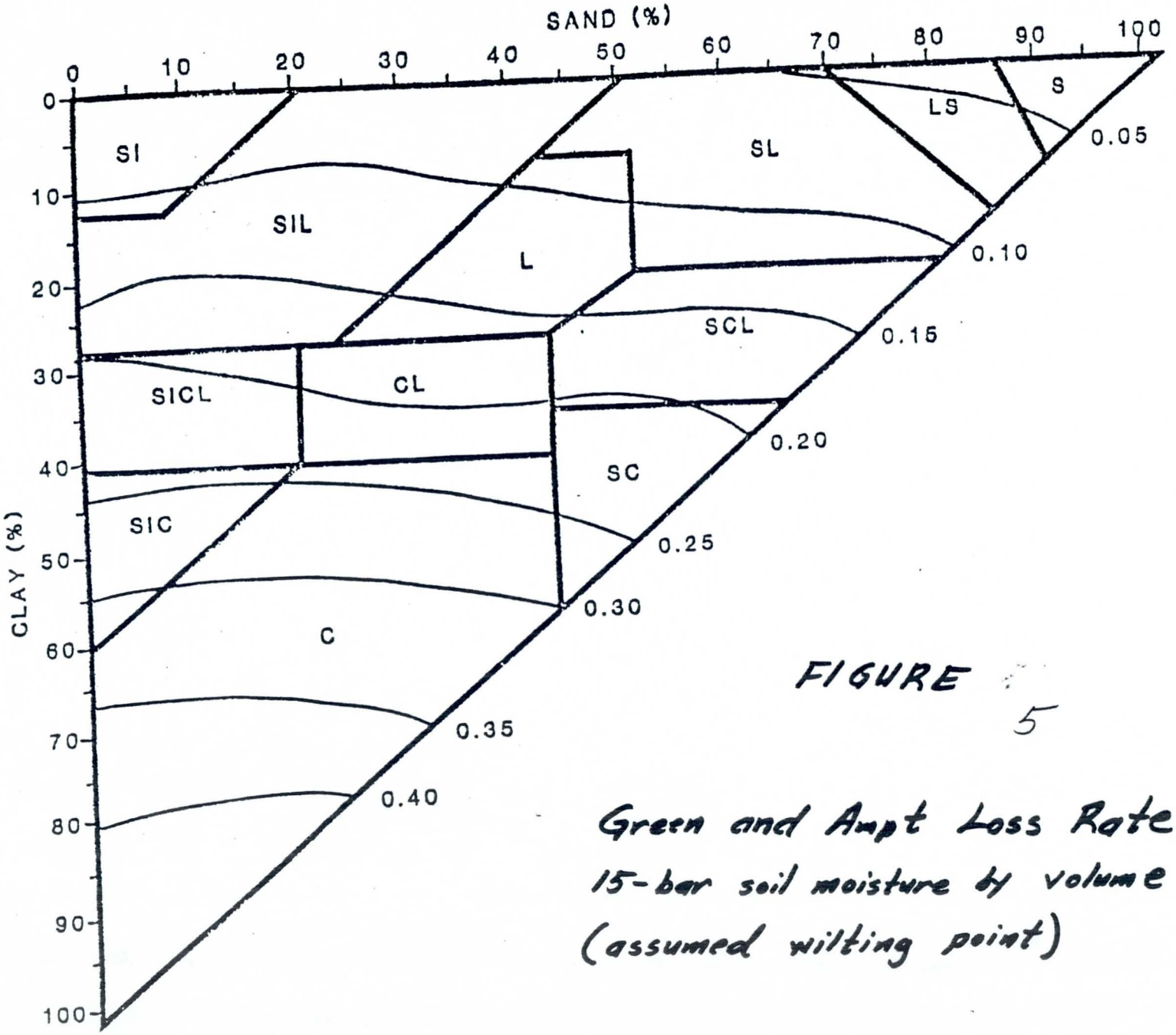


FIGURE 5

Green and Ampt Loss Rate
15-bar soil moisture by volume
(assumed wilting point)

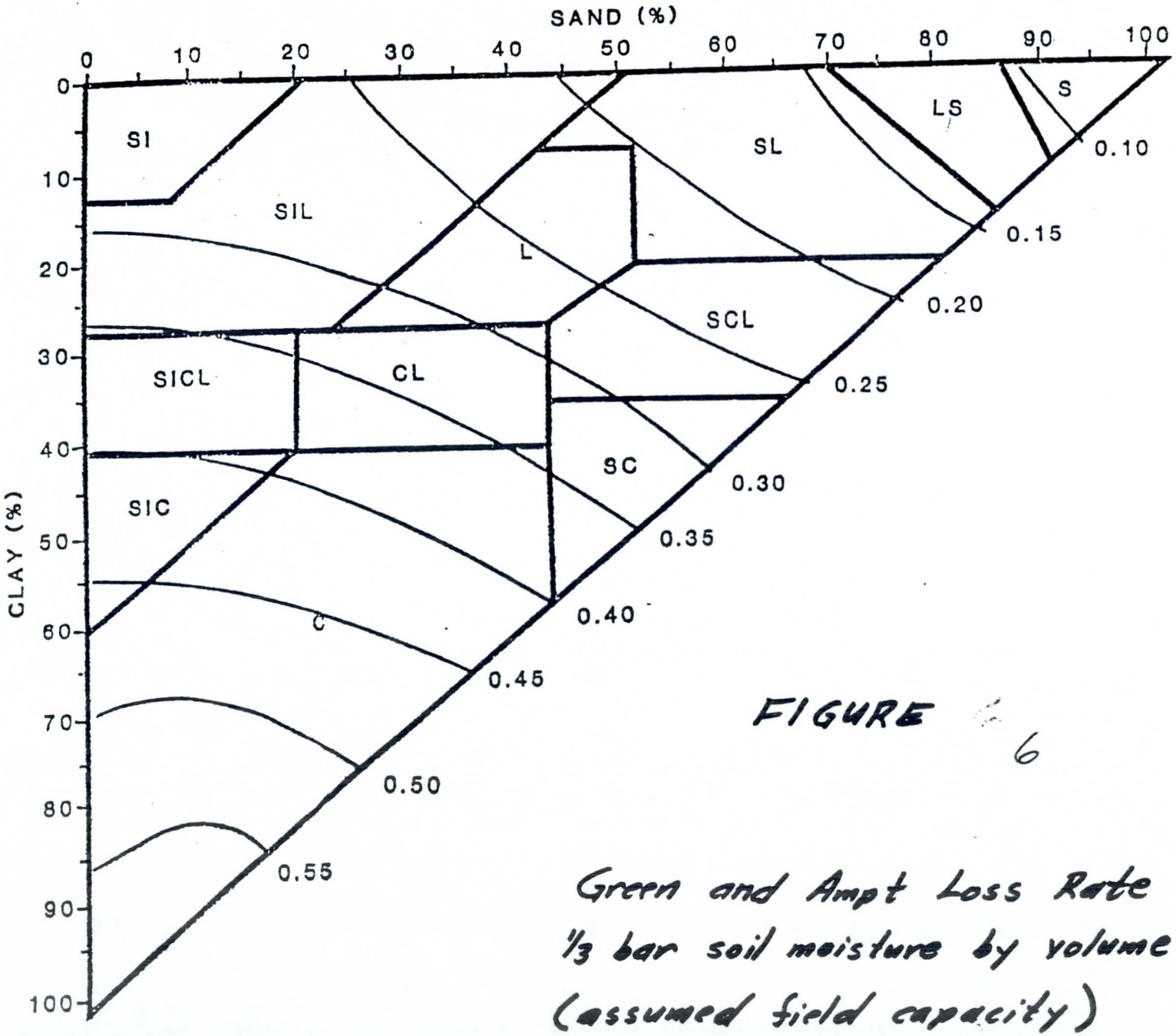


FIGURE 6

Green and Ampt Loss Rate
1/3 bar soil moisture by volume
(assumed field capacity)

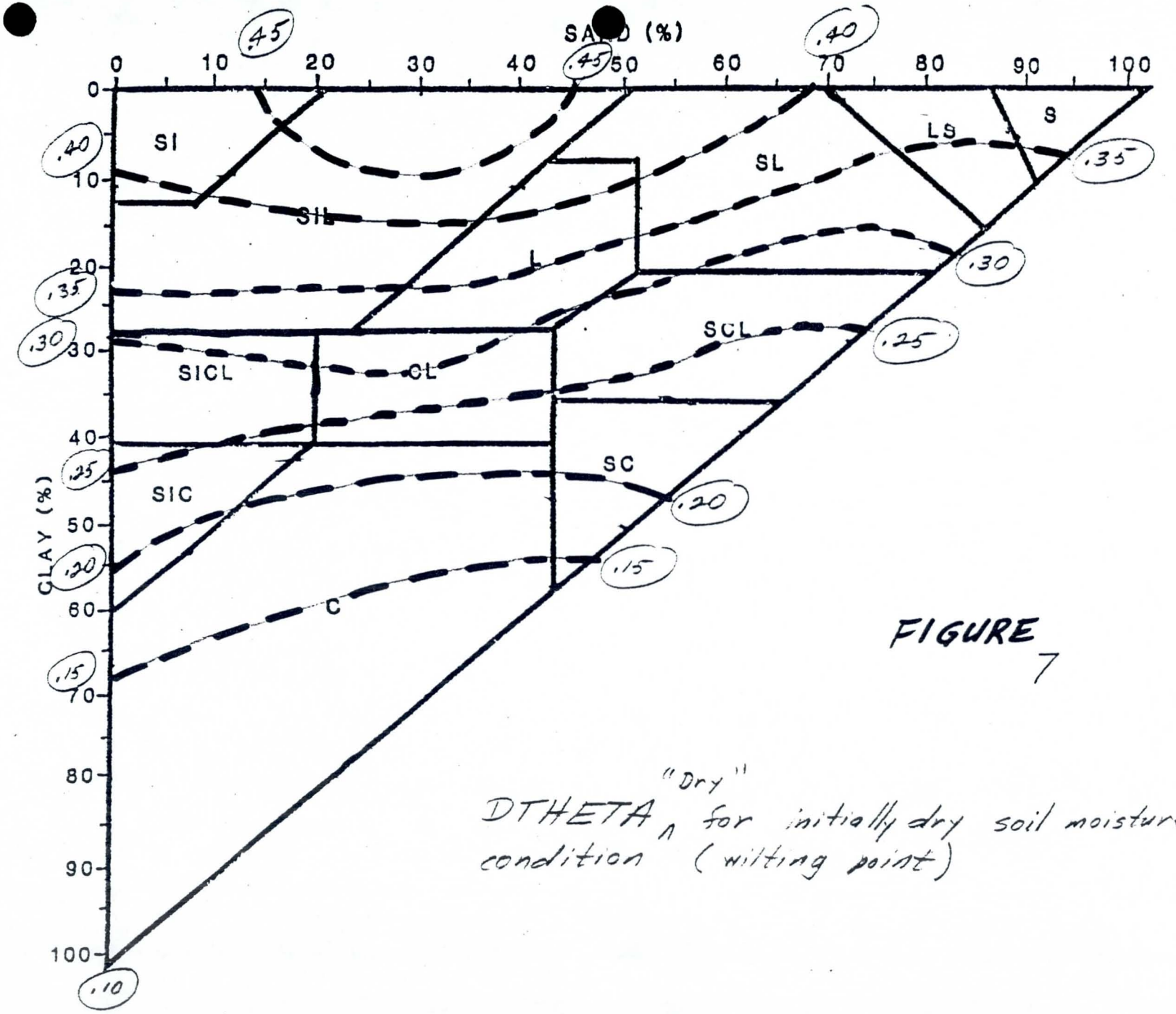


FIGURE 7

DTHETA "Dry" for initially dry soil moisture condition (wilting point)

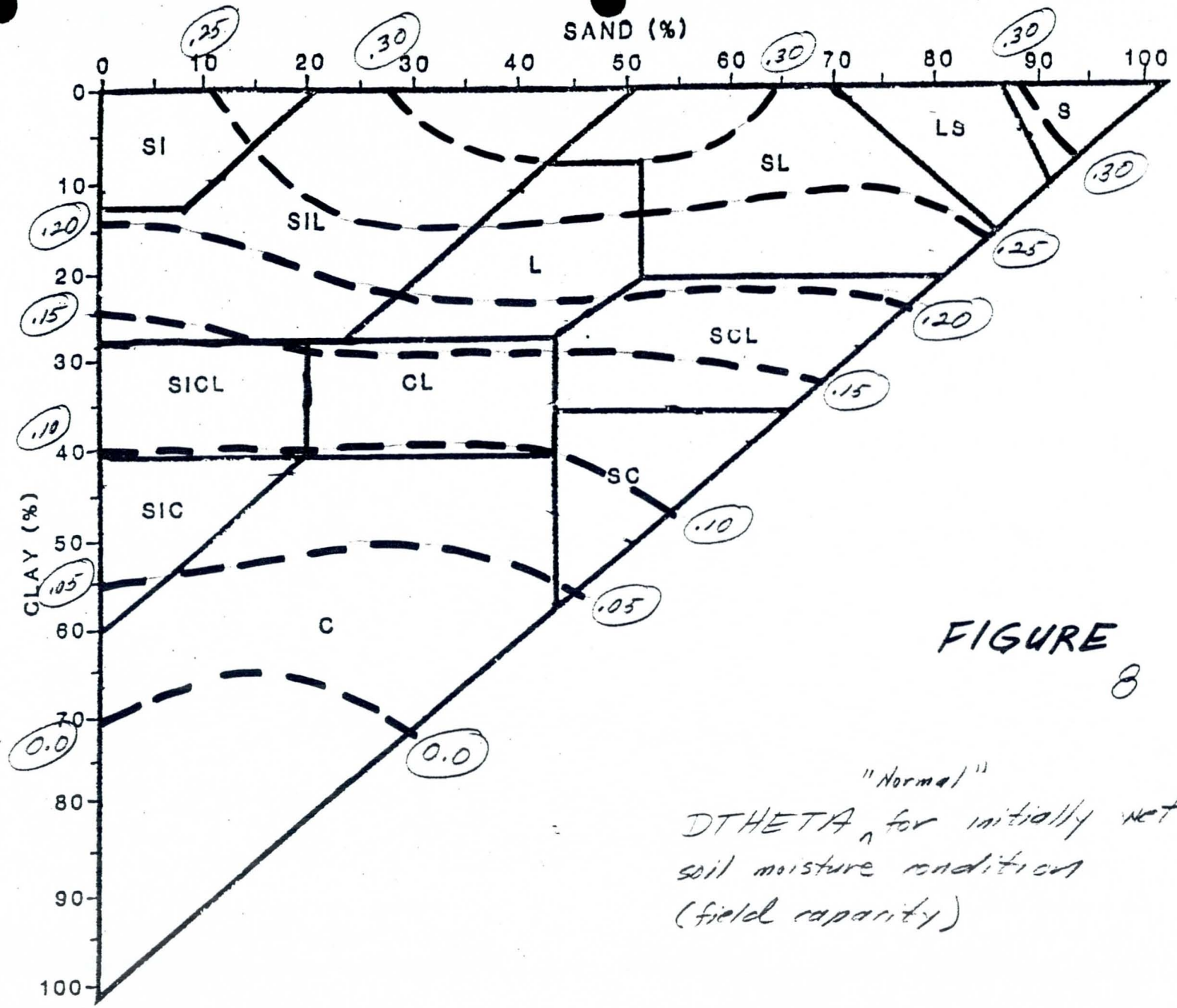


FIGURE 8

"Normal" DTHETA for initially wet soil moisture condition (field capacity)

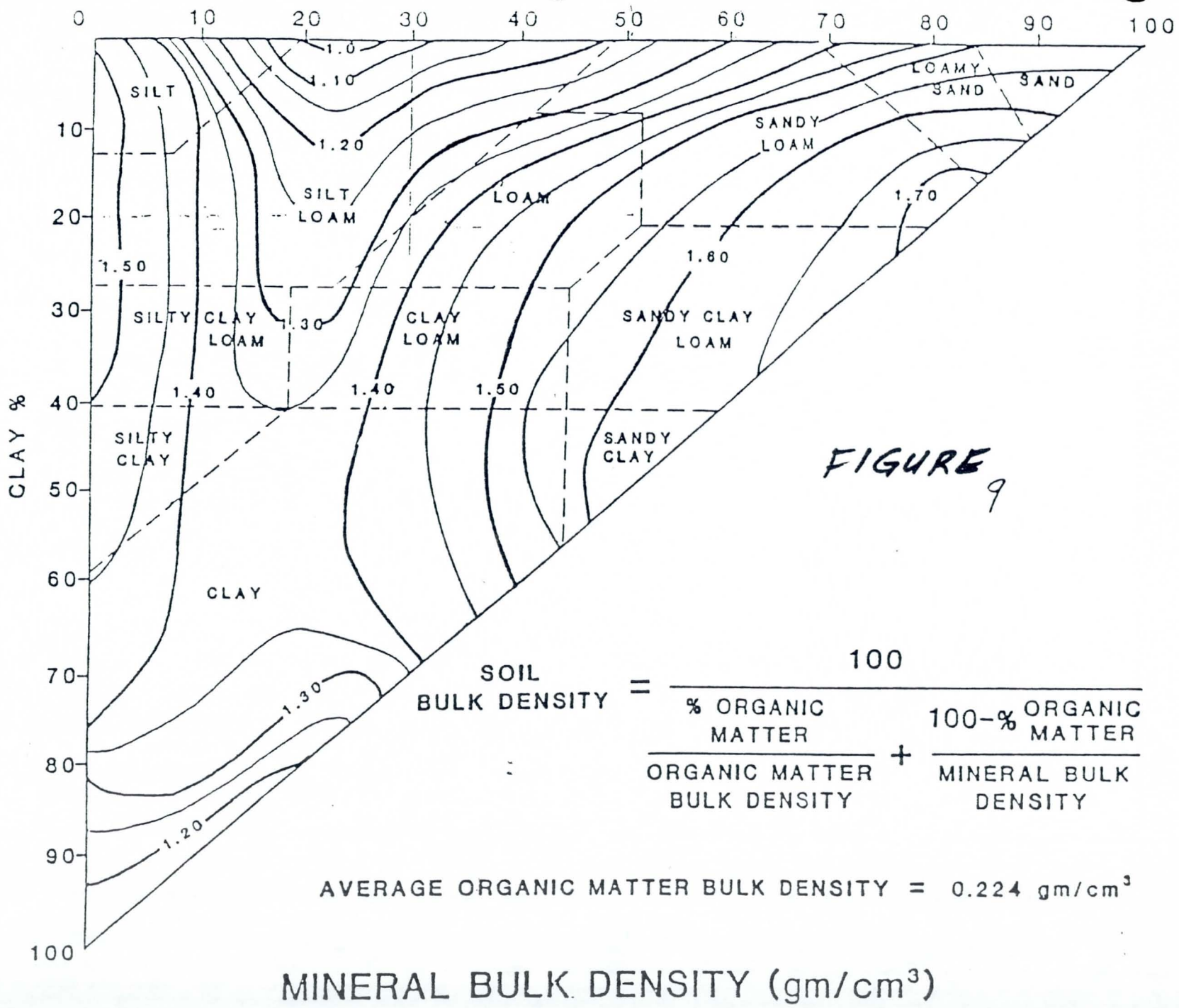


FIGURE 9

$$\text{SOIL BULK DENSITY} = \frac{100}{\dfrac{\%\ \text{ORGANIC MATTER}}{\text{ORGANIC MATTER BULK DENSITY}} + \dfrac{100-\%\ \text{ORGANIC MATTER}}{\text{MINERAL BULK DENSITY}}}$$

AVERAGE ORGANIC MATTER BULK DENSITY = 0.224 gm/cm³

~~Fig. 1. Determination of soil bulk density.~~

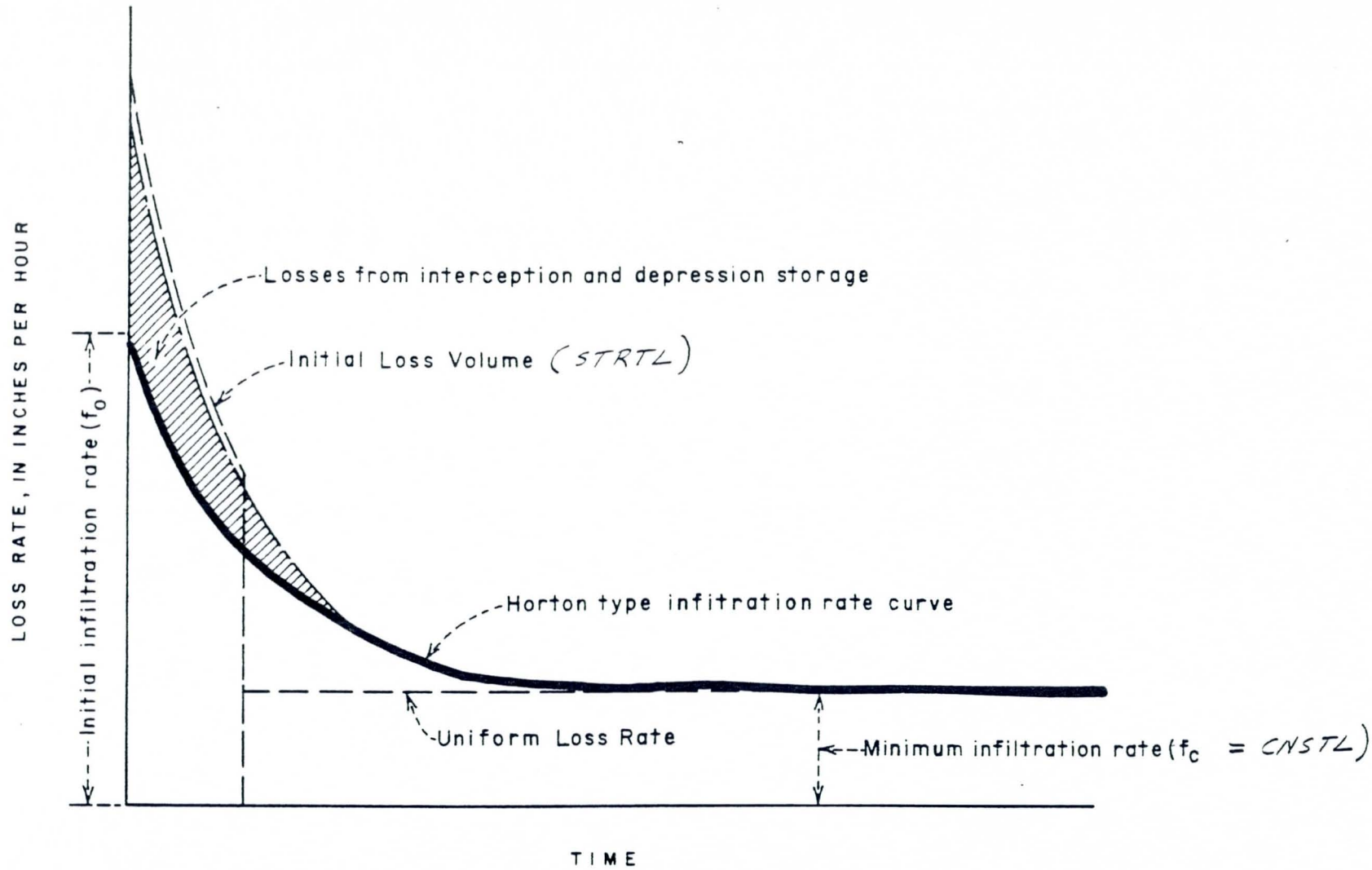


FIGURE 10

SIMULATION OF RAINFALL LOSSES BY THE INITIAL LOSS PLUS UNIFORM LOSS RATE METHOD

Essentially he's saying use HEC 1

UNIT HYDROGRAPH PROCEDURES / Dec 88

Too much dependency upon empirical equations to derive: Tc, n, R, Time-area, Lag,

PRELIMINARY
For Review Only

General

Rainfall excess can be routed from a watershed to produce a storm discharge hydrograph at a downstream location (concentration point) by one of two methods: 1) hydraulic routing involving the complete or some simplified form of the equations of motion, that is, the momentum equation plus the continuity equation; or 2) hydrologic routing involving the application of the continuity equation. Kinematic wave routing, as available in HEC-1, is an example of hydraulic routing. Hydrologic routing is usually accomplished by either direct application of the equation of continuity;

$$I - O = dS/dt \qquad (1)$$

or, a graphical procedure such as the application of the principles of the unit hydrograph. Examples of hydrologic routing by direct application of the equation of continuity are the Clark Unit Hydrograph (Clark, 1945), the Santa Barbara Urban Hydrograph (Stubchaer, 1975), and the Single Linear Reservoir Model (Pedersen and others, 1980). Both the Santa Barbara Urban Hydrograph and the Single Linear Reservoir Model are simplified (one parameter) versions of the Clark Unit Hydrograph (three parameter) procedure (Sabol and Ward, 1985). Examples of unit hydrographs that require a graphical procedure are the SCS Dimensionless Unit Hydrograph, Snyder's Unit Hydrograph, S-graphs, and unit hydrographs that are derived directly from recorded runoff data. Graphical or tabular methods of routing rainfall excess by unit hydrographs are very amenable to hand-calculation methods which were common practice prior to the ready availability of computers. Direct mathematical solution of the equation of continuity, such as the Clark Unit Hydrograph, is more efficiently conducted with computers and appropriate computer programs.

The procedure that is recommended for routing rainfall excess in Maricopa County is either the Clark Unit Hydrograph or the application of selected S-graphs. The Clark Unit Hydrograph

procedure, as described herein, is limited to watersheds or sub-basins less than about 5 square miles in size. The application of S-graphs is recommended for use with major watercourses in Maricopa County.

A unit hydrograph is a graph of the time distribution of runoff from a specific watershed as the result of one inch of rainfall excess that is distributed uniformly over the watershed and that is produced during a particular time interval of the rainfall (duration). It is noted that the duration of rainfall excess is not generally equal to the rainfall duration. In that a unit hydrograph is derived from or is to be representative of a specific watershed, it is a lumped parameter and it reflects all of the physical characteristics of the watershed that will affect the time rate at which rainfall excess will drain from the land surface.

The principles of the unit hydrograph were introduced by Sherman (1932). Sherman observed that for a watershed all hydrographs resulting from a rain of the same duration have the same time base, and that ordinates of each storm hydrograph from the watershed are proportional to the volume of runoff if the time and areal distributions of the rainfalls are similar. The principles that are applied when using an unit hydrograph are:

1. For a watershed, hydrograph base lengths are equal for rainfall excesses of equal duration.
2. Hydrograph ordinates are proportional to the amount of rainfall excess.
3. A storm hydrograph can be developed by linear superposition of incremental hydrographs.

Application of these principles requires a linear relation between watershed outflow and storage within the watershed, $S = KO$. However, Mitchell (1962) has shown that nonlinear storage, $S = KO^x$, is a condition that occasionally occurs in natural watersheds. A method has been developed by Shen (1962) to evaluate the linearity of the storage-outflow relation for

gaged watersheds. Mitchell (1972) developed the model hydrograph for use in watersheds that have nonlinear storage-outflow characteristics. Presently, however, there is no method that has been devised to evaluate the linearity of an ungaged watershed, and the assumption of linearity is a practical necessity in virtually all cases.

Clark Unit Hydrograph

Theory

Hydrologic routing by the Clark Unit Hydrograph method is analogous to the routing of an inflow hydrograph through a reservoir. This analogy is illustrated in Figure 1. The inflow hydrograph, called the translation hydrograph in the Clark method, is determined from the temporal and spatial distribution of rainfall excess over the watershed. The translation hydrograph is then routed by a form of the equation of continuity

$$O_i = CI_i + (1 + C)\, O_{i-1} \qquad (2)$$

$$\text{where } C = \frac{2\,dt}{2R + dt} \qquad (3)$$

O_i is the instantaneous flow at the end of the time period, O_{i-1} is the instantaneous flow at the beginning of the time period, I_i is the ordinate of the translation hydrograph, dt is the computation time interval, and R is the watershed storage coefficient. The Clark Unit Hydrograph of duration dt is obtained by averaging two instantaneous unit hydrographs spaced dt units apart

$$Q_i = 0.5(O_i + O_{i-1}) \qquad (4)$$

where Q_i are the ordinates of the Clark Unit Hydrograph.

The Clark method uses two numeric parameters, T_c and R, and a graphical parameter, the time-area relation. The first parameter, time of concentration (T_c) is the travel time of water from the hydraulically most distant point in the watershed to the outflow location. Clark (1945) defined this time as the time from the end of effective rainfall over the watershed to the inflection point on the recession limb of the surface runoff hydrograph as shown in Figure 2. In practice, for ungaged watersheds this time is usually estimated by empirical equations since runoff hydrographs from the watershed are not available. ? Hydraulics

The second parameter is the storage coefficient, R, which has the dimension of time. This parameter is used to account for the effect that temporary storage in the watershed has on the hydrograph. Several methods are available to estimate R from recorded hydrographs for a basin. As originally proposed by Clark (1945), this parameter can be estimated by dividing the discharge at the point of inflection of the surface runoff hydrograph by the rate of change of discharge (slope of the hydrograph) at the inflection point as shown in Figure 2. Another technique for estimating R is to compute the volume remaining under the recession limb of the surface runoff hydrograph following the point of inflection and to divide the volume by the discharge at the point of inflection. Both of these methods require the ability to identify the inflection point on the recession limb of the runoff hydrograph. This is difficult if not impossible for complex hydrographs and flashy hydrographs such as occur from urban basins and natural watersheds in the Southwest. A method to estimate R by a graphical recession analysis of the hydrograph has been proposed (Sabol, 1988) and this method provides much more consistent results than do the previously described methods. The parameter, R, should be estimated by the analysis of several recorded events; however, in most cases recorded discharge hydrographs are not available and R must be estimated by empirical equations.

The time-area relation, a graphical parameter, is necessary to

compute the translation hydrograph. The time-area relation specifies the accumulated area of the watershed that is contributing runoff to the outlet of the watershed at any point in time. Procedures to develop a time-area relation for a watershed are discussed in a later section of this manual.

The application of the Clark Unit Hydrograph method is best described with a simple example. A watershed is shown in Figure 3(a), and a rainfall hyetograph and rainfall excess distribution are shown in Figure 3(b). For the example watershed and given intensity of rainfall excess the time of concentration is estimated as 25 minutes. An isochrone interval of 5 minutes is selected and the watershed is divided into five zones by isochrones as shown in Figure 3(a). The areas within each isochrone zone are measured and the dimensionless time-area relation is developed as shown in the table and depicted in Figure 3(c). The translation hydrograph of the time rate of runoff is developed by considering each incremental unit of runoff production that would be available as inflow to a watershed routing model. For example, at the end of the first 5 minutes of rainfall excess the runoff that is available at the outlet of the watershed is the product of incremental area A_1, and the rainfall excess R_1.

$$I_1 = (A_1 R_1) \times c/dt$$

where c = 60.5 cfs/acre-inch/minute, and dt = 5 minutes.

$$I_1 = (8 \text{ acres})(.10 \text{ inch})(60.5 \text{ cfs/acre-inch/minute})/(5 \text{ minutes})$$

$$I_1 = 9.7 \text{ cfs}$$

At the end of 10 minutes the available runoff is

$$I_2 = (A_1R_2 + A_2R_1) \times c/dt$$

$$I_2 = (8)(.55) + (24)(.10) \times 60.5/5$$
$$= 82.3 \text{ cfs}$$

At the end of 15 minutes the available runoff is

$$I_3 = (A_1R_3 + A_2R_2 + A_3R_1) \times c/dt$$

$$I_3 = (8)(.30) + (24)(.55) + (38)(.10) \times 60.5/5$$
$$= 234.7 \text{ cfs}$$

At the end of 20 minutes the available runoff is

$$I_4 = (A_1R_4 + A_2R_3 + A_3R_2 + A_4R_1) \times c/dt$$

$$I_4 = (8)(.15) + (24)(.30) + (38)(.55) + (32)(.10) \times 60.5/5$$
$$= 393.5 \text{ cfs}$$

At the end of 25 minutes the available runoff is

$$I_5 = (A_1R_5 + A_2R_4 + A_3R_3 + A_4R_2 + A_5R_1) \times c/dt$$

$$I_5 = (8)(0) + (24)(.15) + (38)(.30) + (32)(.55) + (18)(.10) \times 60.5/5$$
$$= 416.2 \text{ cfs}$$

Notice that all rainfall increments after $R_4 = 0$.
At the end of 30 minutes the available runoff is

$$I_6 = (A_3R_4 + A_4R_3 + A_5R_2) \times c/dt$$

$$I_6 = (38)(.15) + (32)(.30) + (18)(.55) \times 60.5/5$$
$$= 304.9 \text{ cfs}$$

At the end of 35 minutes the available runoff is

$$I_7 = (A_4R_4 + A_5R_3) \times c/dt$$

$$I_7 = (32)(.15) + (18)(.30) \times 60.5/5$$
$$= 123.4 \text{ cfs}$$

$$I_3 = (A_1R_3 + A_2R_2 + A_3R_1) \times c/dt$$

$$I_3 = (8)(.30) + (24)(.55) + (38)(.10) \times 60.5/5$$
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At the end of 20 minutes the available runoff is

$$I_4 = (A_1R_4 + A_2R_3 + A_3R_2 + A_4R_1) \times c/dt$$

$$I_4 = (8)(.15) + (24)(.30) + (38)(.55) + (32)(.10) \times 60.5/5$$
$$= 393.5 \text{ cfs}$$

At the end of 25 minutes the available runoff is

$$I_5 = (A_1R_5 + A_2R_4 + A_3R_3 + A_4R_2 + A_5R_1) \times c/dt$$

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$$I_7 = (32)(.15) + (18)(.30) \times 60.5/5$$
$$= 123.4 \text{ cfs}$$

At the end of 40 minutes the available runoff is

$$I_8 = (A_5R_4) \times c/dt$$

$$I_8 = (18)(.15) \times 60.5/5$$
$$= 32.7 \text{ cfs}$$

After 45 minutes (rainfall excess of 20 minutes plus travel time of 25 minutes) the available runoff is $I_9 = 0$ cfs

The translation hydrograph (I_1) is shown in Figure 3(d). This theoretical hydrograph has the correct volume of runoff from the watershed, however it does not reflect the effects of routing through the watershed. The translation hydrograph is then routed and averaged using Equations 2 through 4 resulting in the final runoff hydrograph. For this example, assume that R = 15 minutes, and the runoff hydrograph is shown in Figure 3(d). Notice that the Clark Unit Hydrograph itself was never really developed but that the three principles of the unit hydrograph were applied directly (mathematically) without having to perform graphical superposition of ratios of a unit hydrograph. Computationally, this process can be completed very quickly and conveniently with a computer program such as is done with HEC-1.

Limitations and Applications

There are no theoretical limitations governing the application of the Clark Unit Hydrograph; however, there are some practical limitations that should be observed. The method that is used to estimate the parameters may dictate limitations in regard to the type or size of watershed that is being considered. If the parameters are estimated through an analysis or reconstitution of a recorded rainfall-runoff event, the parameters would be considered to be appropriate for that particular watershed, regardless of type or size. This is the preferred method of parameter estimation, but there will be limited opportunity for this approach because of the scarcity of instrumented watersheds in Maricopa County. The parameters could be estimated by

At the end of 40 minutes the available runoff is

$$I_8 = (A_5R_4) \times c/dt$$

$$I_8 = (18)(.15) \times 60.5/5$$
$$= 32.7 \text{ cfs}$$

After 45 minutes (rainfall excess of 20 minutes plus travel time of 25 minutes) the available runoff is $I_9 = 0$ cfs

The translation hydrograph (I_i) is shown in Figure 3(d). This theoretical hydrograph has the correct volume of runoff from the watershed, however it does not reflect the effects of routing through the watershed. The translation hydrograph is then routed and averaged using Equations 2 through 4 resulting in the final runoff hydrograph. For this example, assume that R = 15 minutes, and the runoff hydrograph is shown in Figure 3(d). Notice that the Clark Unit Hydrograph itself was never really developed but that the three principles of the unit hydrograph were applied directly (mathematically) without having to perform graphical superposition of ratios of a unit hydrograph. Computationally, this process can be completed very quickly and conveniently with a computer program such as is done with HEC-1.

Limitations and Applications

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indirect methods, such as a regional analysis of recorded data. In this case, application of the parameter estimation procedures should be applied only to those ungaged watersheds that are representative of the watersheds in the data base. Most often, the parameters are estimated by generalized relations that may have been developed from a relatively large and diverse data base. The parameter estimation procedures that are recommended herein are of this last category.

The Clark Unit Hydrograph parameter estimation procedures that are presented in this manual have been adopted, modified, or developed from an analysis of a large data base of instrumented watersheds, controlled experimental watersheds, and laboratory studies; therefore, the application of these procedures is considered to be appropriate for most conditions that occur in Maricopa County. The types of watersheds for which the procedures can be applied include urban, rangeland, developed and natural alluvial fans, agricultural, hillslopes, and mountains.

Watershed size should be limited to 5 square miles or less. Watersheds larger than 5 square miles should be divided into smaller sub-basins for modeling purposes. Many watersheds smaller than 5 square miles should also be divided into sub-basins depending on the drainage network and degree of homogeneity of the watershed. The subdivision of the watershed into near homogeneous units should result in improved accuracy. Subdivision may also be desirable or required to determine discharges at concentration points within the watershed.

Development of Parameter Estimators

The procedures for parameter estimation are based on available literature, research results, and analysis of original data. For example, the T_c equation is based on the recent research of Papadakis and Kazan (1987). A large data base of recorded rainfall-runoff data was compiled and analyzed in developing and testing the procedures. These data are for instrumented watersheds in Arizona, New Mexico, Colorado, and Wyoming. A

discussion of the development and testing of these procedures is contained in the Documentation Manual that is a companion to this Hydrology Manual.

Estimation of Parameters

The following procedures are recommended for the calculation of the Clark Unit Hydrograph parameters for use in Maricopa County. Other general procedures, as previously discussed, can be used, however, these should be approved by the jurisdictional agency prior to adopting such procedures.

Time of Concentration -- Time of concentration is defined as the travel time, during the corresponding period of most intense rainfall excess, for water to travel from the hydraulically most distant point in the watershed to the point of interest (concentration point). An empirical equation for time of concentration, T_c, has been adopted with some procedural modifications from Papadakis and Kazan (1987)

$$T_c = 11.4\ L^{.50}\ n^{.52}\ s^{-.31}\ i^{-.38} \qquad (5)$$

where T_c is in hours,
L is length of the flow path for T_c, in miles,
n is a representative watershed resistance coefficient,
S is watercourse slope, in feet/mile, and ?
i is the average rainfall excess intensity, during the time T_c, in inches/hour. ?

The selection of a representative watershed resistance coefficient, "n," similar in concept to Manning's "n" in open-channel flow, is very subjective and therefore a high degree of uncertainty is associated with its use. To diminish this uncertainty and to increase the reproducibility of the procedure, a graph is provided for the selection of "n." This graph shown in Figure 4 provides for the selection of "n" based on watershed classification and watershed size. Interpolation can be used for a given watershed size and mixed classification. Equations for estimating "n" are given in Table 1.

Uncertainty in rainfall excess intensity

TABLE 1

Equation for estimating "n" in the T_c equation.

$$n = m \log A + b$$

where A is drainage area, in acres

Land Classification (1)	Equation Parameters m (2)	b (3)
Urban	-.0025	.02
Bare or nearly bare ground (alluvial fan, agricultural land, desert rangeland)	-.00625	.04
Rough and/or moderate vegetation (hillslopes)	-.01375	.08
Very rough and/or dense vegetation (mountains)	-.025	.15

The value of "i" in Equation 5 requires the knowledge of both the distribution of rainfall excess intensity and the time of concentration, which is, of course, unknown. Therefore, Equation 5 must be solved in a trial-and-error procedure. First, the time distribution of rainfall excess must be estimated for the design rainfall distribution and a graph of average rainfall excess intensity versus time prepared. Then a value of T_c is assumed and the corresponding value of "i" is read from the graph. Equation 5 is solved with that value of "i." If the calculated value of T_c is reasonably close to the value that was assumed for "i" then the solution is finished; if not, then assume a new value of T_c, recalculate "i," and recalculate T_c with Equation 5. The solution for T_c should converge within three trials.

Storage Coefficient -- Very little literature exists on the estimation of the storage coefficient, R, for the Clark Unit Hydrograph. Clark (1945) had originally proposed a relation between T_c and R since they can both be defined by locating the inflection point of a runoff hydrograph (Figure 2). The Corps of

Engineers has discussed the development of regionalized relations for T_c and R as functions of watershed characteristics in Training Document No. 15 (U.S. Army Corps of Engineers, 1982b). According to Corps procedures, T_c and R are estimated from relations of $T_c + R$ and $R/(T_c + R)$ as functions of watershed characteristics. These forms of empirical equations indicate an interrelation of T_c and R, and such dependence was observed in the data base as discussed in the Documentation Manual. The equation for estimating R for Maricopa County is

$$R = 0.37\ T_c^{1.11}\ A^{-0.57}\ L^{0.80} \qquad (6)$$

where R is in hours,

T_c is time of concentration, in hours,

A is drainage area, in square miles, and

L is length of flow path, in miles.

Time-Area Relation -- Either a synthetic time-area relation must be adopted or the time-area relation for the watershed must be developed. If a synthetic time-area relation is not used, the time-area relation is developed by dividing the watershed into incremental runoff producing areas that have equal incremental travel times to the outflow location. This is a difficult task and well defined and reliable procedures for this are not available. The following general procedure is often used. First, using a topographic map of the watershed, the distance from the hydraulically most distant point in the watershed is traced along the flow path to the outflow location; this defines L in both Equations 5 and 6. Isochrones are drawn on the map that represent equal travel time to the outflow location. These isochrones can be established by considering the land surface slope and resistance to flow, and also whether the runoff would be sheet flow or would be concentrated in watercourses. A good deal of judgement and interpretation is required for this. Next, the incremental areas are measured and tabulated in an upstream sequence along with the corresponding travel time for each area. A graph is prepared of travel time versus contributing area, or a dimensionless graph can be prepared of time as a percent of T_c

versus contributing area as a percent of total area. The dimensionless graph is preferred because this facilitates the rapid development of new time-area relations should there be a need to revise the estimate of T_c.

Synthetic time-area relations can be used such as the default relation in the HEC-1 program

$$A^* = 1.414(T^*)^{1.5} \qquad 0 \quad T \quad 0.5 \qquad (7)$$

$$1-A^* = 1.414(1-T^*)^{1.5} \qquad .5 \quad T \quad 1.0$$

where A is contributing area, in percent of total area, and

T^* is time, in percent of T_c.

Equation 7 is a symmetric relation and is not recommended for most watersheds in Maricopa County.

Two other dimensionless time-area relations have been developed during the reconstitution of recorded rainfall-runoff events as described in the Documentation Manual. These dimensionless relations for urban and natural watersheds are shown in Figures 5 and 6, respectively. Each of these figures show a synthetic time-area relation and a shaded zone where the time-area relation is expected to lie. It is recommended that for an urban watershed that the synthetic time-area relation of Figure 5 be used, and for a natural (undeveloped) watershed that the synthetic time-area relation of Figure 6 be used. If a time-area relation is developed from the watershed map, which is generally recommended for unusually shaped watersheds, then the resulting relation should lie within the shaded zones in either Figures 5 or 6. The HEC-1 default time-area relation is shown for comparison in each Figure. Tabulated values of the dimensionless time-area relations are shown in Table 2.

TABLE 2

Values of the synthetic dimensionless time-area relations for the Clark Unit Hydrograph

Time as a Percent of Time of Concentration	Contributing Area as a Percent of Total Area		
	Urban Watersheds	Natural Watersheds	HEC-1 Default
(1)	(2)	(3)	(4)
0	0	0	0.0
10	5	3	4.5
20	16	5	12.6
30	30	8	23.2
40	65	12	35.8
50	77	20	50.0
60	84	43	64.2
70	90	75	76.8
80	94	90	87.4
90	97	96	95.5
100	100	100	100.0

S-Graphs

Theory

An S-graph is a dimensionless form of a unit hydrograph and it can be used in the place of a unit hydrograph in performing flood hydrology studies. The concept of the S-graph dates back to the development of the unit hydrograph itself, although the application of S-graphs has not been as widely practiced as that of the unit hydrograph. The use of S-graphs has been practiced mainly by the U.S. Army Corps of Engineers, Los Angeles District, (referred to as the Los Angeles District), and the U.S. Bureau of Reclamation (USBR).

An example of an S-graph is shown in Figure 7. The discharge scale is expressed as percent of ultimate discharge (Q_{ult}), and the time scale is expressed as percent lag. Lag is defined as the elapsed time, usually in hours, from the beginning of an assumed continuous series of unit rainfall excess increments over

the entire watershed to the instant when the rate of resulting runoff equals 50 percent of the ultimate discharge. The intensity of rainfall excess is 1 inch per duration of computation interval (D). An equivalent definition of lag is the time for 50 percent of the total volume of runoff of a unit hydrograph to occur. It is to be noted that there are numerous definitions for lag in hydrology and the S-graph lag should not be calculated by methods that are not consistent with this definition.

Ultimate discharge is the maximum discharge that will be achieved from a particular watershed when subjected to a continuous intensity of rainfall excess of 1 inch per duration (D) uniformly over the basin. Ultimnate discharge (Q_{ult}), in cubic feet per second (cfs), can be calculated from Equation 1 ?

$$Q_{ult} = \frac{645.33\ A}{D} \qquad (8)$$

where A is drainage area, in square miles, and
D is duration of the 1 inch of rainfall excess, in hours.

S-graphs are developed by summing a continuous series of unit hydrographs, each lagged behind the previous unit hydrograph by a time interval that is equal to the duration of rainfall excess for the unit hydrograph. The resulting summation is a graphical distribution that resembles an S-graph except that the discharge scale is accumulated discharge and the time scale is in units of measured time. This graph is terminated when the accumulated discharge equals Q_{ult} which occurs at a time equal to the base time of the unit hydrograph less one duration interval. The basin lag can be determined from this graph at the time at which the accumulated discharge equals 50 percent of Q_{ult}. This summation graph is then converted to a dimensionless S-graph by dividing the discharge scale by Q_{ult} and the time scale by lag.

In practice, S-graphs have generally been developed by reconstituting observed floods to define a representative unit

hydrograph and then converting this to an S-graph. Prior to the advent of computerized models, such as HEC-1, flood reconstitution was a laborious task of rainfall and hydrograph separation along with numerous hand-cranked simulations to define the representative unit hydrograph. Modern S-graph development generally relies on use of optimization techniques, such as coded into HEC-1, to identify unit hydrograph parameters that best reproduce the observed flood.

Although an S-graph is completely dimensionless and does not have a duration of rainfall excess associated with it as does a unit hydrograph, its general shape and the magnitude of lag is influenced by the distribution of rainfall over the watershed and the time distribution of the rainfall. Therefore, the transposition of an S-graph from a gaged watershed to application in another watershed must be done with consideration of both the physiographic characteristics of the watersheds and the hydrologic characteristics of the rainfalls for the two watersheds.

Limitations and Applications

S-graphs are empirical, lumped parameters that represent runoff characteristics for the watershed for which the S-graph was developed. S-graphs that are developed from recorded runoff data from one watershed can be applied to another watershed only if the two watersheds are hydrologically and physiographically similar. In addition, a recent study for the Flood Control District of Maricopa County (Sabol, 1987) has demonstrated that the shape of S-graphs is significantly affected by storm characteristics, particularly the maximum intensity of the rainfall. Therefore, it may not be advisable to adopt S-graphs that have been developed from one hydrologic zone and to apply these to watersheds in other hydrologic zones because of possible differences in rainfall characteristics in the two zones that may affect the shape of the S-graph.

Application of S-graphs requires the selection of an appropriate

S-graph and the estimation of the one parameter, basin lag. Two S-graphs have been selected for use in Maricopa County and a method to estimate lag is provided.

The USBR has revised the Flood Hydrology Studies chapter of the Third Edition of Design of Small Dams (USBR, 1987), and it has identified six S-graphs for application in generalized regional and physiographic type of watersheds. The flood hydrology procedure in Design of Small Dams should be reviewed and used as a reference when performing drainage studies for major watersheds in Maricopa County. Recently the S-graph has been adopted as the unit hydrograph procedure by Orange County and San Bernardino County, California, and selected S-graphs are presented in the hydrology manuals for those counties. The S-graphs in those hydrology manuals have been selected primarily from S-graphs that previously had been defined by the Los Angeles District from a rather long and extensive history of analyses of floods in California.

An S-graph can, in theory, be used in any application for which an unit hydrograph can be used. In practice an S-graph must be first converted to an unit hydrograph, and this can be done by one of two methods. First, The S-graph can be converted to an unit-hydrograph manually; or second, the S-graph can be converted to an unit hydrograph by use of the LAPRE1 program. The LAPRE1 program is a HEC-1 preprocessor program that converts a psuedo-HEC-1 input file containing input for an S-graph to a valid HEC-1 input file. The LAPRE1 program outputs the HEC-1 input file with the S-graph converted to a unit hydrograph, and the unit hydrograph is written to the HEC-1 input file using the UI (Given Unit Graph) record. The use of LAPRE1 greatly facilitates the use of S-graphs and an implementation guide for the microcomputer version of LAPRE1 is contained in Appendix A.

An example of the manual conversion of an S-graph to an unit hydrograph follows.

Example: Conversion of an S-graph to a unit hydrograph

(To be supplied.)

Although an S-graph is completely dimensionless and does not have a rainfall excess duration associated with it, an unit hydrograph does require the specification of a duration. As a general rule, the duration selected for the development of the unit hydrograph should equal about 0.15 times the lag. A duration in the range 0.10 to 0.25 times the lag is usually acceptable.

Sources of S-Graphs

S-graphs for Maricopa County have been selected from a compilation of S-graphs for the Sothwestern United States that was recently completed (Sabol, 1987). The source of S-graphs for that compilation was reports and file data of the Los Angeles District and the USBR. That compilation included 55 individual S-graphs and 18 regional S-graphs. An individual S-graph is one that can be identified with the watershed from which data was used to develop the S-graph. Regional S-graphs are those that are graphical averages or modifications of individual S-graphs to produce an S-graph that is respresentative of a specific physiographic type of watershed.

S-Graphs for Use in Maricopa County

Two S-graphs have been selected for use in flood hydrology studies of major watercourses in Maricopa County. These two are referred to as the Phoenix Mountain and the Phoenix Valley S-graphs. The Phoenix Mountain S-graph is to be used in flood hydrology studies of watersheds that drain predominantly mountainous terrain. For example, this S-graph should be used for the Agua Fria River above Rock Springs, New River above the Town of New River, the Verde River, Tonto Creek, and the Salt River. This S-graph is also appropriate for Indian Bend Wash.

The Phoenix Valley S-graph is to be used in flood hydrology studies of watersheds that have little topographic relief. For example, this S-graph should be used for the Agua Fria River below Rock Springs, New River below the Town of New River, Skunk

Creek, Cave Creek, and urbanized watersheds.

These two S-graphs are shown in Figures 8 and 9, and the coordinates of the graphs listed in Table 3. These same two S-graphs have been selected for similar use in Maricopa County by the U.S. Army Corps of Engineers (1974 and 1982). The justification for the selection of these two S-graphs is provided in the Documentation Manual, and a more comprehensive presentation of S-graphs for Maricopa County is provided in the S-Graph Study report for the Flood Control District of Maricopa County (Sabol, 1987).

Estimation of Lag

The application of an S-graph requires the estimation of the parameter, basin lag. a general relationship for basin lag as a function of watershed characteristics is given by Equation 9

$$Lag = C \left(\frac{L L_{ca}}{S^p} \right)^m \qquad (9)$$

where Lag is basin lag, in hours,

L is length of the longest watercourse, in miles,

L_{ca} is length along the watercourse to a point opposite the centroid, in miles,

S is watercourse slope, in feet per mile,

C is a coefficient, and

m and p are exponents.

The Los Angeles District often uses C = 20n where "n" is the estimated mean Manning's "n" for all the channels within an area, and m = 0.38. The USBR (1987) has recommended that C = 26n and m = 0.33. Both sets of values in Equation 9 will often result in similar estimates for Lag. Traditionally the exponent, p, on the slope is equal to 0.5.

It should be noted that "n" is a measure of the hydraulic efficiency of the watershed and it is not necessarily a constant

TABLE 3

Tabulation of coordinates for the Phoenix Valley and the Phoenix Mountain S-Graphs

Percent Ultimate Discharge	Time, in Percent Lag	
	Phoenix Valley	Phoenix Mountain
(1)	(2)	(3)
0	0.0	0.0
2	23.0	23.0
4	30.0	31.0
6	36.0	37.0
8	41.0	42.0
10	45.7	46.0
12	50.0	49.8
14	54.1	53.4
16	58.0	56.8
18	61.7	60.0
20	65.2	63.1
22	68.5	66.1
24	71.6	69.0
26	74.6	71.8
28	77.5	74.4
30	80.2	76.8
32	82.7	79.1
34	85.0	81.2
36	87.2	83.2
38	89.0	85.1
40	91.1	86.8
42	92.9	88.8
44	94.6	91.0
46	96.3	93.8
48	98.1	96.8
50	100.0	100.0
52	102.0	103.4
54	104.1	107.0
56	106.3	110.8
58	108.6	114.7
60	111.0	118.7
62	113.5	122.9
64	116.1	127.3
66	118.8	131.9
68	121.6	136.7
70	124.5	141.7
72	127.5	147.1
74	130.7	152.8
76	134.1	158.8
78	137.7	165.5
80	141.5	172.9
82	145.5	181.6
84	149.9	191.0
86	154.6	201.0
88	159.6	212.0
90	165.6	226.0
92	173.6	244.0
94	186.6	265.0
96	200.6	295.0
98	223.6	342.0
100	298.6	462.0

for a given watershed for all rainfall depths and rainfall intensities. As rainfall depth and/or rainfall intensity increases the efficiency of runoff increases and "n" decreases. Therefore, some adjustment in "n" should be made for use with rainfalls of different magnitudes (frequencies). Generally, "n" is the smallest for extreme floods such as PMFs and increases as the frequency of event increases.

Several graphical relations are available for estimating basin lag. One such relation (U.S. Army Corps of Engineers, 1982) is shown in Figure 10. Several other relations that should be consulted when using S-graphs are contained in Design of Small Dams (USBR, 1987).

When estimating basin lag the following steps should be used:

1. From an appropriate map of the watershed, measure drainage area (A), and the values of L, L_{ca}, and S.
2. Calculate the basin factor ($L\ L_{ca}/S^{0.5}$).
3. Use data in Figure 10 and the tables in Design of Small Dams (USBR, 1987) to attempt to identify watersheds of the same physiographic type and similar drainage area and basin factor. Make a list of watersheds with similar drainage areas and basin factors, and tabulate the estimated value of "n" for those watersheds, and the measured lag.
4. Estimate "n" for the watershed by inspection of the tabulation from step 3.
5. Estimate lag by Equation 9. Use values of C and m corresponding to the source (U.S. Army Corps of Engineers or USBR) that was used to estimate "n".
6. Compare the calculated lag with the measured lag for similar watersheds from step 3.

The use of measured values of "n" from hydrograph reconstitutions of similar watersheds will provide the most reliable estimates of "n" and basin lag.

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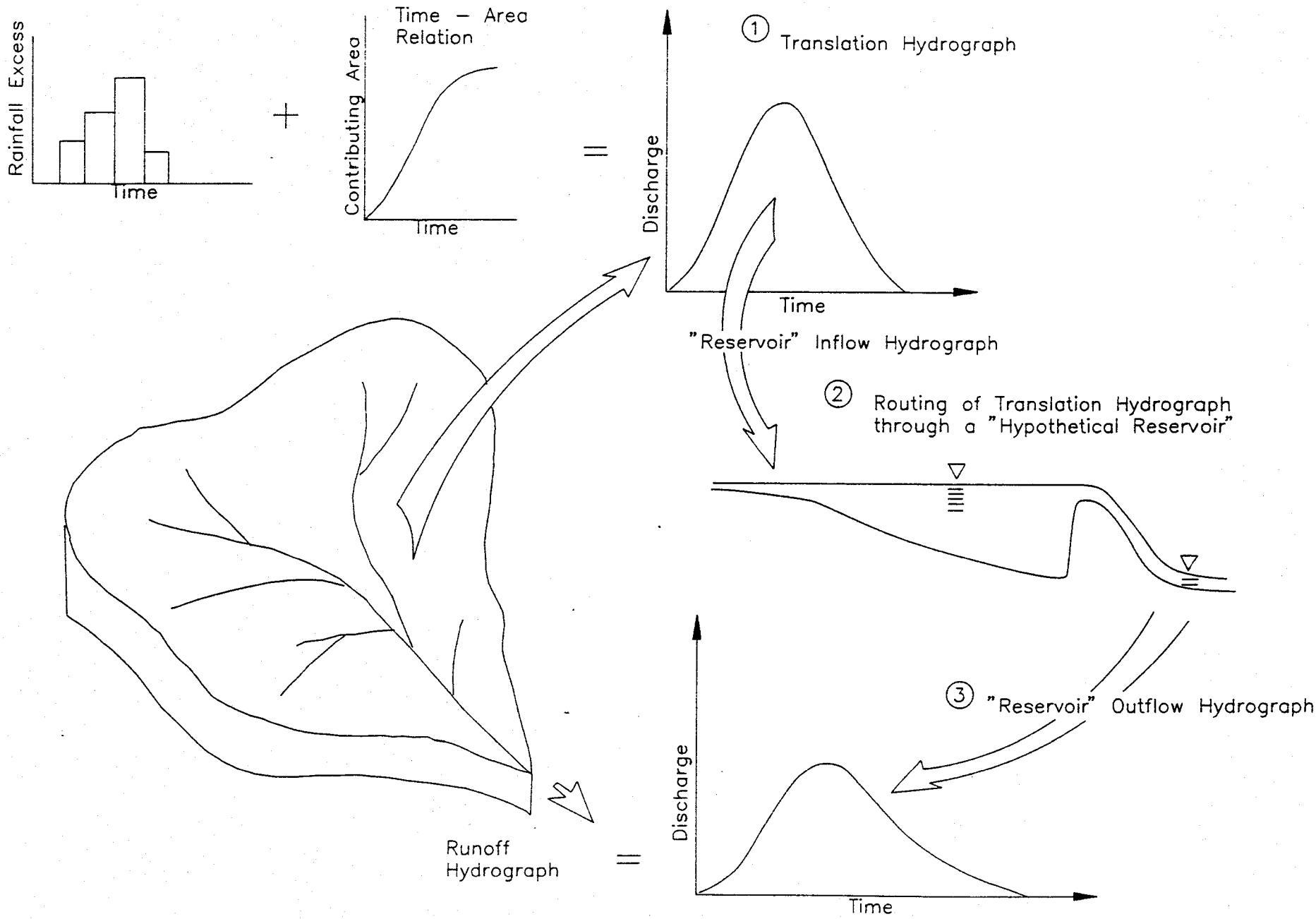


FIGURE 1 Conceptual analogy of linear reservoir routing to generation of a storm hydrograph by the Clark Unit Hydrograph method

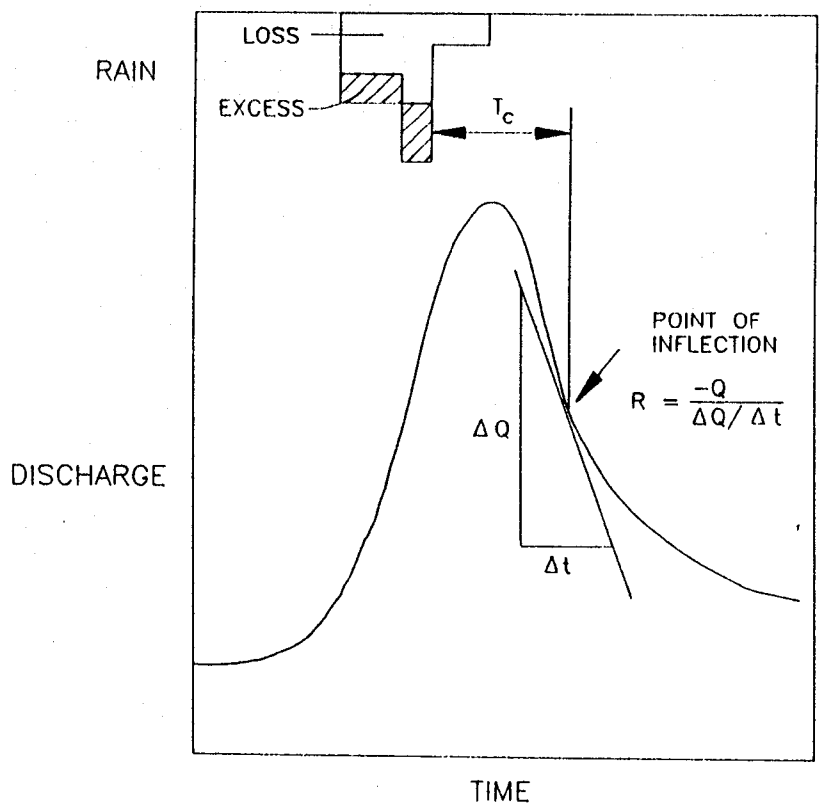
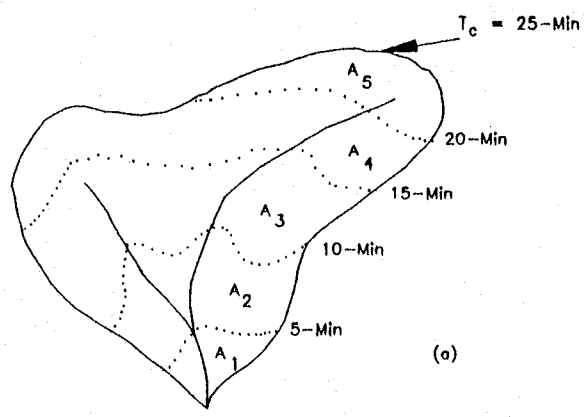
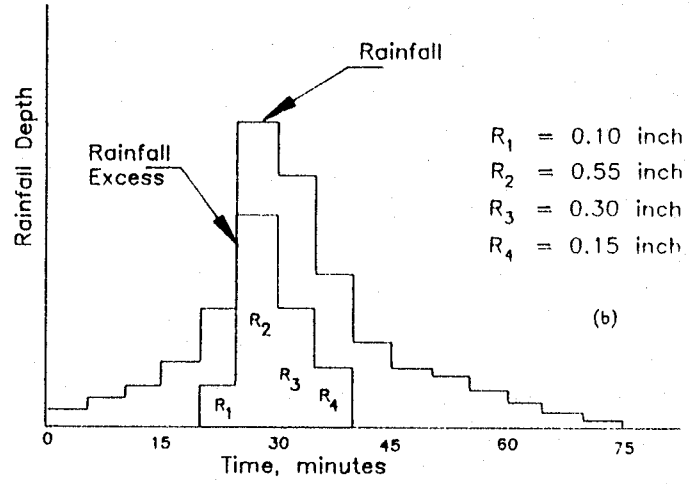


FIGURE 2
Definition sketch of Clark Unit Hydrograph parameters from hydrograph analysis.



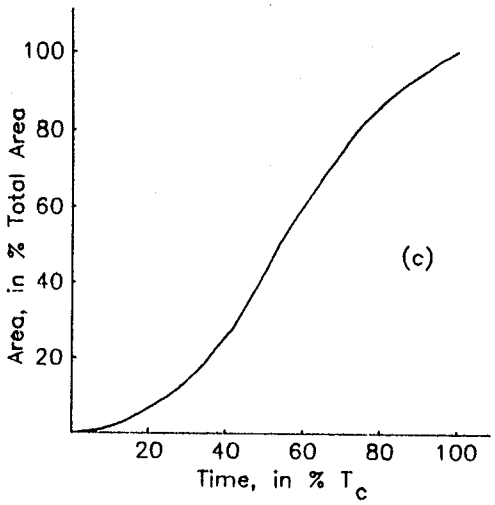
Watershed Map and Isochrones



Rainfall hydrograph and rainfall excess distribution

Table showing development of dimensionless time-area relation

Isochrone Zone (1)	Area Acres (2)	Accumulated Area (3)	Accumulated Area as % of Total Area (4)	Travel Time as % of T_c (5)
A_1	8	8	6.7	20
A_2	24	32	26.7	40
A_3	38	70	58.3	60
A_4	32	102	85.0	80
A_5	18	120	100.0	100



Dimensionless Time-Area Relation

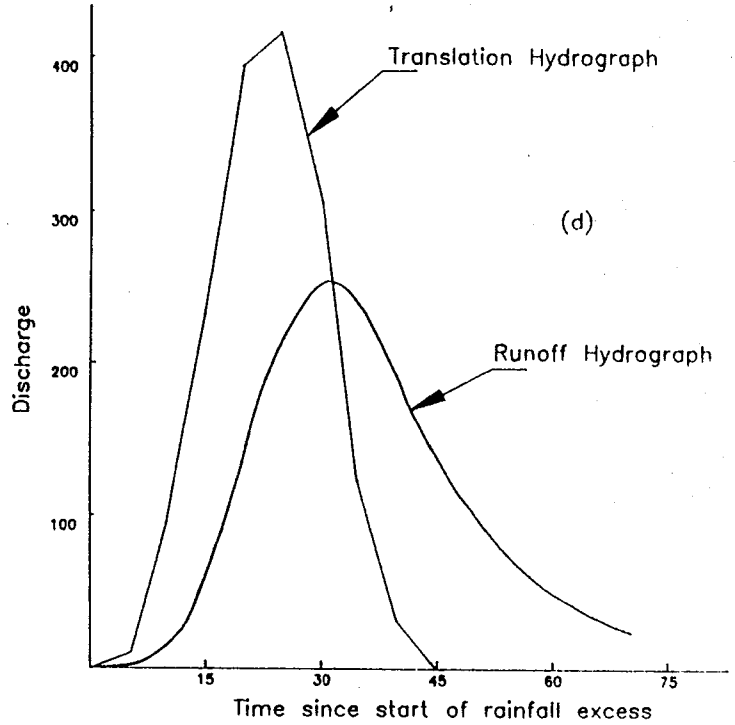


FIGURE 3

Example of storm hydrograph generation using the Clark Unit Hydrograph method

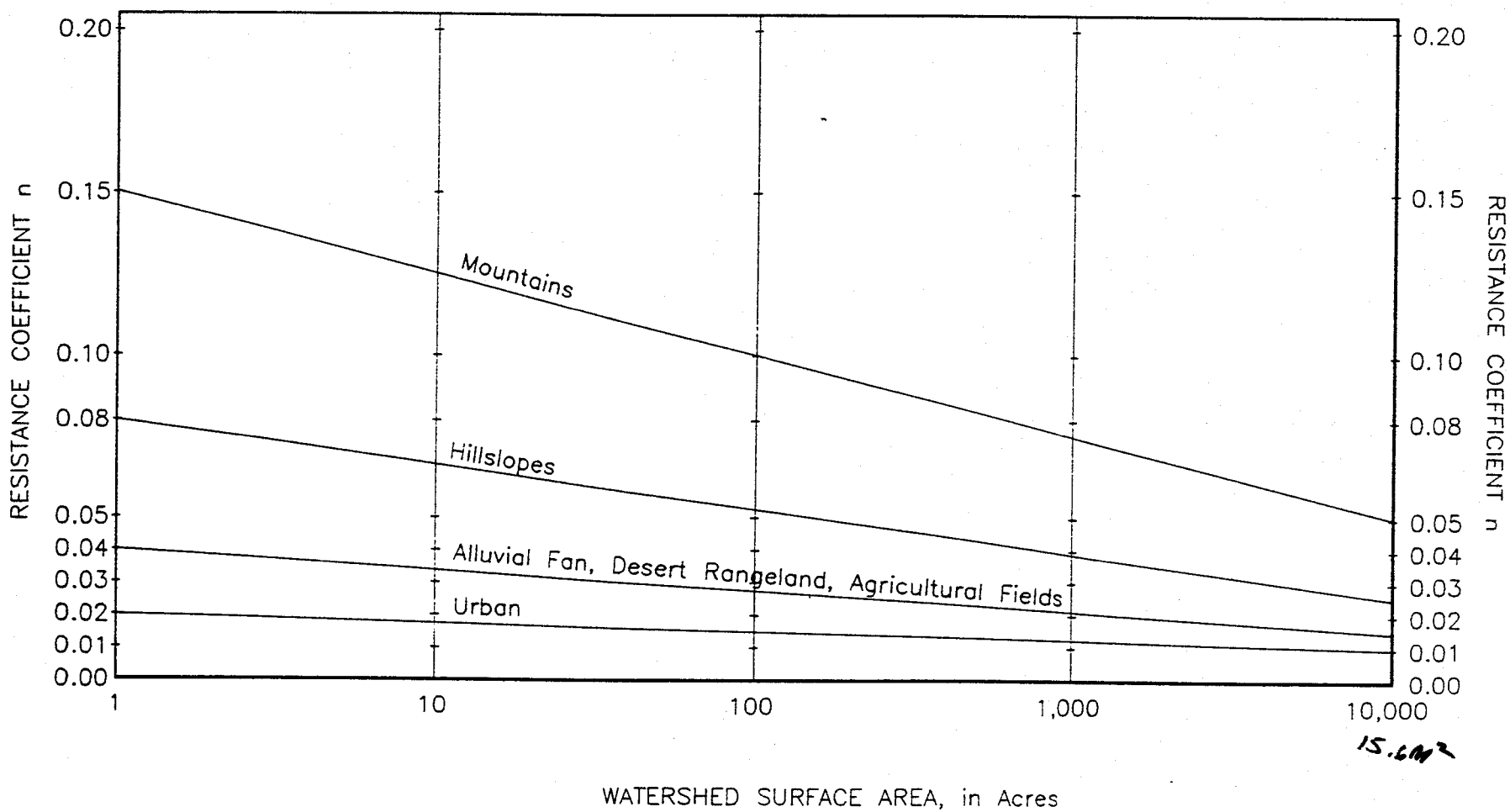


FIGURE 4

Resistance coefficient "n" as a function of watershed type and size

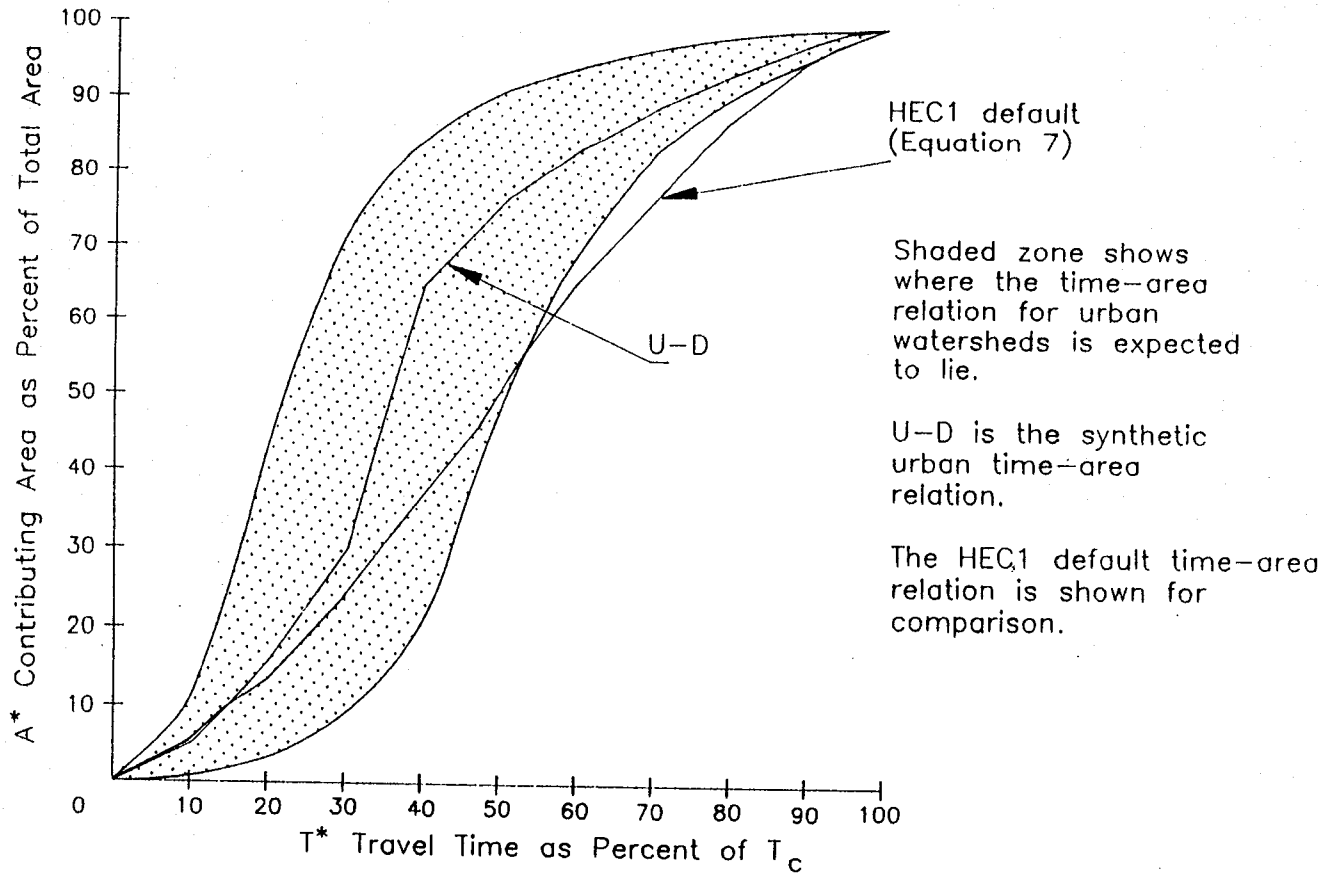
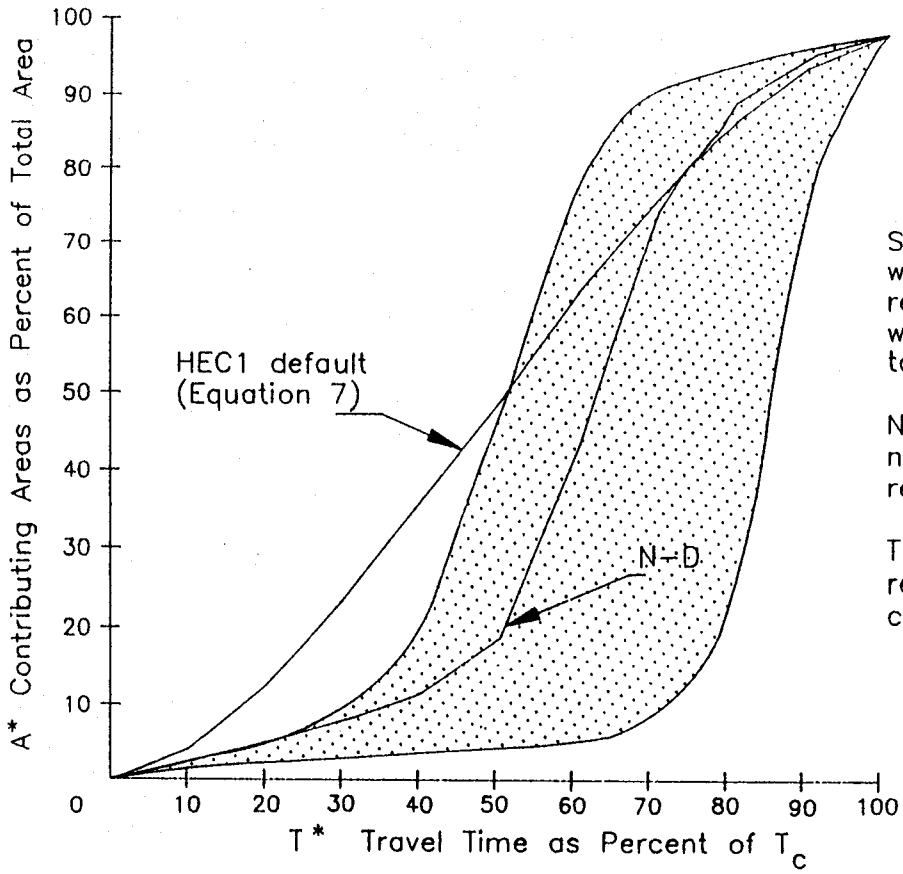


FIGURE 5
Synthetic Time – Area Relation for Urban Watershed



Shaded zone shows where the time-area relation for natural watersheds is expected to lie.

N-D is the synthetic natural time-area relation.

The HEC1 default time-area relation is shown for comparison.

FIGURE 6
Synthetic Time – Area Relation for Natural Watersheds

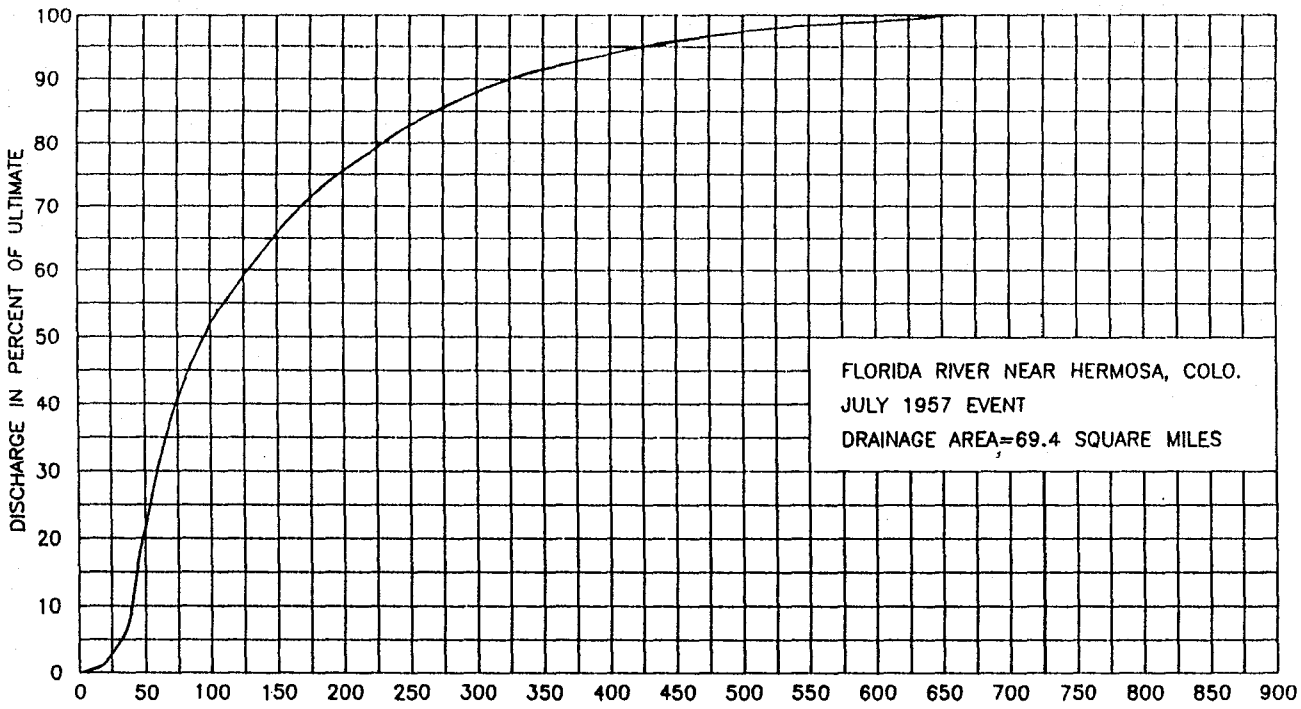


FIGURE 7

Example of S-Graph from Design of Small Dams (USBR, 1987)

% of Lag

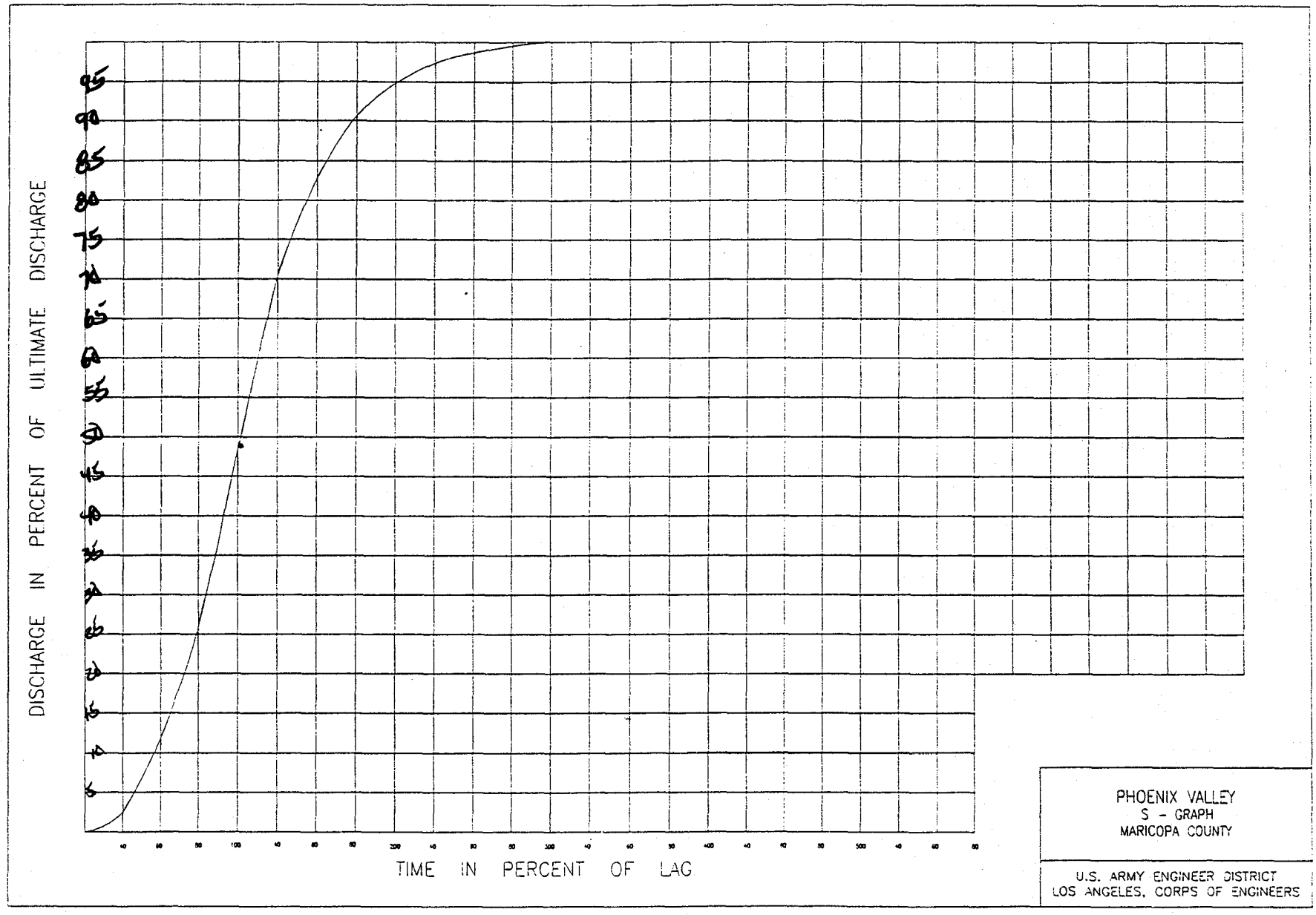

DISCHARGE IN PERCENT OF ULTIMATE DISCHARGE
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
TIME IN PERCENT OF LAG
PHOENIX VALLEY
S - GRAPH
MARICOPA COUNTY
U.S. ARMY ENGINEER DISTRICT
LOS ANGELES, CORPS OF ENGINEERS

FIGURE 8

DISCHARGE IN PERCENT OF ULTIMATE DISCHARGE
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
TIME IN PERCENT OF LAG
PHOENIX MOUNTAIN
S - GRAPH
MARICOPA COUNTY
U.S. ARMY ENGINEER DISTRICT
LOS ANGELES, CORPS OF ENGINEERS

FIGURE 9

		CONTRIBUTING AREA SQ. MI.	L MILES	L_{ca} MILES	S FT./MI.	LAG HOURS	ESTIMATED $\bar{n}$
1.	SAN GABRIEL RIVER AT SAN GABRIEL DAM, CA	162.0	23.2	11.6	350	3.3	0.050
2.	WEST FORT SAN GABRIEL RIVER AT COGSWELL DAM, CA	40.4	9.3	4.3	450	1.6	.050
3.	SAN ANITA CREEK AT SANTA ANITA DAM, CA	10.8	5.8	2.5	690	1.1	.050
4.	SAN DIMAS CREEK AT SAN DIMAS DAM, CA	16.2	8.6	4.8	440	1.5	.050
5.	EATON WASH AT EATON WASH DAM, CA	9.5	7.3	4.4	600	1.3	.050
6.	SAN ANTONIO CREEK NEAR CLAREMONT, CA	16.9	5.9	3.0	1017	1.2	.055
7.	SANTA CLARA RIVER NEAR SAUGAS, CA	355.0	36.0	15.8	140	5.6	.050
8.	TEMECULA CREEK AT PAUBA CANYON, CA	168.0	26.0	11.3	150	3.7	.050
9.	SANTA MARGARITA RIVER NEAR FALLBROOK, CA	645.0	46.0	22.0	105	7.3	.055
10.	SANTA MARGARITA RIVER AT YSIDORA, CA	740.0	61.2	34.3	85	9.5	.055
11.	LIVE OAK CREEK AT LIVE OAK DAM, CA	2.3	2.9	1.5	700	0.8	.070
12.	TUJUNGA CREEK AT BIG TUJUNGA DAM, CA	81.4	15.1	7.3	290	2.5	.050
13.	MURRIETA CREEK AT TEMECULA, CA	220.0	27.2	10.3	95	4.0	.050
14.	LOS ANGLES RIVER AT SEPULVEDA DAM, CA	152.0	19.0	9.0	145	3.5	.050
15.	PACOIMA WASH AT PACOIMA DAM, CA	27.8	15.0	8.0	315	2.4	.050
16.	ALHAMBRA WASH ABOVE SHORT STREET, CA	14.0	9.5	4.6	85	0.6	.015
17.	BROADWAY DRAIN ABOVE RAYMOND DIKE, CA	2.5	3.4	1.7	100	0.28	.015
18.	GILA RIVER AT CONNOR NO. 4 DAM SITE, AZ	2840.0	131.0	71.0	29	21.5	.050
19.	SAN FRANCISCO RIVER AT JUNCTION WITH BLUE RIVER, AZ	2000.0	30.0	74.0	32	20.6	.050
20.	BLUE RIVER NEAR CLIFTON, AZ	790.0	77.0	37.0	65	10.3	.050
21.	SALT RIVER NEAR ROOSEVELT, AZ	4310.0	160.0	66.0	45	18.6	.050
22.	NEW RIVER AT ROCK SPRINGS, AZ	67.3	20.2	9.7	141	3.1	.045
23.	NEW RIVER AT NEW RIVER, AZ	85.7	23.2	13.6	145	3.7	.045
24.	NEW RIVER AT BELL ROAD, AZ	187.0	47.6	20.7	83	5.3	.037
25.	SKUNK CREEK NEAR PHOENIX, AZ	64.6	17.6	10.0	89	2.4	.033

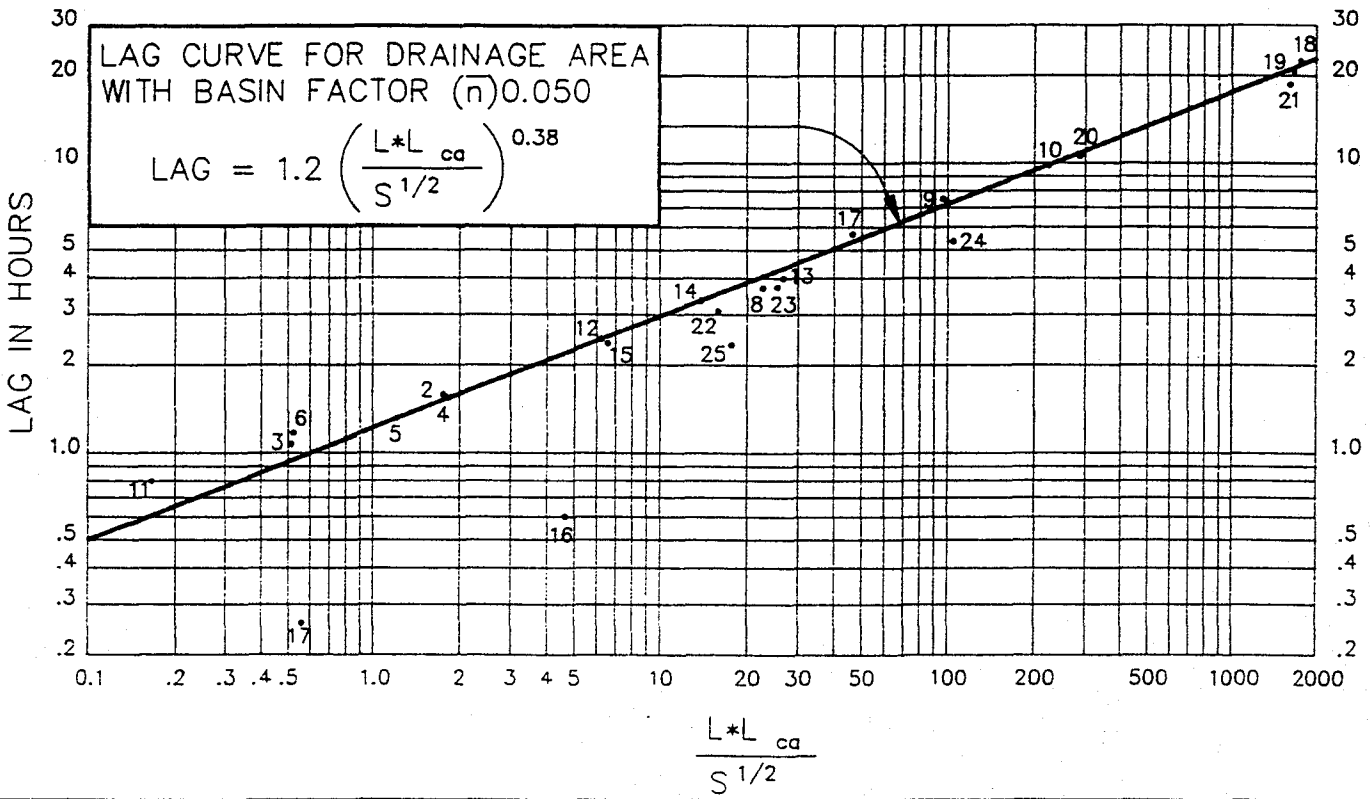
GUIDE FOR ESTIMATING BASIN FACTOR ($\bar{n}$)

$\bar{N}$ = 0.200: DRAINAGE AREAS HAS COMPARATIVELY UNIFORM SLOPES AND SURFACE CHARACTERISTICS SUCH THAT CHANNELIZATION DOES NOT OCCUR. GROUND COVER CONSISTS OF CULTIVATED CROPS OR SUBSTANTIAL GROWTHS OF GRASS AND FAIRLY DENSE SMALL SHRUBS, CACTI, OR SIMILAR VEGETATION. NO DRAINAGE IMPROVEMENTS EXIST IN THE AREA.

$\bar{n}$ = 0.050: DRAINAGE AREA IS QUITE RUGGED, WITH SHARP RIDGES AND NARROW, STEEP CANYONS THROUGH WHICH WATERCOURSES MEANDER AROUND SHARP BENDS, OVER LARGE BOULDERS, AND CONSIDERABLE DEBRIS OBSTRUCTION. THE GROUND COVER, EXLUDING SMALL AREAS OF ROCK OUTCROPS, INCLUDES MANY TREES AND CONSIDERABLE UNDERBRUSH, NO DRAINAGE IMPROVEMENTS EXIST IN THIS AREA.

$\bar{n}$ = 0.030: DRAINAGE AREA IS GENERALLY ROLLING, WITH ROUNDED RIDGES AND MODERATE SIDE SLOPES, WATERCOURSES MEANDER IN FAIRLY STRAIGHT, UNIMPROVED CHANNELS WITH SOME BOULDERS AND LODGED DEBRIS. GROUND COVER INCLUDES SCATTERED BRUSH AND GRASSES. NO DRAINAGE IMPROVEMENTS EXIST IN THE AREA.

$\bar{n}$ = 0.015: DRAINAGE AREA HAS FAIRLY UNIFORM GENTLE SLOPES WITH MOST WATERCOURSES EITHER IMPROVED OR ALONG PAVED STREETS. GROUND COVER CONSISTS OF SOME GRASSES WITH APPRECIABLE AREAS DEVELOPED TO THE EXTENT THAT A LARGE PERCENTAGE OF THE AREA IS IMPERVIOUS.



TERMINOLOGY

L = LENGTH OF LONGEST WATERCOURSE

L_{ca} = LENGTH ALONG LONGEST WATERCOURSE, MEASURED UPSTREAM TO POINT OPPOSITE CENTER CENTER OF AREA.

S = OVER-ALL SLOPE OF LONGEST WATERCOURSE BETWEEN HEADWATER AND COLLECTION POINT.

LAG = ELAPSED TIME FROM BEGINNING OF UNIT PRECIPITATION TO INSTANT THAT SUMMATION HYDROGRAPH REACHES 50% OF ULTIMATE DISCHARGE.

$\bar{n}$ = VISUALLY ESTIMATED MEAN OF THE n (MANNING'S FORMULA) VALUES OF ALL THE CHANNELS WITHIN AN AREA.

NOTE:
TO OBTAIN THE LAG (IN HOURS) FOR ANY AREA, MULTIPLY THE LAG OBTAINED FROM THE CURVE BY:

$\frac{\bar{n}}{0.050}$ OR 20n

FIGURE 10

LAG RELATIONSHIPS

U.S. ARMY CORPS OF ENGINEERS (1982)

APPENDIX 5-F

Review Comments and Correspondence with Dr. Herb Osborn

Herb Osborn

George,

If you want me to take another shot at this after you have considered my initial comments, send it down. I did, and do, have some problems with the current draft.

Herb

RAINFALL

2.1 GENERAL

Precipitation in Maricopa County is strongly influenced by variation in climate, changing from a warm and arid desert environment to a cool and moderately humid mountainous area. Mean annual precipitation ~~changes~~ ranges from about 7 inches in the Phoenix vicinity to more than 30 inches in the mountain regions of northern Maricopa County. ~~The~~ Precipitation is typically divided into two seasons, summer season (June through September) and winter (December through March), and is divided equally in depth. The storm patterns are generally categorized into three types, though any combination of the storm types is possible. Warm moist tropical air can move into Arizona at any time of the year, but most often in the summer months.

2.1.1 General Winter Storms. This type of storm normally moves in from the north Pacific Ocean ~~, which will~~ and produces light to moderate precipitation over relatively large areas. These storms occur between late October and May, producing the heaviest precipitation from December to early March. A pattern could last over several days with slight breaks in-between storms. ~~They generally represent~~ Because of orographic effects ~~and as a result~~ the mountain areas generally receive ~~a higher~~ more precipitation ~~as compared to~~ than the lower ~~elevation~~ desert areas. These storms are characterized by low intensity, long duration, ~~events over a~~ and large areal extent ~~, which can~~ but occasionally, with an additional surge of moisture from the southwest, can contribute to substantial runoff volumes and peak discharge on major river systems.

2.1.2 General Summer Storms.

The Pacific Ocean north of the equator and south of Mexico is a breeding ground for tropical storms. On the average, about 2 days tropical storms and hurricanes are spawned in this area ~~between~~ from June through early October. Most move in a ~~[illegible]~~ northwesterly direction and do not affect coastal areas. ~~[illegible]~~ Occasionally a storm ~~[illegible]~~ moves in a more northerly direction. ~~[illegible]~~ ~~[illegible]~~ The remnants of these storms can be caught up in the east coast circulation around a low in ~~the~~ southern California and can bring a persistent flow of moist tropical air into Arizona. The storm pattern consists of a band of fairly heavy rain cells within which there are of light to moderate rainfall. Whereas, general unstable flow ~~[illegible]~~ mountains cover the entire state, ~~[illegible]~~ general thunderstorms ~~[illegible]~~ are more localized along southeast to northwest axes of rainfall. They are similar to winter storms in that ~~[illegible]~~ higher elevations receive greater ~~[illegible]~~ rainfall because of orographic influences. The period of late September through October may have storms follow a track similar to the early general summer and autumn events.

2.1.2 General Summer Storms. General summer storms are the result of warm ~~and~~ moist tropical air ~~from the southeast or the southern region~~. As these systems ~~move into Arizona~~ they turn into tropical storms or hurricanes. They can occur any time from late June to mid-October, producing the most amount of rainfall during late July to early October. The storm pattern consists of local heavy cells, ~~and a~~ light to moderate rainfall, ~~which could~~ last one to three days. They are similar to general winter storms in that, ~~they also reflect~~ orographic influence, ~~with~~ higher elevations receiving most of the rainfall. These storms are characterized by high intensity, short duration events with an areal extent smaller than the winter storms. The generated peak ~~discharge~~ and volume from these storms are smaller than the winter storms, producing higher infiltration rates for large river systems. The period of late September through October may have storm patterns which are similar to ~~both~~ the winter ~~and~~ summer general storms.

2.1.3 Local Storms. These storms are ~~mostly~~ heavy downpours of rain over ~~small~~ areas of up to about 300 square miles for a time period ~~of~~ about 6 hours. They are typically associated with lightening and thunder, and are referred to as "thunderstorms" or "cloudbursts." While they can occur any time during the year, they are more frequent during summer months (July to September) when tropical moisture enters the area ~~on a frequent basis~~ from the southeast or ~~the~~ southern ~~region~~. These storms turn into longer duration events in late summer and may be associated with general summer storms. Local storms generally produce ~~a high~~ peak ~~events affecting~~ small areas. It can result in flash floods, and sometimes loss of life and property damage.

2.2 DEPTH-DURATION-FREQUENCY ANALYSIS

The commonly required precipitation parameters used in hydrologic modeling are depth, intensity, duration, spatial distribution and frequency of rainfall. The selection of a design frequency is often ~~an~~ influenced by administrative or economic decisions ~~rather than~~ as well as a hydrologic one. The duration of the design storm is usually a function of the size and topography of the watershed~~, though it too can be administratively selected~~. In general, one should insure that the design storm is of sufficient duration to allow the entire watershed to be contributing to the flow at the point of interest.

Spatial and temporal variation of precipitation, and lack of long term data in Maricopa County requires a procedure for rainfall input for design purposes. Regardless of ~~weather~~ whether the desired output is a peak discharge for sizing a conveyance structure, or a volume for sizing a basin, or the overland flow from a natural watershed, the designer needs to know the total depth of the design precipitation event and how it is structured both in time and space. However, selection of the appropriate event is constrained by availability and quality of data.

2.2.1 Source of Data. The ~~only~~ most comprehensive, available source of data for depth-duration-frequency analysis is the Precipitation-Frequency Atlas for Arizona, referred to as NOAA Atlas, published by the United States Department of Commerce, in 1973. ~~The climatological data utilized in the~~ NOAA Atlas is based on data ~~was the source~~ available through 1969. Until a more up to date data base becomes available, NOAA Atlas is to be used for all design purposes within Maricopa County.

2.3 DEPTH-AREA RELATION

The problem of spatial variability of rainfall is quite difficult to handle because of an inverse law ~~due to~~ limited network of raingauge ~~coverage~~. Work in the southwest by the United States Deparment of Agriculture, ~~and~~ Agricultural Research Service indicates that high intensity storms do not have large areal extents, Most ~~usually less than one square mile~~. runoff producing thunderstorm cells less than 20 square miles.

The above argument ~~would~~ supports development of areal reduction curves which reflect the nature of the thunderstorms in the southwest. However, drainage facilities such as storm drains, channels, and culverts should be sized to handle the peak discharge resulting from the design storm critically centered above them so as to create the worst case discharge. Only retention/detention facilities serving as an outfall for a large contributing area would appear to justify areal reduction of the depth. ~~Then~~ areal reduction seems appropriate for runoff calculations of contributing areas larger than 10 square miles.

2.3.1 Procedure For Depth-Area Adjustments. The Depth-Area Reduction Curves in HYDRO-40 are to be used. These curves originally developed by Osborn, Lane, and Myers (1980) are based on data from Walnut Gulch, Arizona and were selected to be appropriate for use in Maricopa County. Figures *** to *** along with the following procedure are for the areal reduction curves:

b. ~~a.~~ Decide if ~~Justify that~~ areal reduction is necessary.

a. ~~b.~~ Determine ~~Indicate~~ the size of the contributing drainage area.

c. Select the appropriate design storm (SECTION 2.4). CALCULATE AVERAGE DEPTH. If the storm duration is greater than 6-hour, use the 6-hour curve.

d. Select the reduction coefficient from the appropriate curve.

e. Multiply the reduction coefficient by the rainfall depth.

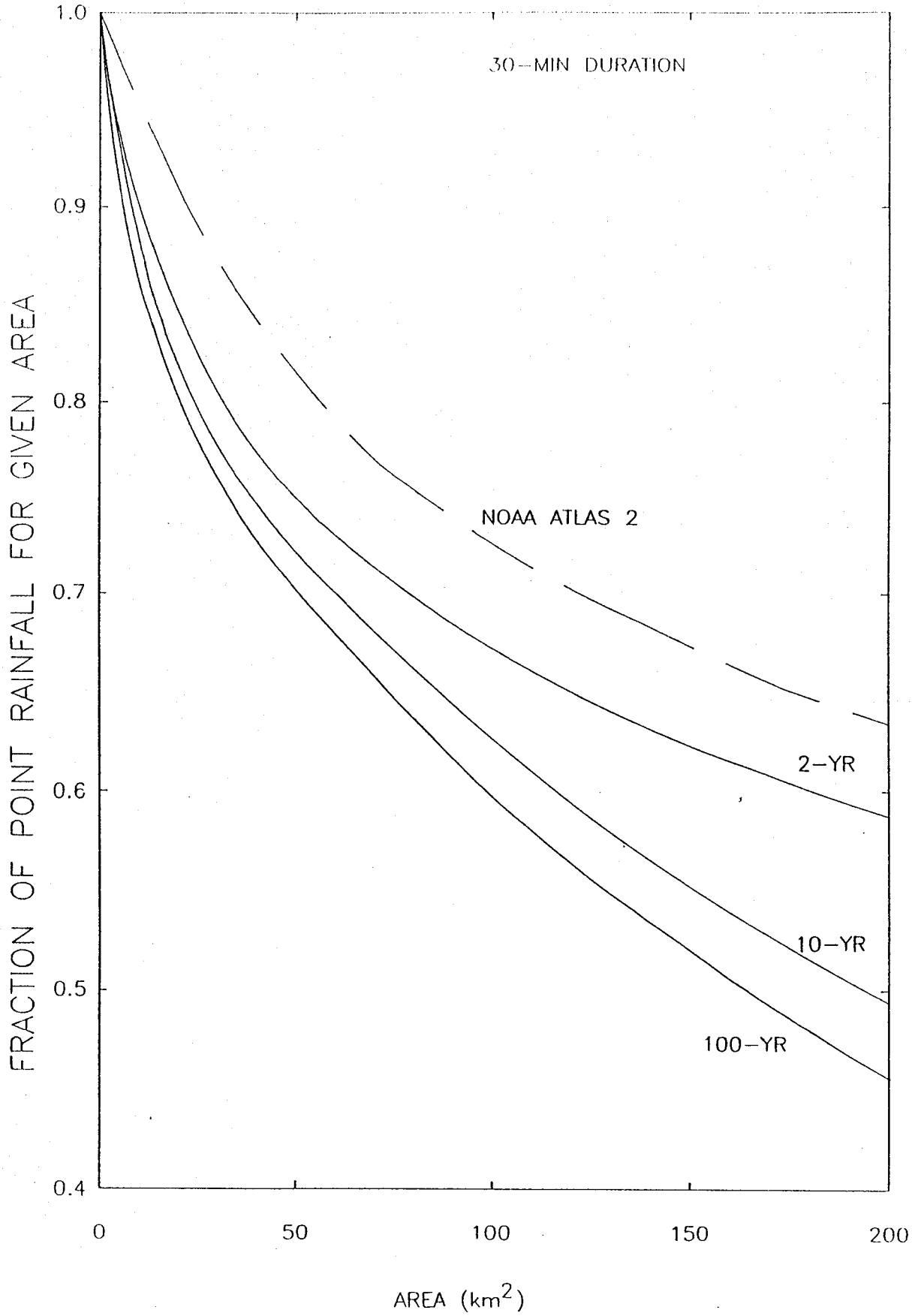


FIGURE Point-to-area conversion rations for 30-min duration rainfalls for selected frequencies.

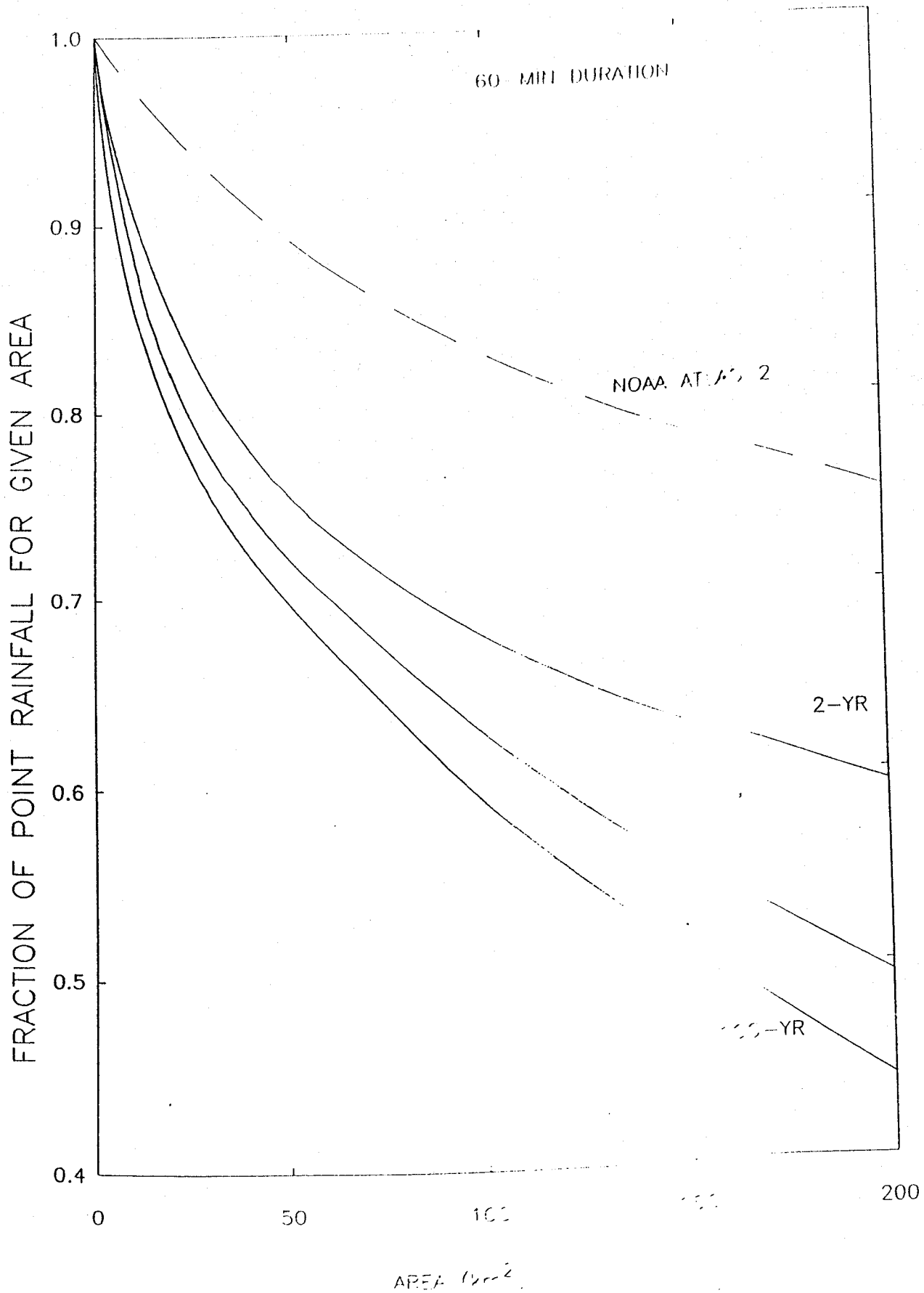


FIGURE Point-to-area conversion [illegible] duration rainfalls for selected frequencies.

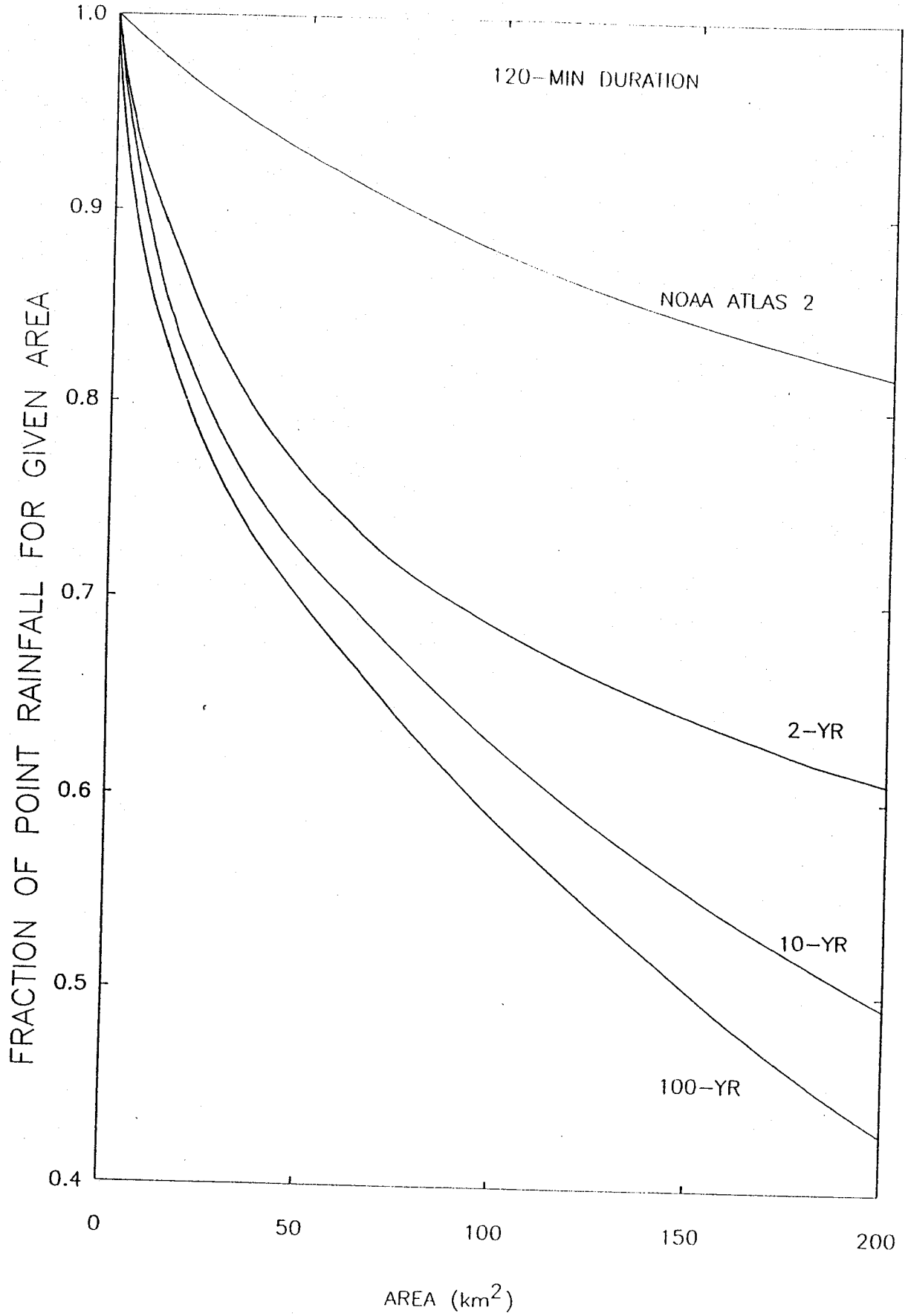


FIGURE Point-to-area conversion ratios for 2-h duration rainfalls for selected frequencies.

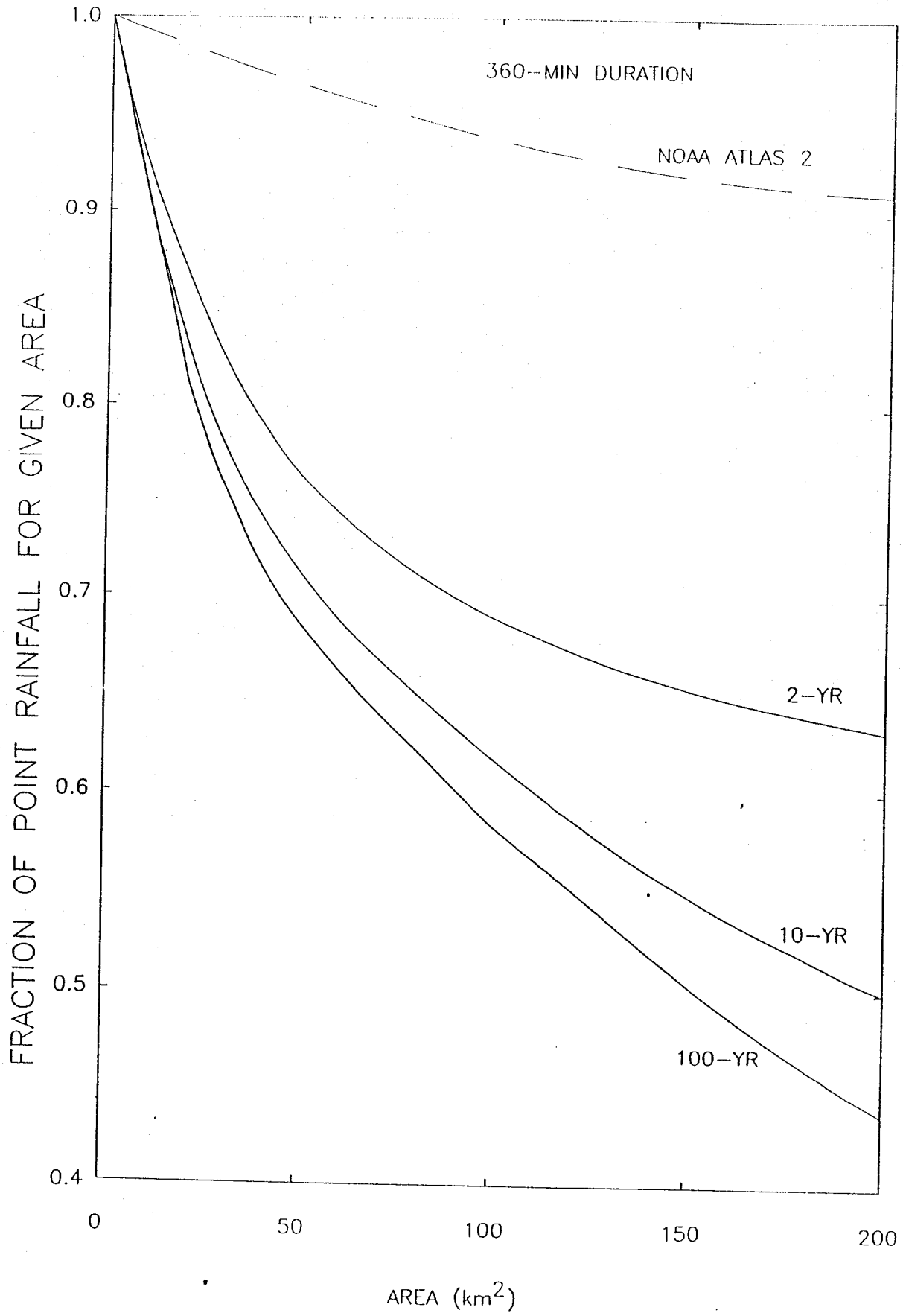


FIGURE Point-to-area conversion ratios for 6-h duration rainfalls for selected frequencies.

4 2.4 SELECTION OF APPROPRIATE DESIGN STORM

The design hydrologist must specify the appropriate rainfall frequency, duration, depth and the corresponding time distribution for any design purposes which require calculation of runoff volume and peak discharge. The only exception to the above statement is with the application of the Rational Formula where a time distribution is not required. For the purposes of the Hydrology Manual the following guidelines are ~~to be~~ used to develop~~ing~~ a design storm:

1) Using Plates 1-12, read rainfall depths for 2-, 5-, 10-, 25-, 50, and 100-year return periods, for 6- and 24-hour durations, employing linear interpolation between isolines when required. The numbers on the isolines represent tenths of inches of rainfall (i.e, 23=2.3 inches).

2) Using Figure ***, verify the selected rainfall depths. As indicated in NOAA Atlas (page 16) the obtained rainfall depths are to be verified by plotting them on the return-period diagram, because of the possibility of error that may have occurred during printing or obtaining of the values. After positioning the data points on Figure ***, fit a straight line to the 6-hour data and another one to the 24-hour data. Check for any deviations from the lines, then pick the corrected values located on the line.

3) At this time the data should include 6-hour and 24-hour durations for all frequencies with the exception of 1-year values. If for any reason there is a need for the 1-year distribution then use:

$$P_1 = P_2 - .16(P_{100} - P_2)$$

where P_2 and P_{100} are the 100-year and the 2-year frequencies, respectively.

4) A particular design may require a duration different from 24-hour or 6-hour. For example retention design requires a 100-year frequency, 2-hour duration design storm. In such cases the following procedure is ~~should be~~ used. Let X1, X2,...,X24 be the estimated precipitation for durations of 1, 2, ...24 hour, respectively.

A. Compute $X_{12} = X_{24} - .51(X_{24} - X_6)$

B. Compute $X_1 = 2X_6 - X_{24}$

C. Check to see that $(X_6 - X_1) = (X_{24} - X_6)$

D. Compute $X_3 = X_6 - .55(X_6 - X_1)$

E. Compute $X_2 = X_6 - .77(X_6 - X_1)$

F. Check to see that $(X_3 - X_2) = .22(X_6 - X_1)$

G. Compute $X_{30\ minutes} = .79X_1$

H. Compute $X_{15\ minutes} = .57X_1$

~~In the above procedure,~~ Unless ~~if~~ the designer needs the rainfall depth for less than a 2-hour duration, there is no need to continue beyond that point.

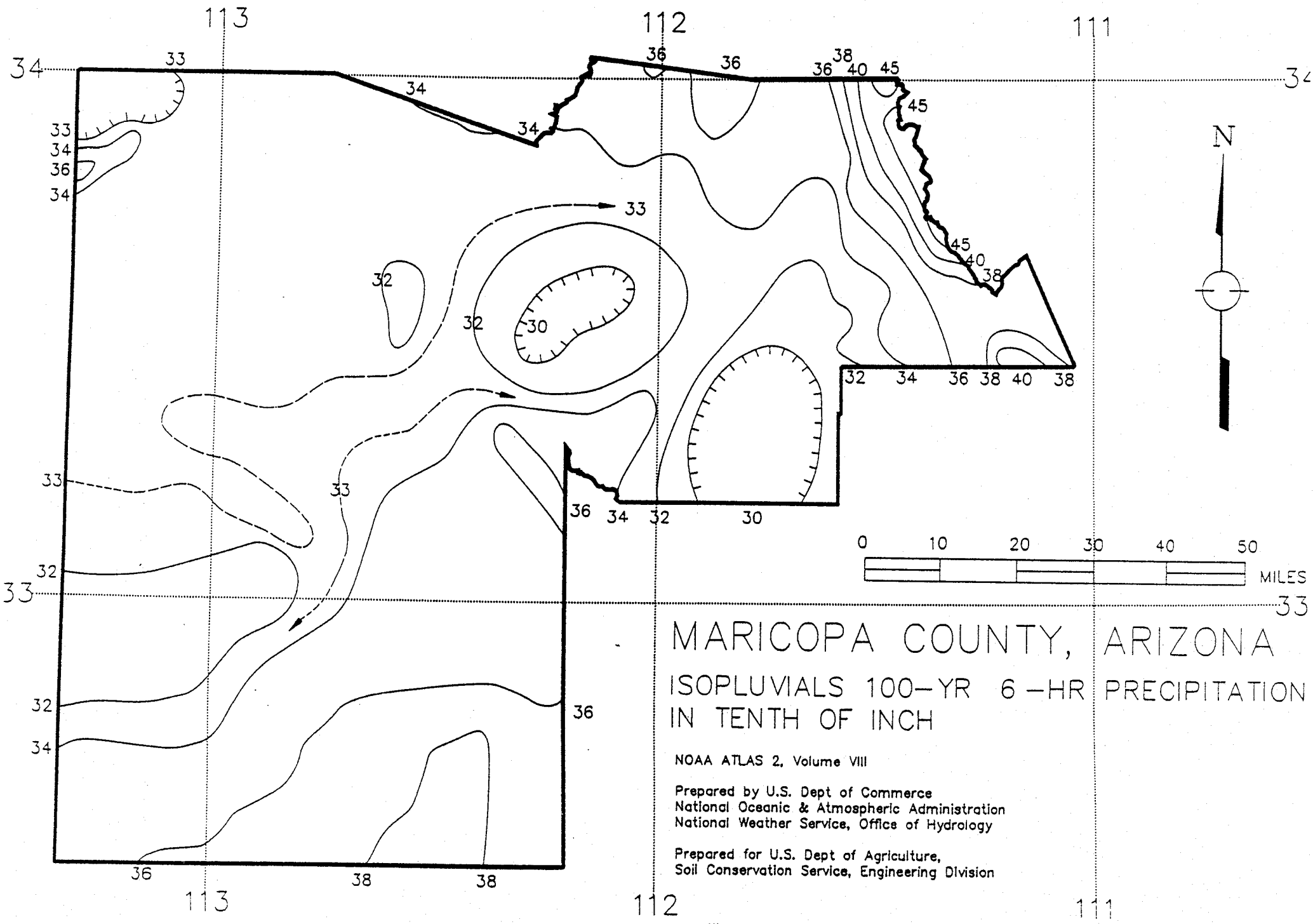
2.5 DEVELOPMENT OF DESIGN STORM DISTRIBUTIONS

The design storms for use in Maricopa County will be a 2-hour, 6-hour, or a 24-hour distribution. The 2-hour storm is ~~to be~~ used for retention design purposes. The 6-hour storm is for all hydrologic analysis for areas of up to 540 square miles. The 24-hour storm should be used for very large, natural watersheds (> 540 square miles).

The following isopluvial maps of Maricopa County (from NOAA Atlas 2, Volume VIII, Arizona) are to be included in the manual:

2-yr, 6-hr
2-yr, 24-hr
5-yr, 6-hr
5-yr, 24-hr
10-yr, 6-hr
10-yr, 24-hr
25-yr, 6-hr
25-yr, 24-hr
50-yr, 6-hr
50-yr, 24-hr
* 100-yr, 6-hr
100-yr, 24-hr

* This figure is shown in the review draft as an example of all the isopluvial maps that are to be contained.



MARICOPA COUNTY, ARIZONA

ISOPLUVIALS 100-YR 6-HR PRECIPITATION IN TENTH OF INCH

NOAA ATLAS 2, Volume VIII

Prepared by U.S. Dept of Commerce
National Oceanic & Atmospheric Administration
National Weather Service, Office of Hydrology

Prepared for U.S. Dept of Agriculture,
Soil Conservation Service, Engineering Division

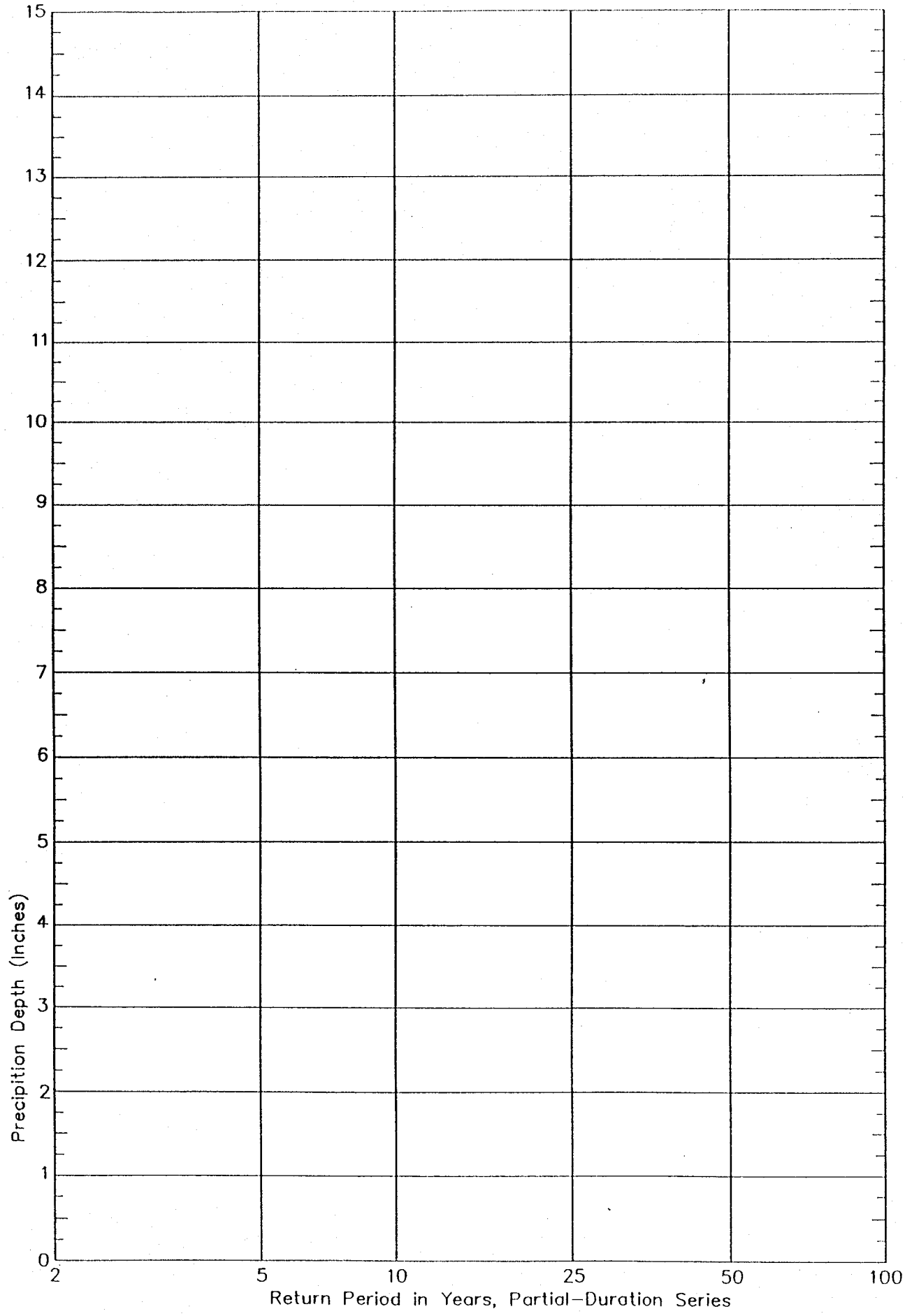


Figure Precipitation depth versus return period for partial--duration series

2.5.1 2-hour Storm distribution. If the Rational Method is ~~to be~~ used, there is no need for a time distribution. The selected depth should be used based on the procedures in Chapter 3 of this manual. If a time distribution is required, i.e., rainfall input for the HEC-1 model, the dimensionless 2-hour cumulative rainfall distribution of Table *** should be used. These values then would be direct input into HEC-1, assuming a 15-minute intensity as the rainfall time step. A graphical representation of this distribution is also shown on Figure ***.

2.5.2 6-hour Storm Distribution. The 6-hour rainfall distribution is a function of drainage area size. ~~For this purpose~~ 5 dimensionless rainfall distributions were developed ~~These distributions are a~~ function of drainage ~~area size of up to 540 square~~ miles. A dimensionless rainfall pattern can be selected from Table *** for direct input into HEC-1, once the size of the drainage area is determined. In this case, also, the 15-minute intensity is ~~to be~~ used for the rainfall time step. Figure *** illustrates graphical representations of the dimensionless rainfall patterns.

2.5.3 24-hour Storm Distribution. The 24-hour storm distribution in Table *** can be used for large, natural watershed areas (> 540 square miles). The rainfall intensity ~~would be of~~ 15-minute for rainfall time step computations. If the designer ~~would~~ prefer another method ~~such~~ as SCS TYPEII, ~~which~~ would better reflect the local conditions, then it should be used. Figure *** shows the graphical representation of the 24-hour dimensionless rainfall distribution.

Time Elapsed (minutes)	% Rainfall Depth
0	.0
15	4.2
30	11.7
45	25.7
60	51.2
75	77.6
90	88.9
105	95.6
120	100.0

Table. 2-hour storm distribution for retention design.

Form a 6-hour duration design storm the following pattern # versus drainage area FIG. #1 should be used in Table. .

For drainage area of up to 10 square miles use pattern #1.

For drainage area of up to 35 square miles use pattern #2.

For drainage area of up to 110 square miles use pattern #3.

For drainage area of up to 270 square miles use pattern #4.

For drainage area of up to 540 square miles use pattern #5.

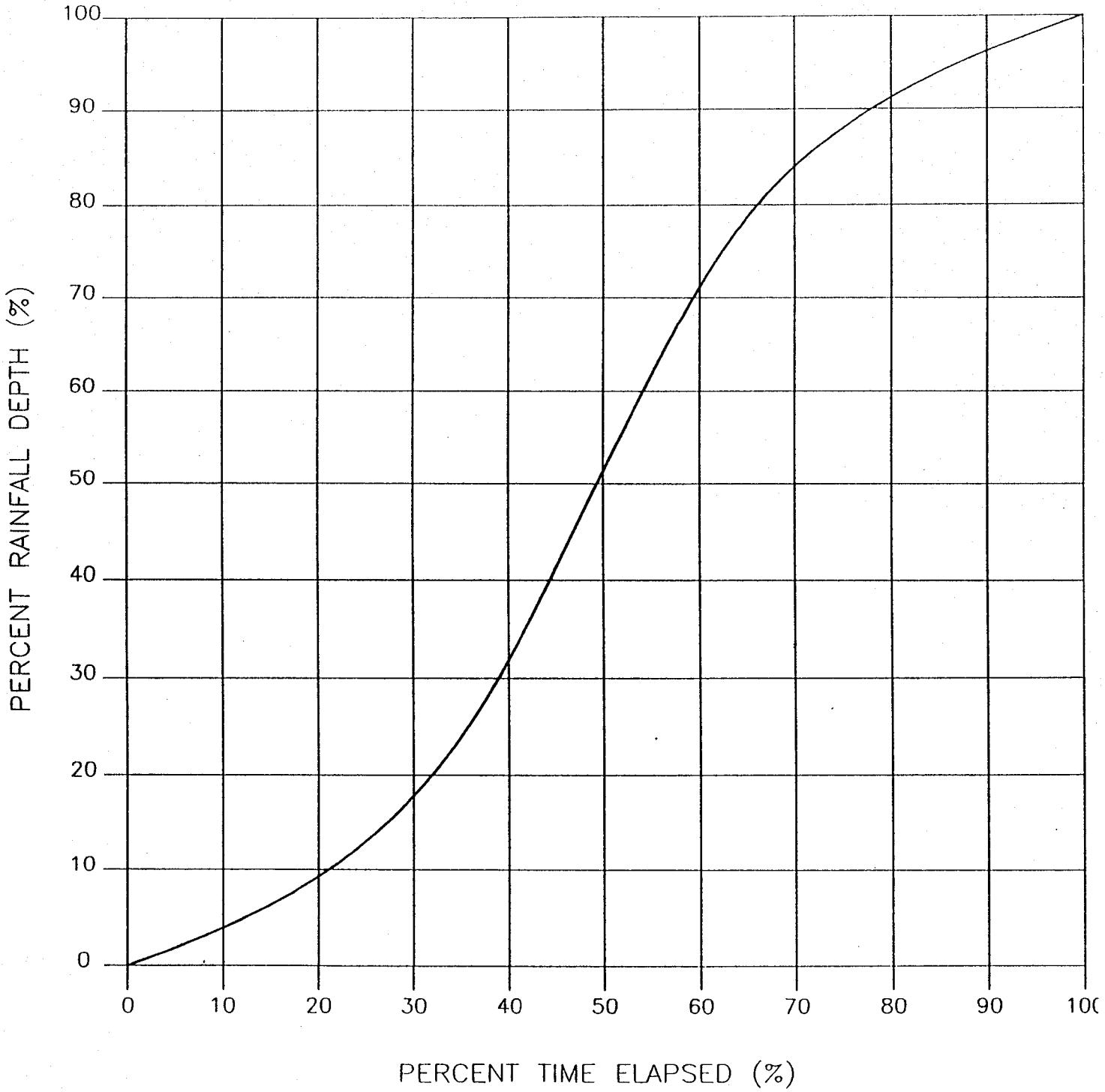


FIGURE 2-HOUR MASS CURVE
FOR RETENTION DESIGN
MARICOPA COUNTY

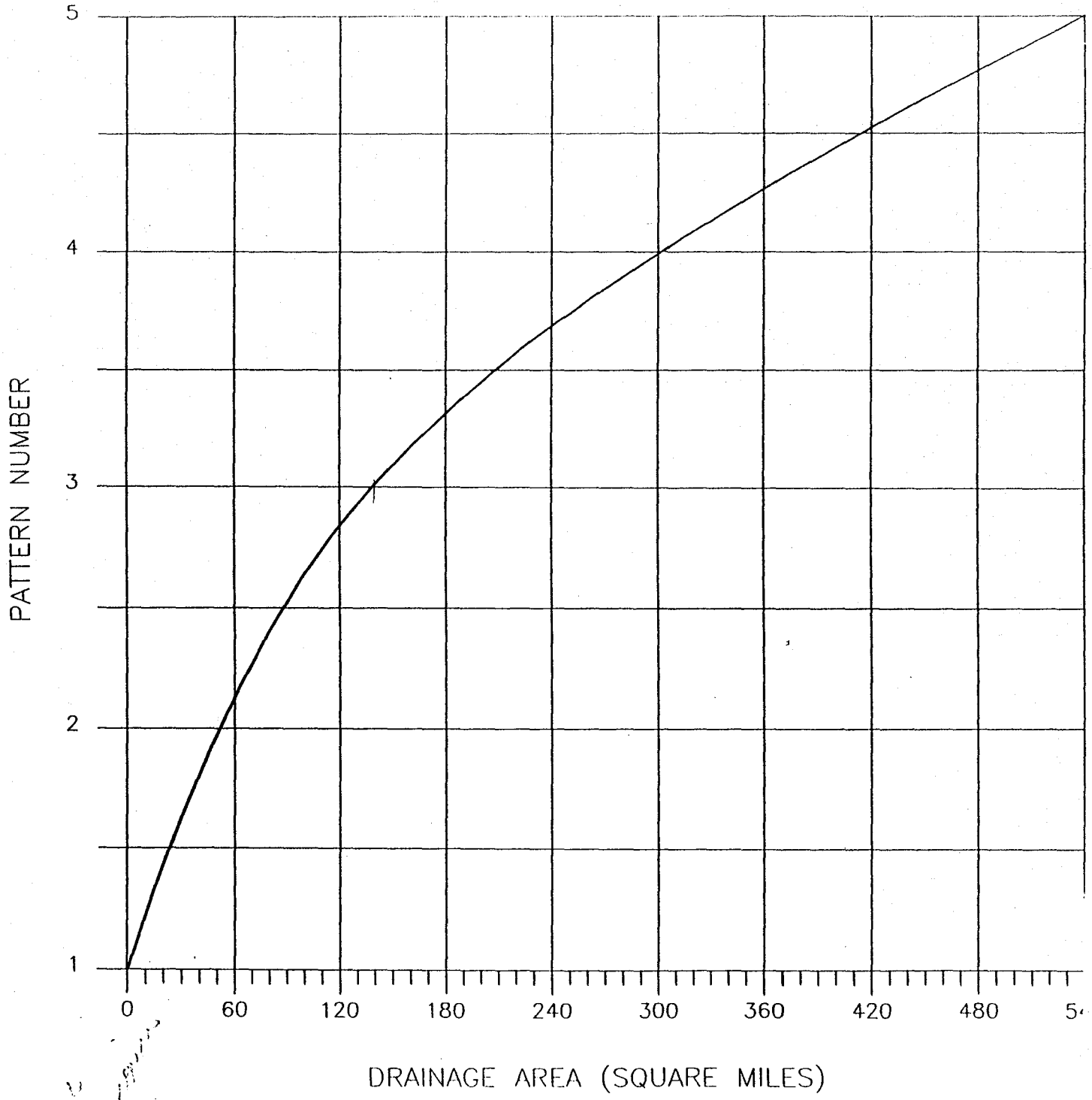


FIGURE AREA VERSUS PATTERN NUMBER FOR MARICOPA COUNTY

Time Elapsed (min)	Pattern #1	Pattern #2	Pattern #3	Pattern #4	Pattern #5
0	.0	.0	.0	.0	.0
15	.6	.6	1.5	2.1	2.4
30	1.2	1.2	2.0	3.5	4.3
45	1.7	2.0	3.0	5.1	5.9
60	2.7	3.1	4.8	7.1	7.8
75	3.7	3.9	6.3	8.7	9.8
90	4.7	4.9	7.6	10.5	11.9
105	5.6	5.7	9.0	12.5	14.1
120	6.7	6.7	10.5	14.3	16.2
135	7.5	7.6	11.9	16.0	18.6
150	8.7	8.7	13.5	17.9	21.2
165	9.9	10.0	15.2	20.1	23.9
180	11.1	12.0	17.5	23.2	27.1
195	12.3	16.3	22.2	28.1	32.1
210	20.8	25.2	30.4	36.4	40.8
225	38.5	45.1	47.2	50.0	51.5
240	84.8	69.4	67.0	65.8	62.7
255	93.3	83.7	79.6	77.3	73.5
270	94.6	90.0	86.8	84.1	81.4
285	95.8	93.8	91.2	88.8	86.4
300	96.9	96.7	94.6	92.7	90.7
315	98.1	98.5	97.4	95.8	94.5
330	98.5	99.0	98.0	96.5	95.5
345	99.0	99.0	98.7	97.6	96.9
360	100.0	100.0	100.0	100.0	100.0

Table. 6-hour distributions. Pattern # represents %rainfall depth.

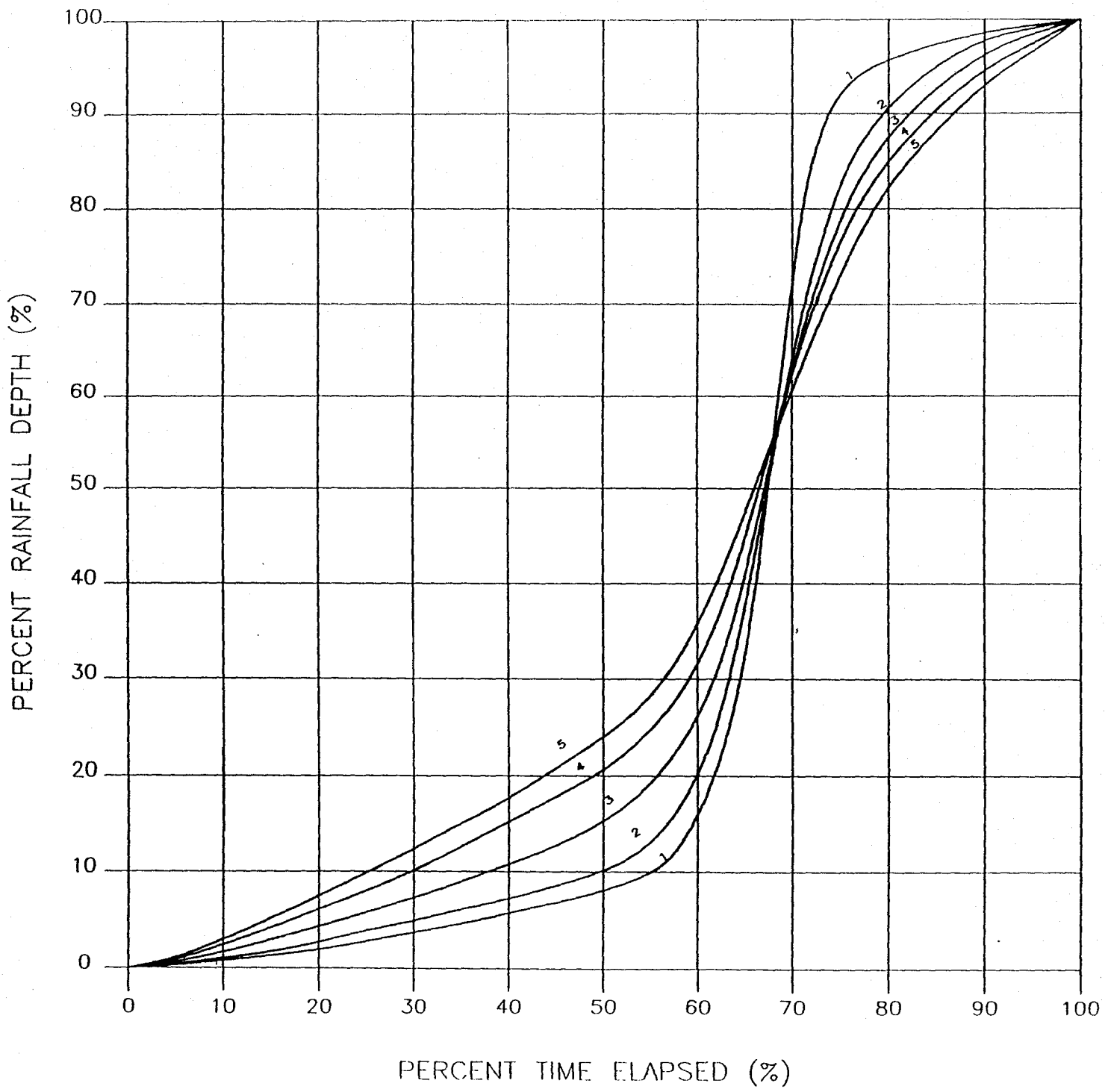


FIGURE 6-HOUR MASS CURVES FOR MARICOPA COUNTY

Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth	Elapsed Time	%Rainfall Depth
0	.0	375	12.4	735	28.4	1095	82.7
15	.6	390	13.0	750	29.6	1110	84.0
30	1.2	405	13.6	765	30.8	1125	85.3
45	1.8	420	14.1	780	31.3	1140	86.4
60	2.4	435	14.6	795	34.3	1155	87.5
75	2.8	450	15.2	810	36.4	1170	88.6
90	3.4	465	15.6	825	38.6	1185	89.8
105	3.8	480	16.3	840	40.8	1200	90.7
120	4.4	495	16.8	855	43.5	1215	91.6
135	4.7	510	17.4	870	46.2	1230	92.5
150	5.1	525	18.0	885	48.8	1245	93.6
165	5.5	540	18.6	900	51.5	1260	94.5
180	5.9	555	19.2	915	54.3	1275	94.8
195	6.4	570	20.0	930	57.1	1290	95.0
210	6.8	585	20.6	945	59.9	1305	95.2
225	7.3	600	21.2	960	62.7	1320	95.5
240	7.8	615	21.9	975	65.4	1335	95.8
255	8.3	630	22.5	990	68.1	1350	96.2
270	8.8	645	23.2	1005	70.8	1365	96.6
285	9.3	660	23.9	1020	73.5	1380	96.9
300	9.8	675	24.7	1035	75.5	1395	97.6
315	10.3	690	25.5	1050	77.4	1410	98.4
330	10.9	705	26.3	1065	79.4	1425	99.2
345	11.4	720	27.1	1080	81.4	1440	100.0
360	11.9						

Table . 24-hour design storm distribution.

TELEPHONE LOG

PROJECT: FCD #5

DATE: 1 March 89

TOPICS: rainfall review

TO/~~FROM:~~ Herb Osborn

ORGANIZATION:

CITY: Tucson

PHONE NO: 602-8834517

ITEMS DISCUSSED:

Rainfall depth - NOAA Atlas OK for now. Have we considered the Osborn & Renard (ASCE ID, 1988) work on short duration rainfall? Yes, no change to NOAA now because MC will probably reanalyze rainfall comprehensively. OK

Rainfall Dist. - He has some problem over the 6-hr distribution, but he also recognizes that it is defensible, and that there is some interest to have a criteria that is compatible with the Corps.

Area Reduction Factor - The Walnut Gulch curves are also applicable to Maricopa County.

General Comment - The description of the criteria must be free of errors or else future reviewers and users that may be critical & will use this against us. There will be a lack of credibility associated with a faulty manual.

FURTHER ACTIONS REQUIRED:

Send him a revised draft, when available.

Discuss a "consultant" review with him.

APPENDIX 5-G

Review Comments and Correspondence with Mr. C.O. Clark

C. O. CLARK
Consulting Engineer
Tulsa, Oklahoma
74114
2121 E. 22nd Pl.
January 10, 1989

Mr. George V. Sabol
Consulting Engineer
1351 East 141st Avenue
Brighton, CO 80601

Dear Mr. Sabol,

Reference is to your letter of December 30, 1988, transmitting for requested review certain pages of the anticipated Hydrology Manual for the Flood Control District of Maricopa County, Arizona, near Phoenix and Sun City.

It has been a pleasure to give this task top priority, and to produce a perhaps severely edited mark-up of your transmitted copy. I hope you will find some useful guides to changes you may wish to make in your final presentation.

That draft is returned herewith.

As this is a major undertaking with significant technical, social, and economic implications to Maricopa County, it is important that certain aspects start out with technical procedures accurate in details that will be sound at higher levels of consideration than are immediately intended. You are wise to provide for serious review.

As your readers will be eventually able to ascertain and appreciate, the Unit Hydrograph Procedures are the only tool capable of use with changing conditions of County Activity, from Natural Conditions that have existed to Changed Conditions that may come about. It should be obvious that the drainage by ditches and streets reduces natural storage of drained water and increases velocities of flow and removal, and that this means a reduction of time of concentration and of the storage constants discussed. It should also be obvious that contoured street development and lengthened street alignment around descending grades have the opposite influence, to increase storage and time of concentration, and hence reduce flow rates which must be borne or accommodated. Unit Hydrograph methods on small areas, even of five square miles, can be feasible to show how much can be thusly accomplished. Eventually, I expect, this will also be important to Maricopa County, and in the State of ARizona, where conserving water and using it for the highest priority of usefulness is a matter of state law.

In one case in Tulsa County, OK., such a unitgraph usage on 300- and 500 acres showed need for storage provision, which, unmade found its storage nevertheless in the over flowed bottom floors of high-rise buildings, damage of $1,000,000 in one flood in one case, and abandonment of the intended use of a major international oil company in the other. The largest loss that I know about through machine use of faulty hydrologic considerations is $4,000,000, in one event.

It is therefore of very high economic and commercial significance.

Since this dissertation is part of this commercial activity, the professional fee

is Four Hundred and Twenty Five Dollars, payable at your convenience.

Thank you for the opportunity to assist you in this vital matter. I would be pleased to see a revised copy of your submission.

Professionally yours,

C. O. Clark

C. O. Clark

C.O. Clark

UNIT HYDROGRAPH PROCEDURES 1 Dec 88

PRELIMINARY
For Review Only

General

Rainfall excess can be transposed, or routed, from a watershed to produce a storm discharge hydrograph at a downstream location (concentration point). ~~by one of~~ Two methods are: 1) hydraulic routing involving the complete or some simplified form of the equations of motion, that is, the momentum equation plus the continuity equation; or 2) hydrologic routing involving the application of the continuity equation. Kinematic wave routing, as available in HEC-1, is an example of hydraulic routing. Hydrologic routing is usually accomplished by either direct application of the equation of continuity;

$$I - O = dS/dt \qquad (1)$$

or, a graphical procedure such as the application of the principles of the unit hydrograph. Examples of hydrologic routing by direct application of the equation of continuity are the Clark Unit Hydrograph (Clark, 1945), the Santa Barbara Urban Hydrograph (Stubchaer, 1975), and the Single Linear Reservoir Model (Pedersen and others, 1980). Both the Santa Barbara Urban Hydrograph and the Single Linear Reservoir Model are simplified (one parameter) versions of the Clark Unit Hydrograph (three parameter) procedure (Sabol and Ward, 1985). Examples of unit hydrographs that require a graphical procedure are the SCS Dimensionless Unit Hydrograph, Snyder's Unit Hydrograph, S-graphs, and unit hydrographs that are derived directly from recorded runoff data. Graphical or tabular methods of routing rainfall excess by unit hydrographs are very amenable to hand-calculation methods by those who have seen the problem which were common practice prior to the ready availability of computers. Direct mathematical solution of the equation of continuity, such as the Clark Unit Hydrograph, is more rapidly ~~efficiently~~ conducted with computers and appropriate computer programs, at much greater cost for the computer.

The procedure that is recommended for routing rainfall excess in Maricopa County is either the Clark Unit Hydrograph or the application of selected S-graphs. The Clark Unit Hydrograph

procedure, has been ~~applied~~ studied and proven on real watersheds from small to hundreds of sq. miles. ~~As~~ described herein, it is limited to watersheds or sub-basins less than about 5 square miles in size. The application of S-graphs is recommended for use with major watercourses in Maricopa County. An S-graph can be made from a Clark Unit Hydrograph, or by less formal approximations. The ~~preference~~ size limitation herein chosen has political rather than physical origins.

A unit hydrograph is a graph of the time distribution of runoff from a specific watershed as the result of one inch of rainfall excess that is distributed uniformly over the watershed and that is produced during a particular time interval of the rainfall (duration). It is ~~noted~~ cautioned that the duration of rainfall excess is not generally equal to the rainfall duration. In that a unit hydrograph is derived from or is to be representative of a specific watershed, it is a lumped parameter and it reflects ~~all~~ several of the physical characteristics of the watershed that will affect the time rate at which rainfall excess will drain from the land surface, [excluding operable elements like reservoirs, lakes, and obstructions]

The principles of the unit hydrograph were introduced by Sherman (1932). Sherman observed that for a watershed all hydrographs resulting from a rain of the same duration have the same time base, and that ordinates of each storm hydrograph from the watershed are proportional to the volume of runoff if the time and areal distributions of the rainfalls are similar. The principles that are applied when using an unit hydrograph are:

1. For a watershed, hydrograph base lengths are equal for rainfall excesses of equal duration.
2. Hydrograph ordinates are proportional to the amount of rainfall excess.
3. A storm hydrograph can be developed by linear superposition of incremental hydrographs.

Application of these principles ~~requires~~ implies, applies (or assumes) a linear relation between watershed outflow and storage within the watershed, $S = KO$. However, or compensating complex elements. Mitchell (1962) has shown that nonlinear storage, $S = KO^x$, is a condition that occasionally occurs in natural watersheds. A method has been developed by Shen (1962) to evaluate the linearity of the storage-outflow relation for

gaged watersheds. Mitchell (1972) developed the model hydrograph for use in watersheds that have nonlinear storage-outflow characteristics. Presently, however, there is no simple method that has been devised to evaluate the non-linearity of an ungaged watershed, and the assumption of linearity is a practical necessity in virtually all practical cases. [Note: A cavernous system under a street system, or a sewered system, is such a system, but its solution is not generally of rural necessity]

Clark Unit Hydrograph

Theory

Hydrologic routing by the Clark Unit Hydrograph method is analogous to the routing of an inflow hydrograph through a reservoir. This analogy is illustrated in Figure 1. The inflow hydrograph, called the translation hydrograph in the Clark method, is determined from the temporal and spatial distribution of rainfall excess over the watershed. The translation hydrograph is then routed by a form of the equation of continuity

$$O_i = CI_i + (1 + C)\, O_{i-1} \qquad (2)$$

$$\text{where } C = \frac{2\,dt}{2R + dt} \qquad (3)$$

O_i is the instantaneous flow at the end of the time period, O_{i-1} is the instantaneous flow at the beginning of the time period, I_i is the ordinate of the translation hydrograph, dt is the computation time interval, and R is the watershed storage coefficient. The Clark Unit Hydrograph of duration dt is obtained by averaging two instantaneous unit hydrographs spaced dt units apart

$$Q_i = 0.5(O_i + O_{i-1}) \qquad (4)$$

where successive values of Q_i are the ordinates of the Clark Unit Hydrograph.

The Clark method uses two numeric parameters, T_c and R, and a graphical parameter, the time-area relation. The first parameter, time of concentration (T_c) is the travel time of water from the hydraulically most distant point in the watershed to the outflow location. Clark (1945) defined this time as the time from the end of effective rainfall over the watershed to the inflection point on the recession limb of the surface runoff hydrograph as shown in Figure 2. In practice, for ungaged watersheds this time is usually estimated by empirical equations since runoff hydrographs from the watershed are not available.

The second parameter is the storage coefficient, R, which has the dimension of time. This parameter is used to account for the effect that temporary storage in the watershed has on the hydrograph. Several methods are available to estimate R from recorded hydrographs for a basin. As originally proposed by Clark (1945), this parameter can be estimated by dividing the discharge at the point of inflection of the surface runoff hydrograph by the rate of change of discharge (slope of the hydrograph) at the inflection point as shown in Figure 2. Another technique for estimating R is to compute the volume remaining under the recession limb of the surface runoff hydrograph following the point of inflection and to divide the volume by the discharge at the point of inflection. Both of these methods require the ability to identify the inflection point on the recession limb of the runoff hydrograph. This is difficult if not impossible for complex hydrographs and flashy hydrographs such as occur from urban basins and natural watersheds in the Southwest. A method to estimate R by a graphical recession analysis of the hydrograph has been proposed (Sabol, 1988) and this method provides much more consistent results than do the previously described methods. The parameter, R, should be estimated by the analysis of several recorded events; however, in most cases recorded discharge hydrographs are not available and R must be estimated by empirical equations.

The time-area relation, a graphical parameter, is necessary to

compute the translation hydrograph. The time-area relation specifies the accumulated area of the watershed that is contributing runoff to the outlet of the watershed at any point in time. Procedures to develop a time-area relation for a watershed are discussed in a later section of this manual.

The application of the Clark Unit Hydrograph method is best described with a simple example. A watershed is shown in Figure 3(a), and a rainfall hyetograph and rainfall excess distribution are shown in Figure 3(b). For the example watershed and given intensity of rainfall excess the time of concentration is estimated as 25 minutes. An isochrone interval of 5 minutes is selected and the watershed is divided into five zones by isochrones as shown in Figure 3(a). The areas within each isochrone zone are measured and the dimensionless time-area relation is developed as shown in the table and depicted in Figure 3(c). The translation hydrograph of the time rate of runoff is developed by considering each incremental unit of runoff production that would be available as inflow to a watershed routing model. For example, at the end of the first 5 minutes of rainfall excess the runoff that is available at the outlet of the watershed is the product of incremental area A_1, and the rainfall excess R_1.

$$I_1 = (A_1 R_1) \times c/dt$$

where c = 60.5 cfs/acre-inch/minute, and dt = 5 minutes.

$$I_1 = (8 \text{ acres})(.10 \text{ inch})(60.5 \text{ cfs/acre-inch/minute})/(5 \text{ minutes})$$

$$I_1 = 9.7 \text{ cfs}$$

At the end of 10 minutes the available runoff is

$$I_2 = (A_1R_2 + A_2R_1) \times c/dt$$

$$I_2 = (8)(.55) + (24)(.10) \times 60.5/5$$
$$= 82.3 \text{ cfs}$$

At the end of 15 minutes the available runoff is

$$I_3 = (A_1R_3 + A_2R_2 + A_3R_1) \times c/dt$$

$$I_3 = (8)(.30) + (24)(.55) + (38)(.10) \times 60.5/5$$
$$= 234.7 \text{ cfs}$$

At the end of 20 minutes the available runoff is

$$I_4 = (A_1R_4 + A_2R_3 + A_3R_2 + A_4R_1) \times c/dt$$

$$I_4 = (8)(.15) + (24)(.30) + (38)(.55) + (32)(.10) \times 60.5/5$$
$$= 393.5 \text{ cfs}$$

At the end of 25 minutes the available runoff is

$$I_5 = (A_1R_5 + A_2R_4 + A_3R_3 + A_4R_2 + A_5R_1) \times c/dt$$

$$I_5 = (8)(0) + (24)(.15) + (38)(.30) + (32)(.55) + (18)(.10) \times 60.5/$$
$$= 416.2 \text{ cfs}$$

Notice that all rainfall increments after $R_4 = 0$.
At the end of 30 minutes the available runoff is

$$I_6 = (A_3R_4 + A_4R_3 + A_5R_2) \times c/dt$$

$$I_6 = (38)(.15) + (32)(.30) + (18)(.55) \times 60.5/5$$
$$= 304.9 \text{ cfs}$$

At the end of 35 minutes the available runoff is

$$I_7 = (A_4R_4 + A_5R_3) \times c/dt$$

$$I_7 = (32)(.15) + (18)(.30) \times 60.5/5$$
$$= 123.4 \text{ cfs}$$

At the end of 40 minutes the available runoff is

$$I_8 = (A_5R_4) \times c/dt$$

$$I_8 = (18)(.15) \times 60.5/5$$
$$= 32.7 \text{ cfs}$$

After 45 minutes (rainfall excess of 20 minutes plus travel time of 25 minutes) the available runoff is $I_9 = 0$ cfs

~~[Note: A significant~~

The translation hydrograph (I_i) is shown in Figure 3(d). This theoretical hydrograph has the correct volume of runoff from the watershed, however it does not reflect the effects of routing through the watershed. The translation hydrograph is then routed and averaged using Equations 2 through 4 resulting in the final runoff hydrograph. For this example, assume that R = 15 minutes, and the runoff hydrograph is shown in Figure 3(d). Notice that the Clark Unit Hydrograph itself was never really developed but that the three principles of the unit hydrograph were applied directly (mathematically) without having to perform graphical superposition of ratios of a unit hydrograph. Computationally, this process can be completed very quickly and conveniently with a computer program such as is done with HEC-1.

Limitations and Applications

There are no theoretical limitations governing the application of the Clark Unit Hydrograph; however, there are some practical limitations that should be observed. The method that is used to estimate the parameters may dictate limitations in regard to the type or size of watershed that is being considered. If the parameters are estimated through an analysis or reconstitution of a recorded rainfall-runoff event, the parameters would be considered to be appropriate for that particular watershed, regardless of type or size. This is the preferred method of parameter estimation, but there will be limited opportunity for this approach because of the scarcity of instrumented watersheds in Maricopa County. The parameters could be estimated by

indirect methods, such as a regional analysis of recorded data. In this case, application of the parameter estimation procedures should be applied only to those ungaged watersheds that are representative of the watersheds in the data base. Most often, the parameters are estimated by generalized relations that may have been developed from a relatively large and diverse data base. The parameter estimation procedures that are recommended herein are of this last category.

The Clark Unit Hydrograph parameter estimation procedures that are presented in this manual have been adopted, modified, or developed from an analysis of a large data base of instrumented watersheds, controlled experimental watersheds, and laboratory studies; therefore, the application of these procedures is considered to be appropriate for most conditions that occur in Maricopa County. The types of watersheds for which the procedures can be applied include urban, rangeland, developed and natural alluvial fans, agricultural, hillslopes, and mountains.

For study of data and influence of variables on parameters, Watershed size should be limited to 5 square miles or less. The original Clark procedures ~~covered~~ included calculation of components hydrographs. Watersheds larger than 5 square miles should be divided into smaller sub-basins for modeling purposes. Many watersheds smaller than 5 square miles should also be divided into sub-basins depending on the drainage network and degree of homogeneity of the watershed. The subdivision of the watershed into near homogeneous units should result in improved accuracy. Subdivision may also be desirable or required to determine discharges at concentration points within the watershed.

Development of Parameter Estimators

The procedures for parameter estimation are based on available literature, research results, and analysis of original data. For example, the T_c equation is based on the recent research of Papadakis and Kazan (1987). A large data base of recorded rainfall-runoff data was compiled and analyzed in developing and testing the procedures. These data are for instrumented watersheds in Arizona, New Mexico, Colorado, and Wyoming. A

discussion of the development and testing of these procedures is contained in the Documentation Manual that is a companion to this Hydrology Manual.

Estimation of Parameters

The following procedures are recommended for the calculation of the Clark Unit Hydrograph parameters for use in Maricopa County. Other general procedures, as previously discussed, can be used, however, these should be approved by the jurisdictional agency prior to adopting such procedures. If need be. Clark is still living, and has made many improvements over the paper of 1945 which he wrote before the War of 1939, notably in making more real observations.

Time of Concentration -- Time of concentration is defined as the travel time, during the corresponding period of most intense rainfall excess, for water to travel from the hydraulically most distant point in the watershed to the point of interest (concentration point). An empirical equation for time of concentration, T_c, has been adopted with some procedural modifications from Papadakis and Kazan (1987)

$$T_c = 11.4\ L^{.50}\ n^{.52}\ s^{-.31}\ i^{-.38} \qquad (5)$$

where T_c is in hours,

L is length of the flow path for T_c, in miles,

n is a representative watershed resistance coefficient,

S is watercourse slope, in feet/mile, and

i is the average rainfall excess intensity, during the time T_c, in inches/hour.

The selection of a representative watershed resistance coefficient, "n," similar in concept to Manning's "n" in open-channel flow, is very subjective and therefore a high degree of uncertainty is associated with its use. To diminish this uncertainty and to increase the reproducibility of the procedure, a graph is provided for the selection of "n." This graph shown in Figure 4 provides for the selection of "n" based on watershed classification and watershed size. Interpolation can be used for a given watershed size and mixed classification. Equations for estimating "n" are given in Table 1.

TABLE 1

Equation for estimating "n" in the T_c equation.

$$n = m \log A + b$$

where A is drainage area, in acres

Land Classification (1)	Equation Parameters m (2)	b (3)
Urban	-.0025	.02
Bare or nearly bare ground (alluvial fan, agricultural land, desert rangeland)	-.00625	.04
Rough and/or moderate vegetation (hillslopes)	-.01375	.08
Very rough and/or dense vegetation (mountains)	-.025	.15

The value of "i" in Equation 5 requires the knowledge of both the distribution of rainfall excess intensity and the time of concentration, which is, of course, unknown. Therefore, Equation 5 must be solved in a trial-and-error procedure. First, the time distribution of rainfall excess must be estimated for the design rainfall distribution and a graph of average rainfall excess intensity versus time prepared. Then a value of T_c is assumed and the corresponding value of "i" is read from the graph. Equation 5 is solved with that value of "i." If the calculated value of T_c is reasonably close to the value that was assumed for "i" then the solution is finished; if not, then assume a new value of T_c, recalculate "i," and recalculate T_c with Equation 5. The solution for T_c should converge within three trials.

Storage Coefficient -- Very little literature exists on the estimation of the storage coefficient, R, for the Clark Unit Hydrograph. Clark (1945) had originally proposed a relation between T_c and R since they can both be defined by locating the inflection point of a runoff hydrograph (Figure 2). The Corps of

Engineers has discussed the development of regionalized relations for T_c and R as functions of watershed characteristics in Training Document No. 15 (U.S. Army Corps of Engineers, 1982b). According to Corps procedures, T_c and R are estimated from relations of $T_c + R$ and $R/(T_c + R)$ as functions of watershed characteristics. These forms of empirical equations indicate an interrelation of T_c and R, and such dependence was observed in the data base as discussed in the Documentation Manual. The equation for estimating R for Maricopa County is

$$R = 0.37\ T_c^{1.11}\ A^{-0.57}\ L^{0.80} \qquad (6)$$

where R is in hours,

T_c is time of concentration, in hours,

A is drainage area, in square miles, and

L is length of flow path, in miles.

Backwards 1.

Time-Area Relation -- Either a synthetic time-area relation must be adopted or the time-area relation for the watershed must be developed. If a synthetic time-area relation is not used, the time-area relation is developed by dividing the watershed into incremental runoff producing areas that have equal incremental travel times to the outflow location. This is a difficult task and well defined and reliable procedures for this are not available. The following general procedure is often used. First, using a topographic map of the watershed, the distance from the hydraulically most distant point in the watershed is traced along the flow path to the outflow location; this defines L in both Equations 5 and 6. Isochrones are drawn on the map that represent equal travel time to the outflow location. These isochrones can be established by considering the land surface slope and resistance to flow, and also whether the runoff would be sheet flow or would be concentrated in watercourses. A good deal of judgement and interpretation is required for this. Next, the incremental areas are measured and tabulated in an upstream sequence along with the corresponding travel time for each area. A graph is prepared of travel time versus contributing area, or a dimensionless graph can be prepared of time as a percent of T_c

versus contributing area as a percent of total area. The dimensionless graph is preferred because this facilitates the rapid development of new time-area relations should there be a need to revise the estimate of T_c.

Synthetic time-area relations can be used such as the default relation in the HEC-1 program

$$A^* = 1.414(T^*)^{1.5} \qquad 0 \quad T \quad 0.5 \qquad (7)$$
$$1-A^* = 1.414(1-T^*)^{1.5} \qquad .5 \quad T \quad 1.0$$

where A is contributing area, in percent of total area, and
T^* is time, in percent of T_c.

Equation 7 is a symmetric relation and is not recommended for most watersheds in Maricopa County.

Two other dimensionless time-area relations have been developed during the reconstitution of recorded rainfall-runoff events as described in the Documentation Manual. These dimensionless relations for urban and natural watersheds are shown in Figures 5 and 6, respectively. Each of these figures show a synthetic time-area relation and a shaded zone where the time-area relation is expected to lie. It is recommended that for an urban watershed that the synthetic time-area relation of Figure 5 be used, and for a natural (undeveloped) watershed that the synthetic time-area relation of Figure 6 be used. If a time-area relation is developed from the watershed map, which is generally recommended for unusually shaped watersheds, then the resulting relation should lie within the shaded zones in either Figures 5 or 6. The HEC-1 default time-area relation is shown for comparison in each Figure. Tabulated values of the dimensionless time-area relations are shown in Table 2.

Clark taught a tremendous concentration of this real effort into (a) Preparing an area-distance curve in percent of the maxima of area and distance. This is most of the work, but it can be done in the office on nice days. ~~(b)~~ And (b), determining the time of concentration from the most distant point, by more laborous methods involving storms having their most rainfall near the remote point, and producing hydrographs on adjoining ~~streams to~~ smaller streams to show just when the runoff from the remote points really occurred. Using the practical wisdom of observed coord-gamma to express its Clark said "In such analysis, one peak is worth two guesses." and that (c) converting the ~~Area~~-Distance Curve to a ~~Time~~ Area-Time Curve with a second scale of the same curve.

Some of this work is expensive, because it must be done when it is really raining, at whatever inconvenient time. By 1955, Clark was using (Ray dist (and later radar 1955) to geographically locate shadows of rainfall

TABLE 2

Values of the synthetic dimensionless time-area relations for the Clark Unit Hydrograph

Time as a Percent of Time of Concentration	Contributing Area as a Percent of Total Area		
	Urban Watersheds	Natural Watersheds	HEC-1 Default
(1)	(2)	(3)	(4)
0	0	0	0.0
10	5	3	4.5
20	16	5	12.6
30	30	8	23.2
40	65	12	35.8
50	77	20	50.0
60	84	43	64.2
70	90	75	76.8
80	94	90	87.4
90	97	96	95.5
100	100	100	100.0

Excuses for synthetic time-area relations may exist. Most of them are diseases of the nervous system involving a small area of a lazy brain, or a deadly contradiction in the pocket book area. A few areal/aerial photographs will show that ① few natural watersheds are similar and ② some urban waterways were never built where the plans report that they exist!

(A) → Theory

S-Graphs

An S-graph is a dimensionless form of a unit hydrograph and it can be used in the place of a unit hydrograph in performing flood hydrology studies. The concept of the S-graph dates back to the development of the unit hydrograph itself, although the application of S-graphs has not been as widely practiced as that of the unit hydrograph. The use of S-graphs has been practiced mainly by the U.S. Army Corps of Engineers, Los Angeles District, (referred to as the Los Angeles District), and the U.S. Bureau of Reclamation (USBR).

An example of an S-graph is shown in Figure 7. The discharge scale is expressed as percent of ultimate discharge (Q_{ult}), and the time scale is expressed as percent lag. Lag is defined as the elapsed time, usually in hours, from the beginning of an assumed continuous series of unit rainfall excess increments over

(A) Most computer solutions break-down completely in the meteorological conditions that make good floods and times of concentration and theories in ~~good~~ nice sunshiny days leads to this kind of. Reliance on computer methods without machines. Table

the entire watershed to the instant when the rate of resulting runoff equals 50 percent of the ultimate discharge. The intensity of rainfall excess is 1 inch per duration of computation interval (D). An equivalent definition of lag is the time for 50 percent of the total volume of runoff of a unit hydrograph to occur. It is to be noted that there are numerous definitions for lag in hydrology and the S-graph lag should not be calculated by methods that are not consistent with this definition.

Ultimate discharge is the maximum discharge that will be achieved from a particular watershed when subjected to a continuous intensity of rainfall excess of 1 inch per duration (D) uniformly over the basin. Ultimnate discharge (Q_{ult}), in cubic feet per second (cfs), can be calculated from Equation 1

$$Q_{ult} = \frac{645.33\ A}{D} \qquad (8)$$

where A is drainage area, in square miles, and
D is duration of the 1 inch of rainfall excess, in hours.

S-graphs are developed by summing a continuous series of unit hydrographs, each lagged behind the previous unit hydrograph by a time interval that is equal to the duration of rainfall excess for the unit hydrograph. The resulting summation is a graphical distribution that resembles an S-graph except that the discharge scale is accumulated discharge and the time scale is in units of measured time. This graph is terminated when the accumulated discharge equals Q_{ult} which occurs at a time equal to the base time of the unit hydrograph less one duration interval. The basin lag can be determined from this graph at the time at which the accumulated discharge equals 50 percent of Q_{ult}. This summation graph is then converted to a dimensionless S-graph by dividing the discharge scale by Q_{ult} and the time scale by lag.

In practice, S-graphs have generally been developed by reconstituting observed floods to define a representative unit

hydrograph and then converting this to an S-graph. Prior to the advent of computerized models, such as HEC-1, flood reconstitution was a laborious task of rainfall and hydrograph separation along with numerous hand-cranked simulations to define the representative unit hydrograph. Modern S-graph development generally relies on use of optimization techniques, such as coded into HEC-1, to identify unit hydrograph parameters that best reproduce the observed flood.

Although an S-graph is completely dimensionless and does not have a duration of rainfall excess associated with it as does a unit hydrograph, its general shape and the magnitude of lag is influenced by the distribution of rainfall over the watershed and the time distribution of the rainfall. Therefore, the transposition of an S-graph from a gaged watershed to application in another watershed must be done with consideration of both the physiographic characteristics of the watersheds and the hydrologic characteristics of the rainfalls for the two watersheds.

S-graphs are a form of necessary growing-pain to hydrology eminence. All capable flood forecasters have used them in some form or other, until they found more acceptable ways of defining an S.

Limitations and Applications

S-graphs are empirical, lumped parameters that represent runoff characteristics for the watershed for which the S-graph was developed. S-graphs that are developed from recorded runoff data from one watershed can be applied to another watershed only if the two watersheds are hydrologically and physiographically similar. In addition, a recent study for the Flood Control District of Maricopa County (Sabol, 1987) has demonstrated that the shape of S-graphs is significantly affected by storm characteristics, particularly the maximum intensity of the rainfall. Therefore, it may not be advisable to adopt S-graphs that have been developed from one hydrologic zone and to apply these to watersheds in other hydrologic zones because of possible differences in rainfall characteristics in the two zones that may affect the shape of the S-graph.

Application of S-graphs requires the selection of an appropriate

S-graph and the estimation of the one parameter, basin lag. Two S-graphs have been selected for use in Maricopa County and a method to estimate lag is provided.

The USBR has revised the Flood Hydrology Studies chapter of the Third Edition of Design of Small Dams (USBR, 1987), and it has identified six S-graphs for application in generalized regional and physiographic type of watersheds. The flood hydrology procedure in Design of Small Dams should be reviewed and used as a reference when performing drainage studies for major watersheds in Maricopa County. Recently the S-graph has been adopted as the unit hydrograph procedure by Orange County and San Bernardino County, California, and selected S-graphs are presented in the hydrology manuals for those counties. The S-graphs in those hydrology manuals have been selected primarily from S-graphs that previously had been defined by the Los Angeles District from a rather long and extensive history of analyses of floods in California.

More accurate is the reverse statement: An S curve can be made from a correct unit hydrograph.

An S-graph can, in theory, be used in any application for which an unit hydrograph can be used. In practice an S-graph must be first converted to an unit hydrograph, and this can be done by one of two methods. First, The S-graph can be converted to an unit-hydrograph manually; or second, the S-graph can be converted to an unit hydrograph by use of the LAPRE1 program. The LAPRE1 program is a HEC-1 preprocessor program that converts a psuedo-HEC-1 input file containing input for an S-graph to a valid HEC-1 input file. The LAPRE1 program outputs the HEC-1 input file with the S-graph converted to a unit hydrograph, and the unit hydrograph is written to the HEC-1 input file using the UI (Given Unit Graph) record. The use of LAPRE1 greatly facilitates the use of S-graphs and an implementation guide for the microcomputer version of LAPRE1 is contained in Appendix A.

Since ~~if~~ it is a reverse, or inverse, process to start with, one should

An example of the manual conversion of an S-graph to an unit hydrograph follows.

Example: Conversion of an S-graph to a unit hydrograph

not be too surprised to discover the mental illnesses of employees who have spent long hours emulating the backward machines, and have returned to the child like processes of confirmed alcoholics and drug addicts!!

(To be supplied.)

Although an S-graph is completely dimensionless and does not have a rainfall excess duration associated with it, an unit hydrograph does require the specification of a duration. As a general rule, the duration selected for the development of the unit hydrograph should equal about 0.15 times the lag. A duration in the range 0.10 to 0.25 times the lag is usually acceptable.

Sources of S-Graphs

S-graphs for Maricopa County have been selected from a compilation of S-graphs for the Sothwestern United States that was recently completed (Sabol, 1987). The source of S-graphs for that compilation was reports and file data of the Los Angeles District and the USBR. That compilation included 55 individual S-graphs and 18 regional S-graphs. An individual S-graph is one that can be identified with the watershed from which data was used to develop the S-graph. Regional S-graphs are those that are graphical averages or modifications of individual S-graphs to produce an S-graph that is respresentative of a specific physiographic type of watershed.

S-Graphs for Use in Maricopa County

Two S-graphs have been selected for use in flood hydrology studies of major watercourses in Maricopa County. These two are referred to as the Phoenix Mountain and the Phoenix Valley S-graphs. The Phoenix Mountain S-graph is to be used in flood hydrology studies of watersheds that drain predominantly mountainous terrain. For example, this S-graph should be used for the Agua Fria River above Rock Springs, New River above the Town of New River, the Verde River, Tonto Creek, and the Salt River. This S-graph is also appropriate for Indian Bend Wash.

The Phoenix Valley S-graph is to be used in flood hydrology studies of watersheds that have little topographic relief. For example, this S-graph should be used for the Agua Fria River below Rock Springs, New River below the Town of New River, Skunk

Creek, Cave Creek, and urbanized watersheds.

These two S-graphs are shown in Figures 8 and 9, and the coordinates of the graphs listed in Table 3. These same two S-graphs have been selected for similar use in Maricopa County by the U.S. Army Corps of Engineers (1974 and 1982). The justification for the selection of these two S-graphs is provided in the Documentation Manual, and a more comprehensive presentation of S-graphs for Maricopa County is provided in the S-Graph Study report for the Flood Control District of Maricopa County (Sabol, 1987).

Estimation of Lag

The application of an S-graph requires the estimation of the parameter, basin lag. a general relationship for basin lag as a function of watershed characteristics is given by Equation 9

$$\text{Lag} = C \left(\frac{L L_{ca}}{S^p} \right)^m \qquad (9)$$

where Lag is basin lag, in hours,

L is length of the longest watercourse, in miles,

L_{ca} is length along the watercourse to a point opposite the centroid, in miles,

S is watercourse slope, in feet per mile,

C is a coefficient, and

m and p are exponents.

The Los Angeles District often uses C = 20n where "n" is the estimated mean Manning's "n" for all the channels within an area, and m = 0.38. The USBR (1987) has recommended that C = 26n and m = 0.33. Both sets of values in Equation 9 will often result in similar estimates for Lag. Traditionally the exponent, p, on the slope is equal to 0.5.

It should be noted that "n" is a measure of the hydraulic efficiency of the watershed and it is not necessarily a constant

TABLE 3

Tabulation of coordinates for the Phoenix Valley and the Phoenix Mountain S-Graphs

Percent Ultimate Discharge	Time, in Percent Lag	
	Phoenix Valley	Phoenix Mountain
(1)	(2)	(3)
0	0.0	0.0
2	23.0	23.0
4	30.0	31.0
6	36.0	37.0
8	41.0	42.0
10	45.7	46.0
12	50.0	49.8
14	54.1	53.4
16	58.0	56.8
18	61.7	60.0
20	65.2	63.1
22	68.5	66.1
24	71.6	69.0
26	74.6	71.8
28	77.5	74.4
30	80.2	76.8
32	82.7	79.1
34	85.0	81.2
36	87.2	83.2
38	89.0	85.1
40	91.1	86.8
42	92.9	88.8
44	94.6	91.0
46	96.3	93.8
48	98.1	96.8
50	100.0	100.0
52	102.0	103.4
54	104.1	107.0
56	106.3	110.8
58	108.6	114.7
60	111.0	118.7
62	113.5	122.9
64	116.1	127.3
66	118.8	131.9
68	121.6	136.7
70	124.5	141.7
72	127.5	147.1
74	130.7	152.8
76	134.1	158.8
78	137.7	165.5
80	141.5	172.9
82	145.5	181.6
84	149.9	191.0
86	154.6	201.0
88	159.6	212.0
90	165.6	226.0
92	173.6	244.0
94	186.6	265.0
96	200.6	295.0
98	223.6	342.0
100	298.6	462.0

for a given watershed for all rainfall depths and rainfall intensities. As rainfall depth and/or rainfall intensity increases the efficiency of runoff increases and "n" decreases. Therefore, some adjustment in "n" should be made for use with rainfalls of different magnitudes (frequencies). Generally, "n" is the smallest for extreme floods such as PMFs and increases as the frequency of event increases.

Several graphical relations are available for estimating basin lag. One such relation (U.S. Army Corps of Engineers, 1982) is shown in Figure 10. Several other relations that should be consulted when using S-graphs are contained in Design of Small Dams (USBR, 1987).

When estimating basin lag the following steps should be used:

1. From an appropriate map of the watershed, measure drainage area (A), and the values of L, L_{ca}, and S.
2. Calculate the basin factor ($L\ L_{ca}/S^{0.5}$).
3. Use data in Figure 10 and the tables in Design of Small Dams (USBR, 1987) to attempt to identify watersheds of the same physiographic type and similar drainage area and basin factor. Make a list of watersheds with similar drainage areas and basin factors, and tabulate the estimated value of "n" for those watersheds, and the measured lag.
4. Estimate "n" for the watershed by inspection of the tabulation from step 3.
5. Estimate lag by Equation 9. Use values of C and m corresponding to the source (U.S. Army Corps of Engineers or USBR) that was used to estimate "n".
6. Compare the calculated lag with the measured lag for similar watersheds from step 3.

The use of measured values of "n" from hydrograph reconstitutions of similar watersheds will provide the most reliable estimates of "n" and basin lag.

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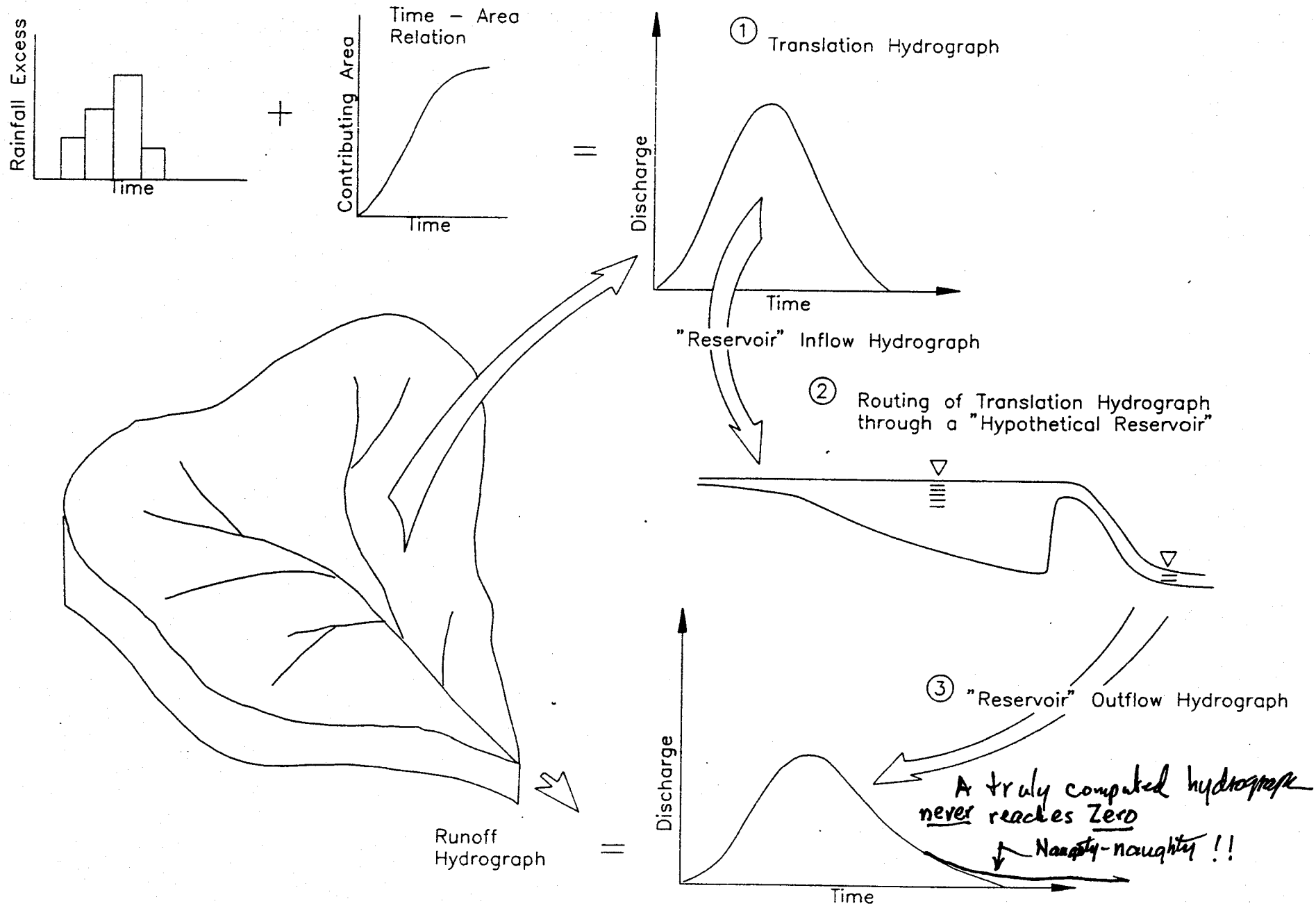


FIGURE 1 Conceptual analogy of linear reservoir routing to generation of a storm hydrograph by the Clark Unit-Hydrograph method

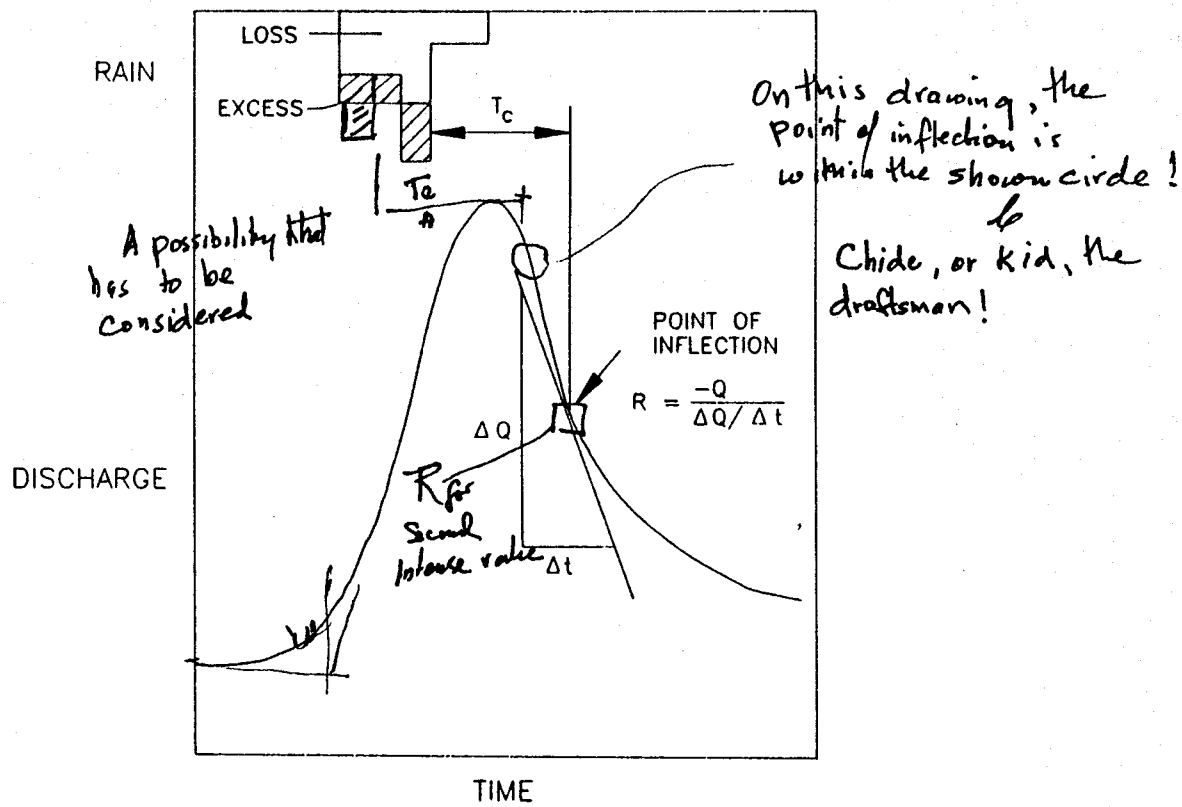
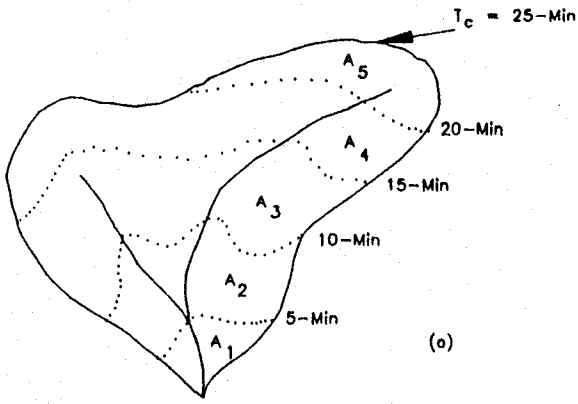
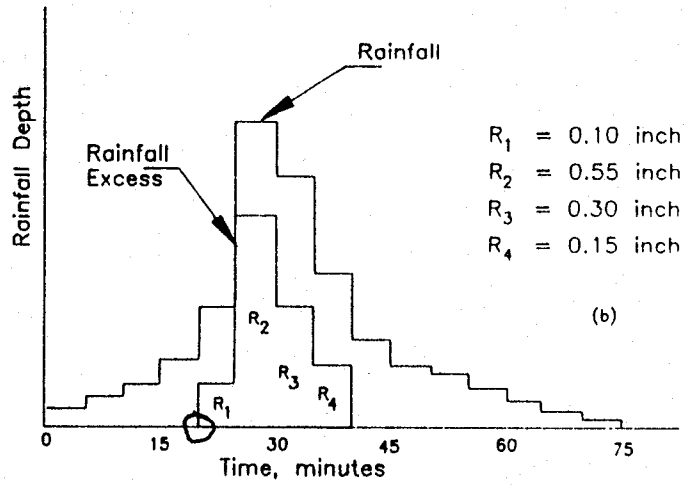


FIGURE 2
Definition sketch of Clark Unit Hydrograph parameters from hydrograph analysis.

If this is a scholarly paper, it might be more free from sketching errors if it were made from real area distance curves and excess periods. This hydrograph shows a rise before there is any rain ?!!



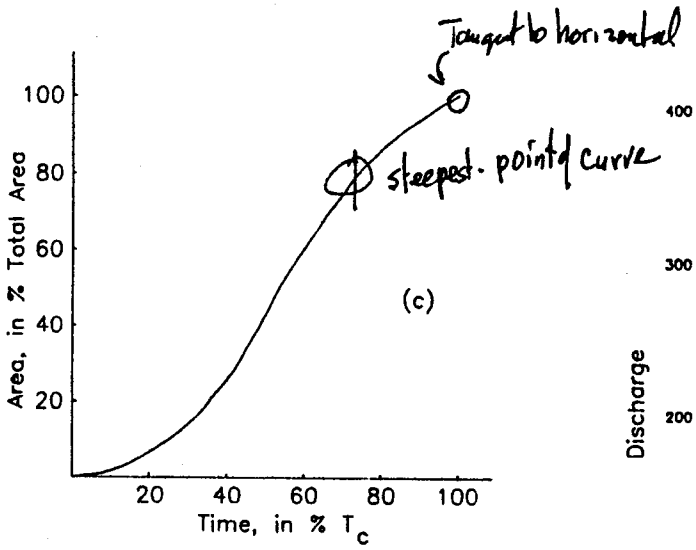
Watershed Map and Isochrones



Rainfall hydrograph and rainfall excess distribution

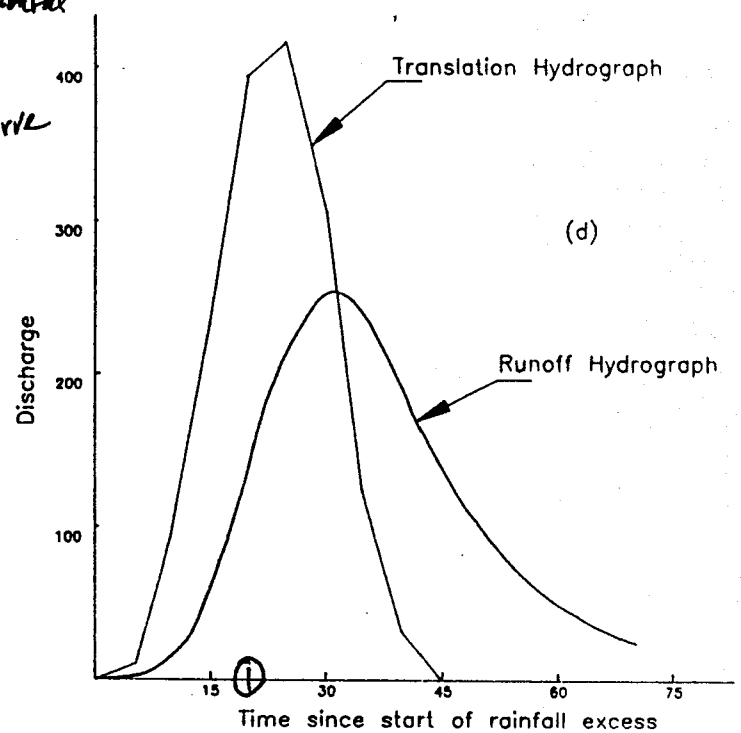
Table showing development of dimensionless time–area relation

Isochrone Zone (1)	Area Acres (2)	Accumulated Area (3)	Accumulated Area as % of Total Area (4)	Travel Time as % of T_c (5)
A_1	8	8	6.7	20
A_2	24	32	26.7	40
A_3	38	70	58.3	60
A_4	32	102	85.0	80
A_5	18	120	100.0	100



Dimensionless Time–Area Relation

Drafting does not really agree with the map shape



Two different time scales

FIGURE 3

Example of storm hydrograph generation using the Clark Unit Hydrograph method

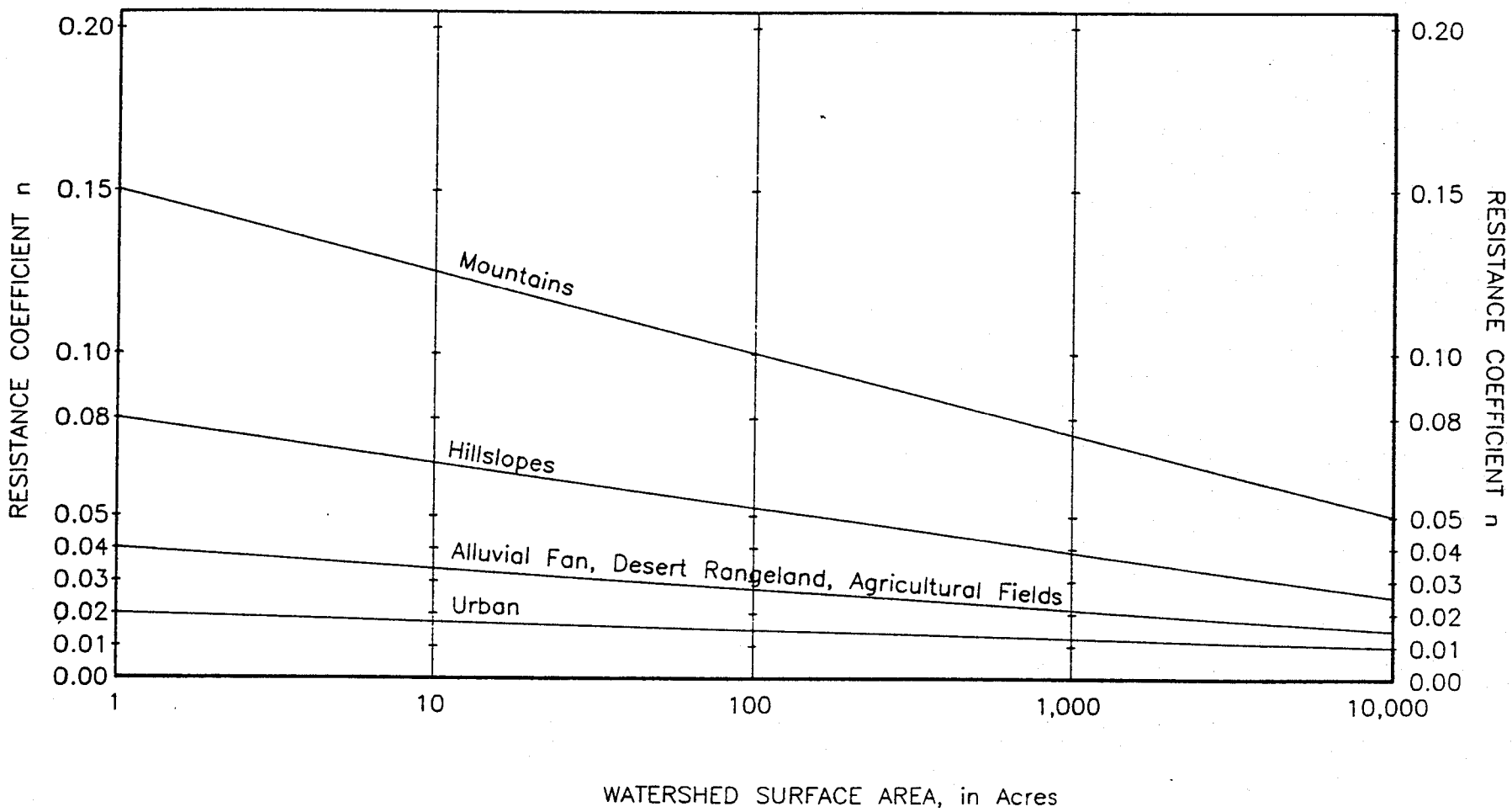


FIGURE 4

Resistance coefficient "n" as a function of watershed type and size

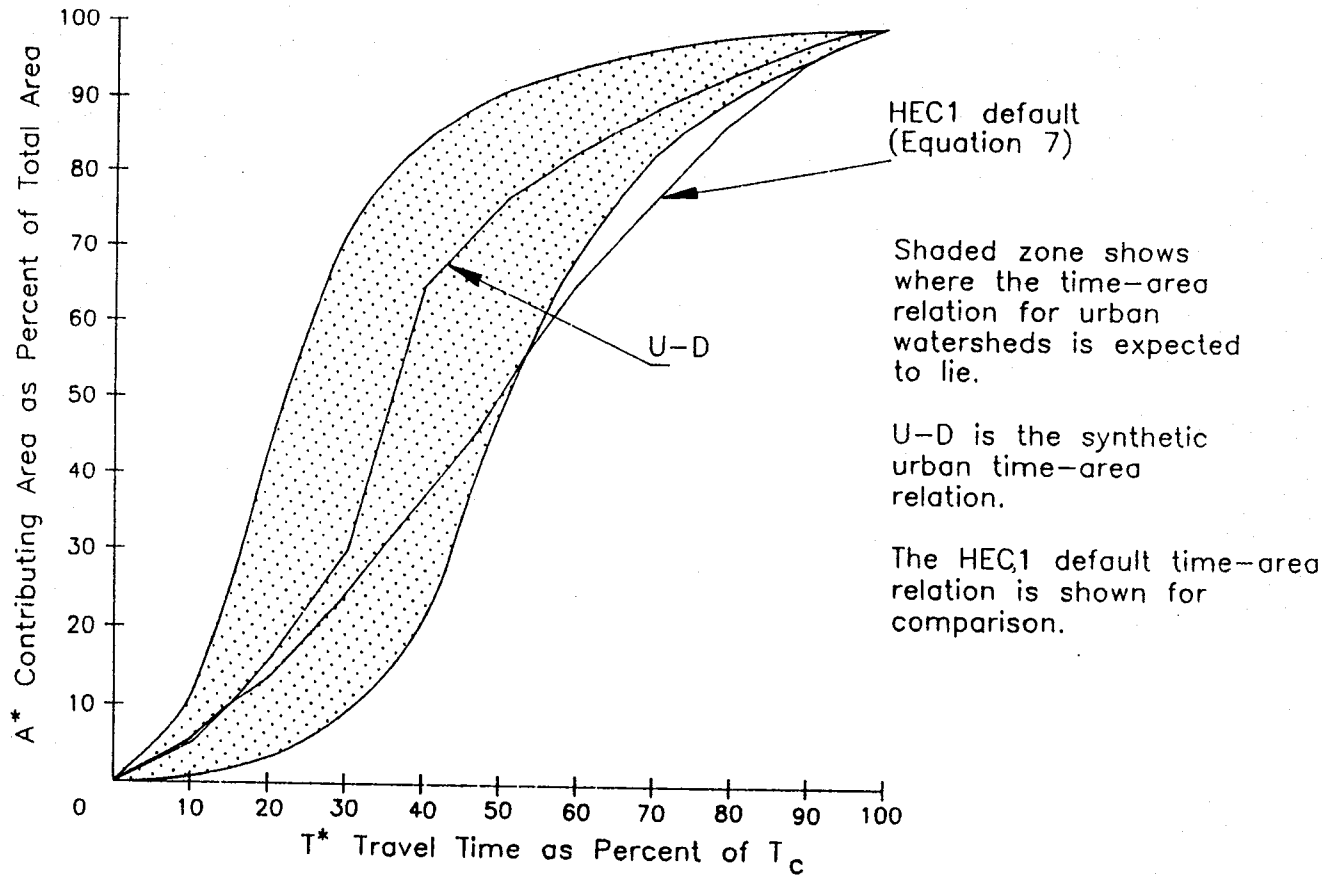
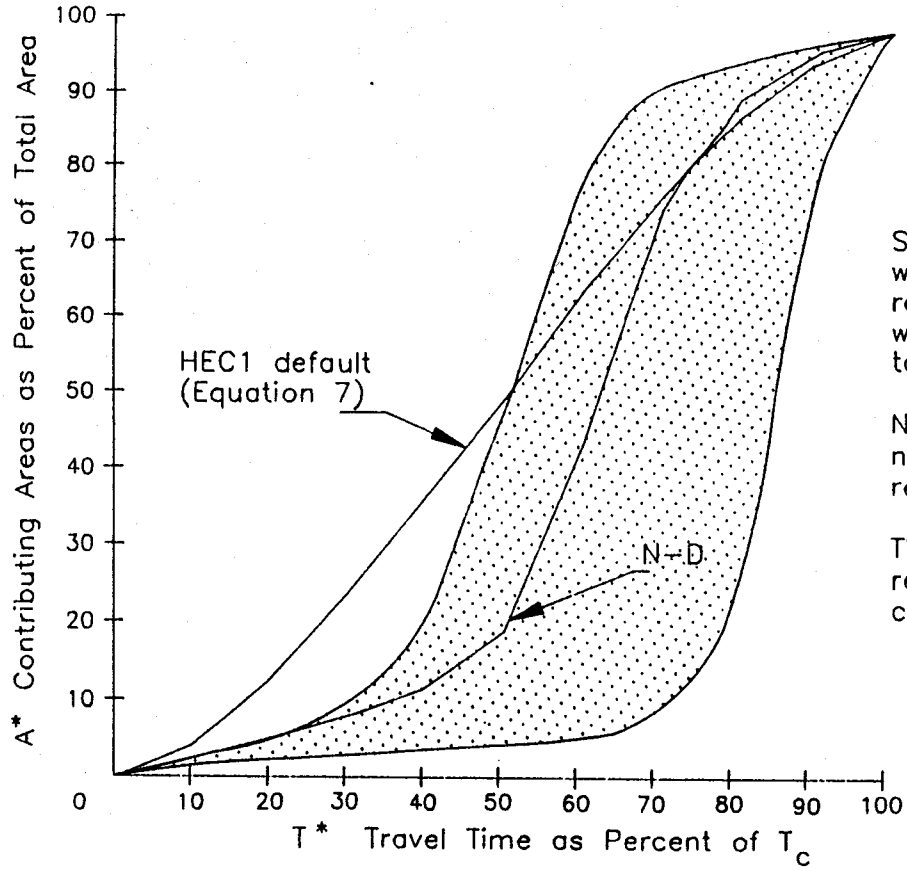


FIGURE 5
Synthetic Time – Area Relation for Urban Watershed



Shaded zone shows where the time-area relation for natural watersheds is expected to lie.

N-D is the synthetic natural time-area relation.

The HEC1 default time-area relation is shown for comparison.

FIGURE 6
Synthetic Time – Area Relation for Natural Watersheds

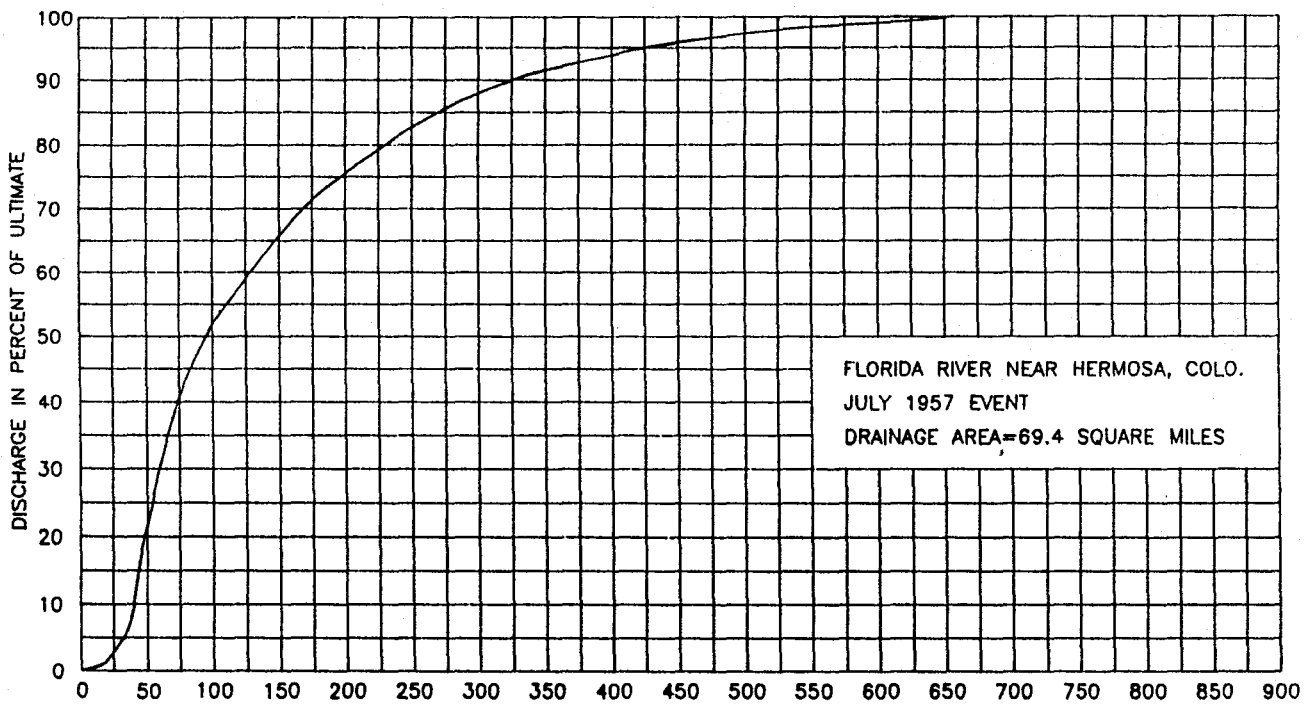


FIGURE 7

Example of S-Graph from Design of Small Dams (USBR, 1987)

This looks suspiciously like a spring-fed surface stream and not a completely surface stream

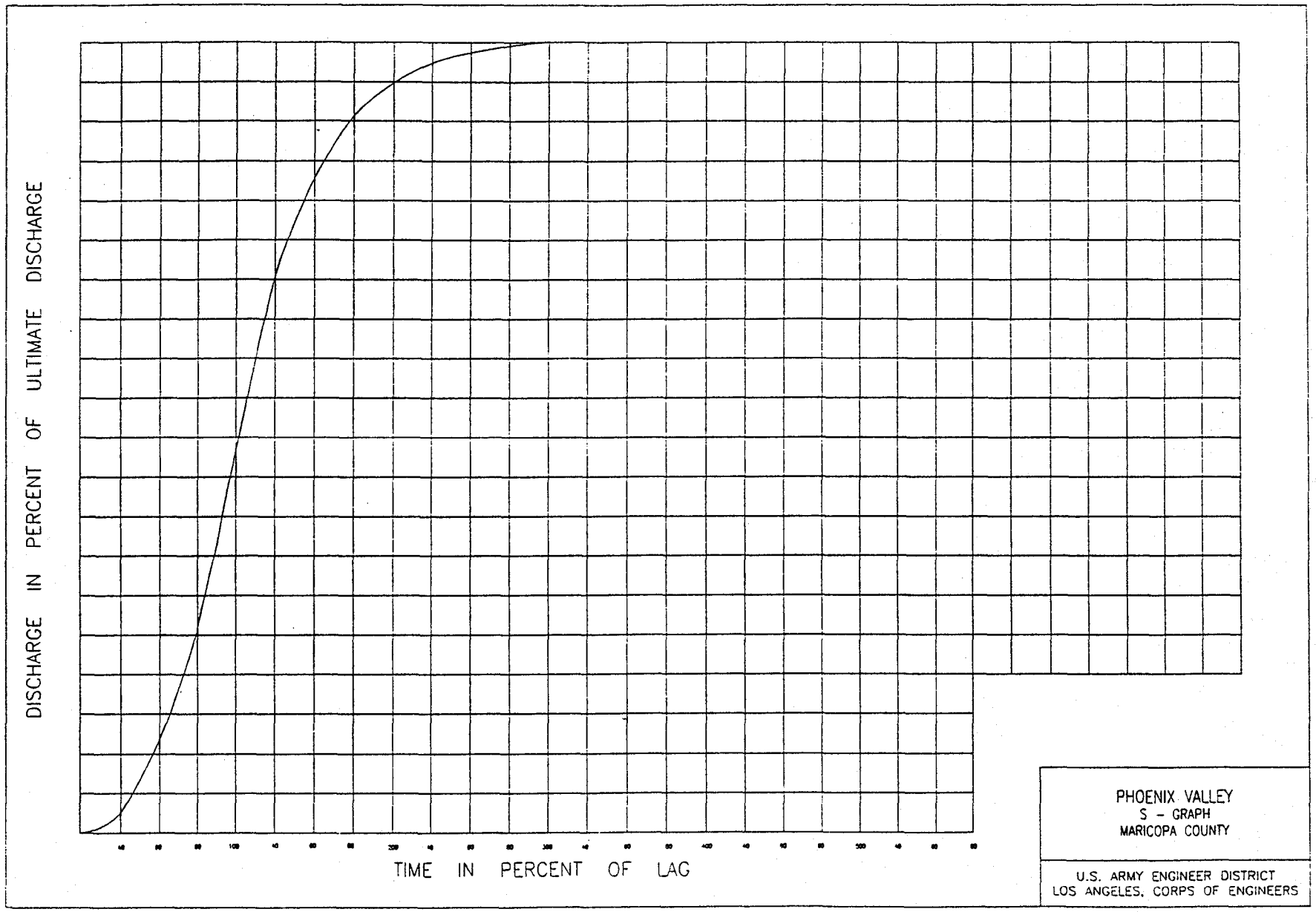

DISCHARGE IN PERCENT OF ULTIMATE DISCHARGE
TIME IN PERCENT OF LAG
PHOENIX VALLEY
S - GRAPH
MARICOPA COUNTY
U.S. ARMY ENGINEER DISTRICT
LOS ANGELES, CORPS OF ENGINEERS

FIGURE 8

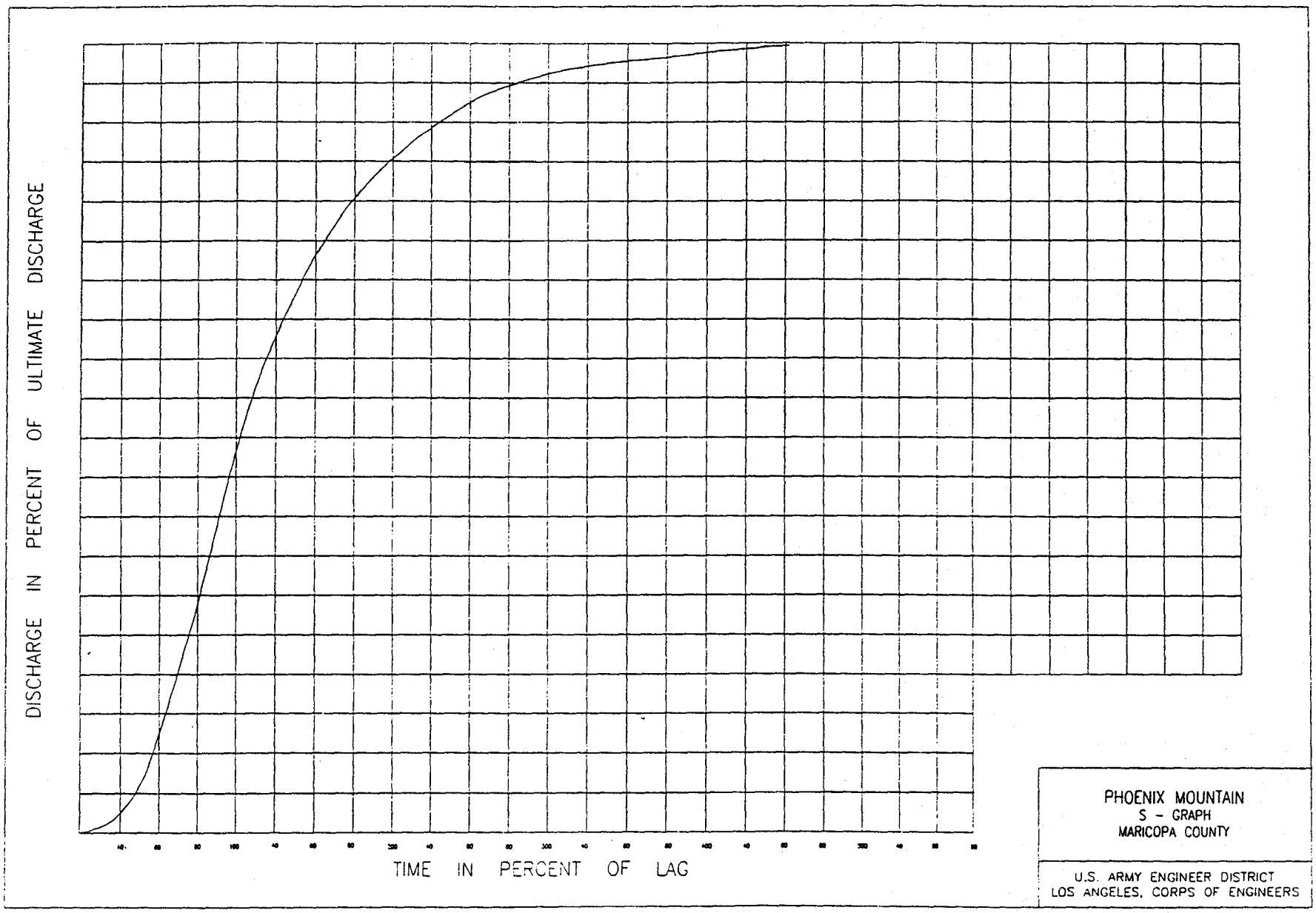

DISCHARGE IN PERCENT OF ULTIMATE DISCHARGE
TIME IN PERCENT OF LAG
PHOENIX MOUNTAIN
S - GRAPH
MARICOPA COUNTY
U.S. ARMY ENGINEER DISTRICT
LOS ANGELES, CORPS OF ENGINEERS

FIGURE 9

		CONTRIBUTING AREA SQ. MI.	L MILES	L_{ca} MILES	S FT./MI.	LAG HOURS	ESTIMATED $\bar{n}$
1.	SAN GABRIEL RIVER AT SAN GABRIEL DAM, CA	162.0	23.2	11.6	350	3.3	0.050
2.	WEST FORT SAN GABRIEL RIVER AT COGSWELL DAM, CA	40.4	9.3	4.3	450	1.6	.050
3.	SAN ANITA CREEK AT SANTA ANITA DAM, CA	10.8	5.8	2.5	690	1.1	.050
4.	SAN DIMAS CREEK AT SAN DIMAS DAM, CA	16.2	8.6	4.8	440	1.5	.050
5.	EATON WASH AT EATON WASH DAM, CA	9.5	7.3	4.4	600	1.3	.050
6.	SAN ANTONIO CREEK NEAR CLAREMONT, CA	16.9	5.9	3.0	1017	1.2	.055
7.	SANTA CLARA RIVER NEAR SAUGAS, CA	355.0	36.0	15.8	140	5.6	.050
8.	TEMECULA CREEK AT PAUBA CANYON, CA	168.0	26.0	11.3	150	3.7	.050
9.	SANTA MARGARITA RIVER NEAR FALLBROOK, CA	645.0	46.0	22.0	105	7.3	.055
10.	SANTA MARGARITA RIVER AT YSIDORA, CA	740.0	61.2	34.3	85	9.5	.055
11.	LIVE OAK CREEK AT LIVE OAK DAM, CA	2.3	2.9	1.5	700	0.8	.070
12.	TUJUNGA CREEK AT BIG TUJUNGA DAM, CA	81.4	15.1	7.3	290	2.5	.050
13.	MURRIETA CREEK AT TEMECULA, CA	220.0	27.2	10.3	95	4.0	.050
14.	LOS ANGLES RIVER AT SEPULVEDA DAM, CA	152.0	19.0	9.0	145	3.5	.050
15.	PACOIMA WASH AT PACOIMA DAM, CA	27.8	15.0	8.0	315	2.4	.050
16.	ALHAMBRA WASH ABOVE SHORT STREET, CA	14.0	9.5	4.6	85	0.6	.015
17.	BROADWAY DRAIN ABOVE RAYMOND DIKE, CA	2.5	3.4	1.7	100	0.28	.015
18.	GILA RIVER AT CONNOR NO. 4 DAM SITE, AZ	2840.0	131.0	71.0	29	21.5	.050
19.	SAN FRANCISCO RIVER AT JUNCTION WITH BLUE RIVER, AZ	2000.0	30.0	74.0	32	20.6	.050
20.	BLUE RIVER NEAR CLIFTON, AZ	790.0	77.0	37.0	65	10.3	.050
21.	SALT RIVER NEAR ROOSEVELT, AZ	4310.0	160.0	66.0	45	18.6	.050
22.	NEW RIVER AT ROCK SPRINGS, AZ	67.3	20.2	9.7	141	3.1	.045
23.	NEW RIVER AT NEW RIVER, AZ	85.7	23.2	13.6	145	3.7	.045
24.	NEW RIVER AT BELL ROAD, AZ	187.0	47.6	20.7	83	5.3	.037
25.	SKUNK CREEK NEAR PHOENIX, AZ	64.6	17.6	10.0	89	2.4	.033

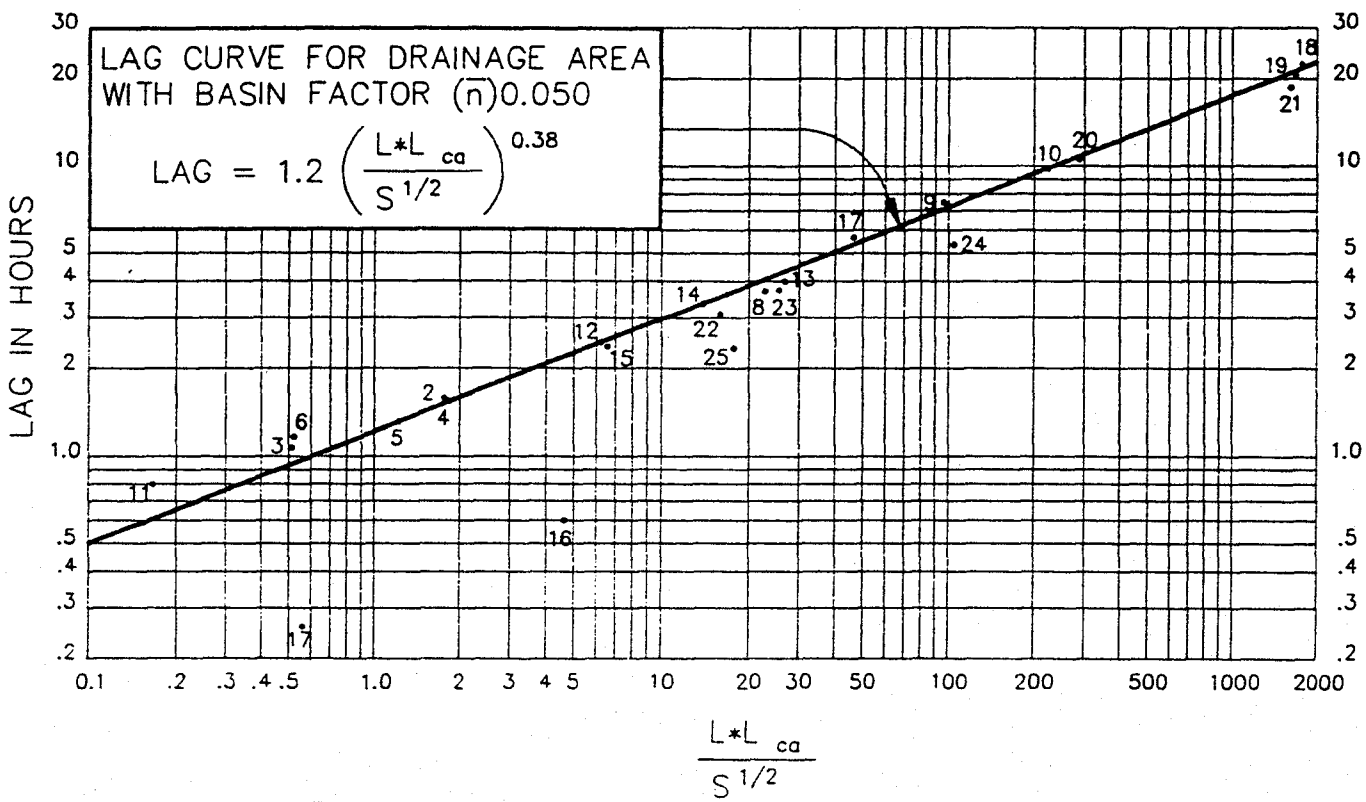
GUIDE FOR ESTIMATING BASIN FACTOR ($\bar{n}$)

$\bar{N}$ = 0.200: DRAINAGE AREAS HAS COMPARATIVELY UNIFORM SLOPES AND SURFACE CHARACTERISTICS SUCH THAT CHANNELIZATION DOES NOT OCCUR. GROUND COVER CONSISTS OF CULTIVATED CROPS OR SUBSTANTIAL GROWTHS OF GRASS AND FAIRLY DENSE SMALL SHRUBS, CACTI, OR SIMILAR VEGETATION. NO DRAINAGE IMPROVEMENTS EXIST IN THE AREA.

$\bar{n}$ = 0.050: DRAINAGE AREA IS QUITE RUGGED, WITH SHARP RIDGES AND NARROW, STEEP CANYONS THROUGH WHICH WATERCOURSES MEANDER AROUND SHARP BENDS, OVER LARGE BOULDERS, AND CONSIDERABLE DEBRIS OBSTRUCTION. THE GROUND COVER, EXLUDING SMALL AREAS OF ROCK OUTCROPS, INCLUDES MANY TREES AND CONSIDERABLE UNDERBRUSH, NO DRAINAGE IMPROVEMENTS EXIST IN THIS AREA.

$\bar{n}$ = 0.030: DRAINAGE AREA IS GENERALLY ROLLING, WITH ROUNDED RIDGES AND MODERATE SIDE SLOPES, WATERCOURSES MEANDER IN FAIRLY STRAIGHT, UNIMPROVED CHANNELS WITH SOME BOULDERS AND LODGED DEBRIS. GROUND COVER INCLUDES SCATTERED BRUSH AND GRASSES. NO DRAINAGE IMPROVEMENTS EXIST IN THE AREA.

$\bar{n}$ = 0.015: DRAINAGE AREA HAS FAIRLY UNIFORM GENTLE SLOPES WITH MOST WATERCOURSES EITHER IMPROVED OR ALONG PAVED STREETS. GROUND COVER CONSISTS OF SOME GRASSES WITH APPRECIABLE AREAS DEVELOPED TO THE EXTENT THAT A LARGE PERCENTAGE OF THE AREA IS IMPERVIOUS.



TERMINOLOGY

L = LENGTH OF LONGEST WATERCOURSE

L_{ca} = LENGTH ALONG LONGEST WATERCOURSE, MEASURED UPSTREAM TO POINT OPPOSITE CENTER CENTER OF AREA.

S = OVER-ALL SLOPE OF LONGEST WATERCOURSE BETWEEN HEADWATER AND COLLECTION POINT.

LAG = ELAPSED TIME FROM BEGINNING OF UNIT PRECIPITATION TO INSTANT THAT SUMMATION HYDROGRAPH REACHES 50% OF ULTIMATE DISCHARGE.

$\bar{n}$ = VISUALLY ESTIMATED MEAN OF THE n (MANNING'S FORMULA) VALUES OF ALL THE CHANNELS WITHIN AN AREA.

NOTE:
TO OBTAIN THE LAG (IN HOURS) FOR ANY AREA, MULTIPLY THE LAG OBTAINED FROM THE CURVE BY:

$\frac{\bar{n}}{0.050}$ OR 20n

FIGURE 10

LAG RELATIONSHIPS

U.S. ARMY CORPS OF ENGINEERS (1982)